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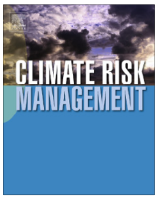

Vulnerabilities to agricultural production shocks: An extreme, plausible scenario for assessment of risk for the insurance sector

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ABSTRACT

Climate risks pose a threat to the function of the global food system and therefore also a hazard to the global financial sector, the stability of governments, and the food security and health of the world's population. This paper presents a method to assess plausible impacts of an agricultural production shock and potential materiality for global insurers. A hypothetical, near-term, plausible, extreme scenario was developed based upon modules of historical agricultural production shocks, linked under a warm phase El Niño-Southern Oscillation (ENSO) meteorological framework. The scenario included teleconnected floods and droughts in disparate agricultural production regions around the world, as well as plausible, extreme biotic shocks. In this scenario, global crop yield declines of 10% for maize, 11% for soy, 7% for wheat and 7% for rice result in quadrupled commodity prices and commodity stock fluctuations, civil unrest, significant negative humanitarian consequences and major financial losses worldwide. This work illustrates a need for the scientific community to partner across sectors and industries towards better-integrated global data, modeling and analytical capacities, to better respond to and prepare for concurrent agricultural failure. Governments, humanitarian organizations and the private sector collectively may recognize significant benefits from more systematic assessment of exposure to agricultural climate risk.

1. Introduction

Climate change presents significant risk to global agricultural systems, including warming and shifts in precipitation patterns (Adams et al., 1998; Fedoroff et al., 2010; Rosenzweig et al., 2014), which has already started affecting the production of major crops (Dai et al., 2004; Lobell et al., 2011; Lobell and Field, 2007). Extreme weather events pose considerable risks for global food production; droughts and floods, in particular, can reduce agricultural productivity in affected areas (Dai, 2011; Postel, 1998; Rosenzweig et al., 2002). Biotic pressures such as pathogens and insects reduce yields and are likely to become increasingly challenging in the future (Juroszek and von Tiedemann, 2013; Kamenidou et al., 2013; Luck et al., 2011; Porter et al., 1991; Sutherst, 1991). Precipitation and temperature extremes have already been linked to climate change (Coumou and Rahmstorf, 2012) and are increasing in frequency and intensity (Alexander et al., 2006; Coumou et al., 2013; Easterling et al., 2000; Groisman et al., 2005; Klein Tank et al., 2006), a phenomenon that is visible at the decadal

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scale (Hansen et al., 2012). These extremes are expected to worsen as the atmosphere continues to warm (Cook et al., 2015; Meehl and Tebaldi, 2004; Sheffield and Wood, 2007), because relatively small changes in mean temperature can result in relatively large increases in the frequency of extreme events (Mearns et al., 1984; Rosenzweig et al., 2001; Trenberth, 2012). Interruptions to the global food system are likely to have strong reverberating impacts upon global human health, and on economies and geopolitics in both the developed and developing world. In addition, global sensitivities to food system interruptions are expected to worsen as population grows, markets become more linked across the world, political fragility intensifies in various regions, and food systems continue to receive less investment than required (Challinor et al., 2010; Comenetz and Caviedes, 2002; Fraser et al., 2005; Godfray et al., 2010; Nelson et al., 2014).

Agricultural climate risk is increasingly recognized as a significant problem not just for industrialized agricultural producers, but for other stakeholders including underwriters and insurers (Maynard et al., 2013), smallholder farmers and vulnerable populations (Headey and Fan, 2008, 2010; Rurinda et al., 2014; Seaman et al., 2014), governments (Kraemer, 2014; McElroy and Baker, 2014), the financial sector, distributors processors and shippers, and other stakeholders. Despite the possible immediacy and potential magnitude of agricultural production failures, the current state of the science to describe and quantify probabilities of specific risks, implications and relevant uncertainties is still nascent (Dai, 2011; Jayanti and Husak, 2013; Naylor et al., 2007; Rosenzweig et al., 2014), further limited by lack of reliable data and other constraints (Müller, 2011; Devarajan, 2013; Fraser et al., 2005; Headey, 2011; Jayanti and Husak, 2013; Jerven, 2014; Maynard et al., 2013; Nelson et al., 2014; Sachs et al., 2010).

This paper presents the results of a partnership between scientific researchers and the insurance sector to explore the plausible impacts of agricultural system disturbances through the development of a multiple-crop production shock scenario. The scenario is based on work done for the Lloyd's of London Emerging Risk Report 2015, Innovation Series: Food System Shock – The Insurance Impacts of Acute Disruption to the Global Food Supply (Maynard, 2015). The scenario is set within one calendar year in a theoretical near future. The scenario does not attempt prediction of specific outcomes, rather proposes a plausible yet extreme confluence of hypothetical events.

2. Methods

To better elucidate agricultural climate risk implications for insurers and underwriters, Lloyd's of London commissioned a hypothetical shock scenario wherein plausible, largely weather-driven events result in a major global shortfall in agricultural production, with follow-on financial, geopolitical and societal effects. Insurers employ a 1-in-200 year regulatory requirement for hypothetical disasters ranging from market shocks, to rioting and unrest to terrorist acts (Heath et al., n.d.; Smillie et al., 2014; von Bomhard, 2010); this 1-in-200 year "rare but plausible" reference point provides a scale by which to stress-test one-year exposure to liability for a variety of events, so the industry can backstop their disaster risk exposure with appropriate precautions such as minimum capital requirements (Clarke et al., 2012; Heath et al., n.d.; Michel-Kerjan and Morlaye, 2008).

Lloyd's of London is a major insurance marketplace based in the United Kingdom, with a regulatory function requiring the production of scenarios to categorize and quantify exposure to an array of different plausible mega-risks, and to make those risks known and available to insurers worldwide. This scenario constitutes a first attempt to assess whether such risks are material to the insurance sector. Insurers and underwriters are increasingly cognizant of exposure to agricultural risk through a variety of potentially significant claims beyond conventional agricultural risk across many classes of insurance, such as terrorism and political violence, aviation and marine, political risk, business interruption, environmental liability, and product liability and recall (Maynard et al., 2013). The range of these claims is far broader and more systemic than currently reflected or regulated because of the obvious global and interconnected natures of markets, finance, agricultural and climatic systems (Goodwin and Hungerford, 2015; Miranda and Glauber, 1997; Xu et al., 2010).

Among the many approaches to scenario development (e.g., Schoemaker, 1995), the insurance sector requires a test to establish whether a particular shock is formally material at an annual average return of at least 1-in-200. Given that most scenario techniques focus on developing future visions that are possible or likely given a set of pre-conditions, even if the scenarios are used to test the extremes of these pre-conditions, the insurance sector uses expert 'best guess.' In this study, plausibility was established by using historical events as models that were then compressed temporally through a series of interactions supported by, or not contraindicated by current scientific understanding. These best-guess events were then rigorously tested through event modeling, either through historic trend analysis, climate modeling or independent expert qualitative interviews. The end result is one, or a set, of narratives that bring a set of events together to generate a plausible impact. Experts judged this scenario to be considerably more probable than 1 in 200 year annual average return. Hypothetical scenario effects take place within one calendar year, the format used by the insurance sector.

The agricultural production shock scenario presented in this paper affects multiple growing regions within an annual cycle, reducing yields of four major commodity crops – maize, wheat, rice, and soybean. The magnitude of each crop production shock was based upon de-trended historical FAO production data from 1961–2013, which was used to collate a modular "library" of different past production shocks of different classes and magnitudes. Three de-trending approaches were employed in the R statistical software package (linear regression, polynomial regression, and Friedman's SuperSmoother (Friedman, 1984) to normalize country-level and global production data against shifts in crop area, yield, technological improvements, and other factors. The midpoints of the range of reduction in production across the three de-trending methods, due to specific historical production shock events, were used to parameterize each component shock in the scenario (Fig. 1).

Production shocks to each individual crop presented within this scenario – wheat, rice, maize and soybean – are equal or smaller than detrended maxima within the past 50 years (Table 1). Biotic crop yield reductions were set from expert consultations and the literature.

Selected historical modules of dispersed meteorological phenomena under an El Niño–Southern Oscillation (ENSO) warm phase that were not contraindicated, and that mirrored historical global teleconnections affecting precipitation and temperature across multiple agricultural regions within the same year were compiled. The ENSO is a primary driver of global weather variability with significant effects upon agricultural production (Adams et al., 1999; Dilley and Heyman, 1995; Hansen et al., 1998; Parthasarathy et al., 1987; Ropelewski and Halpert, 1987; Zubair, 2002). Although prediction of ENSO-mediated teleconnections and weather variability is still limited (Joseph and Nigam, 2006; Trenberth and Fasullo, 2012; Turner and Annamalai, 2012), there is some understanding of the more reliable weather effects such as dryness in central and peninsular India, moisture in northern Argentina and the United States, and dry conditions in Australia. Consequently, an ENSO teleconnective framework was employed to build the scenario.

Historical responses to past agricultural production shocks set a baseline for the political and economic responses in the scenario placed within the political context of the present day. Past events served as benchmarks for scenario price shocks, financial system impacts, and geopolitical ramifications within current global parameters of trade, currency, foreign affairs, food reserves, and other factors. The impact on financial variables is highly uncertain for a future event, depending on current market sentiment, individual behavior, precise relative timing of events and other factors in markets including policy, such as the scale of government intervention including the impact of quantitative easing (QE). We assessed the financial impacts of the food shocks in 1973/4 (which occurred alongside an oil price shock), the 2008 food price shock and the September 11, 2001 terrorist attack on equities, sovereign risk (Kraemer, 2014), stock markets, US Treasury bonds, corporate bond yields and gold.

Expert review and consultation provided key insight and commentary into the plausibility and magnitude of each scenario component. Experts were instructed to note any contraindications and to indicate whether they believed the scenario as a whole to be “plausible yet extreme.” More than twenty leading experts in relevant fields served as reviewers. In multiple cases, outside expert opinion led to the removal and/or alteration of scenario components. Knock-on responses, the plausible

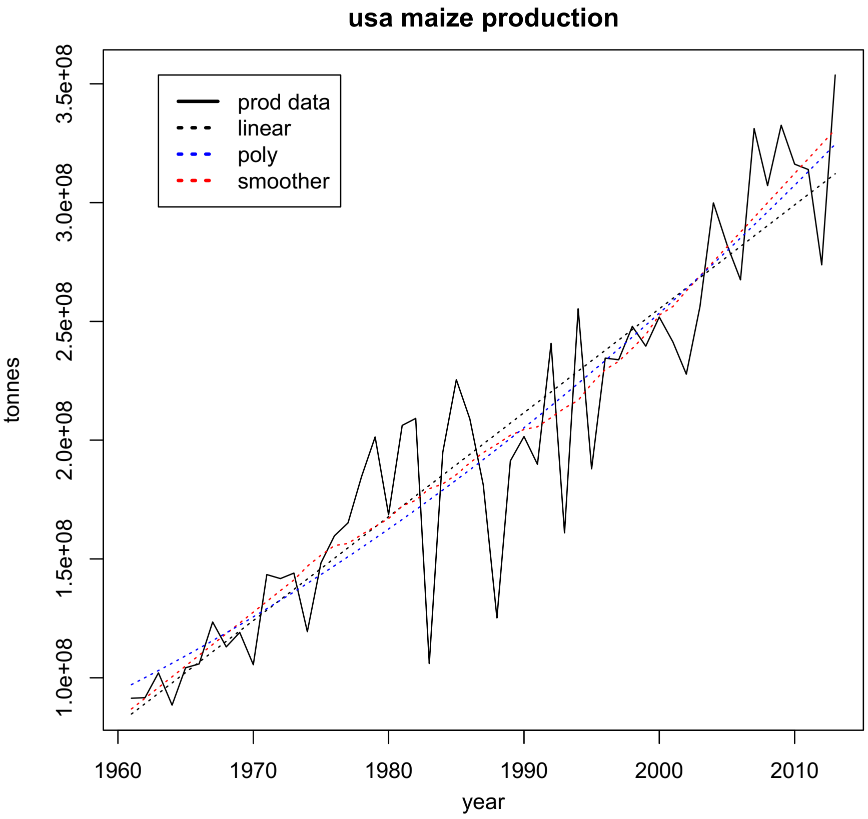

Fig. 1. Historical USA maize production data (FAO) with three trendlines: linear regression, polynomial regression, and Friedman’s SuperSmoother. The average of the three lines was used to de-trend production data to quantify year-to-year variability and historical production shocks.

Table 1
Crop production shock magnitudes, by crop, under the scenario with major contributing factors and historical maximum crop production shocks from 1960–2013 (FAO data), shock year, and major contributing factors to those historical shocks.

Crop	Scenario shock	Contributing factors	Historical max	Year	Contributing factors
Maize	−10%	USA flood	−18%	1983	USA drought
Rice	−7%	India, SE Asia drought	−8%	2002	India drought
Wheat	−7%	Drought, rust	−10%	2003	Low China prod, heat
Soy	−11%	USA flood, rust	−17%	1991	Brazil production shortfall

size of insurance price, and insurance loss or asset valuations, were tested in three workshops hosted by Lloyd's of London and Aviva. Each involved approximately 10 experts from the insurance, investment and actuarial professions. These workshops held in late 2014 and early 2015 presented initial findings of the scenario and plausible responses during which specific aspects of the scenario was adjusted to reflect consensus on the likely scale of impact. The scenario was finalized immediately following these workshops, therefore some projections for markets or the geo-political background have changed. To be relevant to the insurance sector, the scenario is set in the immediate future (a 2016 scenario).

3. Results

The basic outcomes of the scenario are presented in Table 2. For a more in-depth explanation of the meteorological foundations of the scenario, political and economic effects, see Maynard (2015). The combined impacts of the scenario agricultural production shocks result in global crop production declines of 10% for maize, 11% for soy, 7% for wheat and 7% for rice. As a result, quadrupled commodity prices and commodity stock fluctuations, coupled with civil unrest, cause significant negative humanitarian consequences and major financial losses worldwide.

> Wheat, maize and soybean prices increase to quadruple the levels seen around 2000. Rice prices increase 500% as India starts to try to buy from smaller exporters following restrictions imposed by Thailand. Public agricultural commodity stocks increase 100% in share value, agricultural chemical stocks rise 500% and agriculture engineering supply chain stocks rise 150%. Food riots break out in urban areas across the Middle East, North Africa and Latin America. The euro weakens and the main European stock markets lose 10% of their value; US stock markets follow and lose 5% of their value. [Maynard (2015).]

4. Discussion

A major global agricultural production shock will, with certainty, generate an array of impacts of great significance to humanity. The scenario described in this paper is a tool that results from a structured dialog between the academic scientific community and those responsible for assessing emerging risks to insured assets and insurance capital. This tool is specifically relevant to pricing, potential regulatory and other actions on the part of insurers and reinsurers, but a major agricultural production shock would also likely have major effects on governments, potential conflict and unrest, vulnerable and food insecure populations, NGO and aid workers, farmers, and the financial sector. While it is very difficult to predict agricultural production shocks and their ramifications, this work provides a plausible view of a suite of vulnerabilities of global food systems. This scenario has catalyzed and furthered scientific, regulatory, and public policy decisions and discussions of adaptation to and mitigation of such shocks, and approaches to better value risk avoided.

Table 2
Crop production shock factors in the scenario, and global production shocks by crop (Maynard, 2015).

Shock	Description	Crop affected	Location	Timing
Asian soybean rust	Virulent strain expands from Brazil into Argentina after a warm winter	Soybean	Argentina, Brazil	January–June
Mississippi river flood	Winter snows and spring rains flood Mississippi and Missouri rivers	Maize	Midwest United States	February–May
Wheat stem rust	UG99 stem rust expands further from Middle East	Wheat	West Asia, Russia, India	January–June
India drought	Strong drought reminiscent of events in 2002	Rice, wheat	South Asia	June–December
South Asia flood	Torrential rains in the region cause flooding in affected areas	Rice	Nepal, Bangladesh, Northeast India, Pakistan	June–December
Southeast Asia drought	Variations in monsoonal patterns cause precipitation shortfalls	Rice	Southeast Asia	June–December
Australia drought	Strong droughts in wheat producing areas	Wheat	Eastern and Southeastern Australia	June–December

Over the last century there have been several agricultural production shocks that have resulted in 10% of a single global grain crop yield lost in a single year. These production shocks often, but not always, lead to export shocks and price shocks. Past price shocks for major grains have varied from 100% to 200% increases or higher. A production shock becomes a global supply shock if trade and export restrictions result.

There are a number of factors that influence how individuals, organizations and countries respond to an agricultural production shock. Immediate short-term responses include export or customs restrictions, speculation, contract defaults and preferential trade agreements, loss of critical infrastructure for export, management of food stocks, land use changes and black market response. Longer term amplifying or mitigating factors can include issues more directly associated with the food system, such as the level of global food stocks (Wright, 2009), yet they often relate to indirect economic factors such as the strength of the US dollar (Headey and Fan, 2008). Inter-hemispheric crop allocation has been offered as a potential mitigating response to agricultural shocks, as farmers in one hemisphere may see the reduction of a specific crop in the other hemisphere and may base their planting decisions to capitalize on higher prices (Lybbert et al., 2014). However, the spread of crops across hemispheres is not well suited to this buffering. Prior studies do not incorporate multiple crop region failures and only investigate effects of relatively small shocks.

A key factor in whether a production shock leads to a price shock is the level of global stocks (Wright, 2009). Historically when global stocks are low (below 80 days of global consumption), agricultural production shocks can lead to price shocks. When global stocks are high (above 90 days of consumption), a price shock has rarely followed. In 2015, stocks were relatively low. Without a strategic global response to food security, it is unlikely that they will rise. Stock management by countries is currently set out within the World Trade Organization's Uruguay Round reform program. Many commentators have expressed a view that the US biofuel production could be seen as a virtual stock in time of crisis, however, in general, biofuel production increases over the last decade have led to higher food prices (Roberts and Tran, 2013)

An important aspect of food responses is the current state of political fragility (Natalini et al., 2015) and the ability to control exports or imports within a country. To reflect this, key trends in fragile states, or political trends that could lead to increased fragility, were included in the responses considered in this scenario. Past food riots and export restrictions were also considered because countries which have previously experienced food riots or implemented export restrictions are more likely to repeat these in the future.

Policy makers and academics have noted an urgent need to acquire and maintain necessary data, modeling and probabilistic capacities as a public good to adequately characterize and mitigate agricultural exposure and vulnerability to extreme events and climate risks (Selvaraju, 2012) to protect against disturbance to exposed sectors and to limit potentially disastrous consequences for the global economy and people. Accomplishing this task will require integrated and forceful effort from researchers, industry, non-governmental and regulatory bodies, and farmers around the world. In this paper, we highlight the importance of events that could affect multiple agricultural commodities within the same annual cycle. Data needs are large, and gaps are significant. Modeling agricultural production shocks, and concomitant effects requires global historical datasets for agricultural production variables, food stocks and flows, market functions, social unrest, human health outcomes, and weather. Many of these data are unreliable, inaccessible, limited in time horizon, or simply unavailable. Utilizing and synthesizing extant data is difficult and labor intensive due to format and metadata inconsistencies, divergent scales and scopes, and lack of data persistence.

Data integration and sharing through conflation, semantic ontologies, consistent metadata standards, open access and institutional partnership would improve the ability to conduct large-scale analyses and transdisciplinary model building with greater accuracy and effectiveness, and should be prioritized for investment (Andelman et al., 2004; Athanasiadis et al., 2009; Fegraus et al., 2005; Macario and Medeiros, 2009; Madin et al., 2008; Michener, 2006; Rosenzweig et al., 2013; Ruiz et al., 2011). The National Database for Flora and Fauna (NDFF) (Veen et al., 2012), the Agricultural Model Intercomparison and Improvement Project (AGMIP) (Rosenzweig et al., 2013; von Lampe et al., 2014), the Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM) (Whitcraft et al., 2015), and the Human Genome Project (Collins et al., 2003) have grappled with relevant data coordination and management problems, and provide insight into ways forward given adequate scientific and donor support. Existing efforts should be expanded, such as building on the efforts of the National Integrated Drought Information System (NIDIS) to create a global drought and water monitoring portal, or adapting the Famine Early Warning Systems Network (FEWS NET) approach to create an early warning system for global agricultural conditions. The soil is a complex and hidden underpinning of our agricultural productivity, and so have been soil data. With the advent of new analytical approaches, various forms of sensing and strong global collaboration (e.g., GlobalSoilMap and the Global Soil Partnership), new, simplified and functional forms of soil data are being built and made available for integration with data on the other elements of our ecosystems and societies (Arrouays et al., 2014; Vaysse and Lagacherie, 2015). This approach should be replicated with other agricultural data streams and integrated. Expanding upon other national resources such as USDA's World Agricultural Supply and Demand Estimates, combined with data from private sector and/or financial industry information, would improve scientific and market understanding of agricultural stocks and flows. Integrating the efforts of separate but related programs, such as AGMIP and GEOGLAM, should be encouraged, commended, and expanded upon. It would be advantageous to create collaborative, pre-competitive spaces and knowledge systems capable of addressing agricultural futures. Amenable policy environments, public-private collaborations such as exemplified in this study, and prioritization of research funding to focus on the study of dynamics and conditions that could produce and result from multiple breadbasket failure are imperative.

This paper highlights the need to take the next steps to better characterize and quantify probabilities and uncertainties of specific events affecting agricultural systems. Improved capacity to model plausible tail risk, and the shifts in tail risk due to climate change, extreme events and other pressures, will be necessary to better describe the probability of agricultural production shocks now and in the future. The above scenario provides a foundation for future studies that assess probabilities more precisely than the 1-in-200 benchmark used in this approach. Given limited data, high rates of change in agriculture and climate, and the lack of records of crop losses and indirect insurance claims in much of the world, concerted focus and innovative approaches to sensitivities of risk projections will be essential to advance our capability to describe and manage these risks.

As data tools become more available, there will then be an increasing need for a coordinated response by the 'user' community to create knowledge transfer channels to move relevant information into decision-making processes and provide relevant data back to the scientific communities. Some examples of these types of programs include the ARISE initiative for disaster risk-sensitive investments, the 1-in-100 initiative to integrate risks into the financial system, IIASA's GLOBIOM land use model (Ermolieva et al., 2015), and IFPRI's IMPACT model array (Rosegrant and IMPACT Development Team, 2012).

An especially important priority for future work will be to integrate impacts of agricultural climate risk upon smallholder farmers and other highly vulnerable populations, who would not be appropriately represented under analyses of financial system shocks and insurance liabilities. Agricultural climate risk is composed of more than simply production risk, posing hazards to input suppliers, intermediaries, processors, marketers, and consumers (Hill and Pittman, 2012). Future risk analyses must better account for this. When including societal and ecological events in combination, it is likely that multiple methodologies will be required where automated approaches to data and model management could be revolutionary. For example, a scenario may utilize climate models to predict short-term weather events, which then cascade into risks of broader societal effects that may be more difficult to quantify directly such as market responses, or potential for terrorist acts.

Uncommon partnerships between researchers, industry, government and media provide a method to leverage the long reach of agricultural and food system risks towards motivating new scientific knowledge and risk management solutions. Such partnerships also offer a different model of engaging the public with academic inquiry. Lloyd's of London's collaborative leadership in investigating agricultural climate risk with this academic team has spurred further collaborations with other private sector partners, energized focus on scientific and technical gaps and possible solutions, and has spurred the broader re/insurance and financial industries to actively engage with these risks. Other sectors such as pensions, "big agriculture," infrastructure, retail, development aid, environmental and human rights communities would benefit from similar partnerships to explore their specific exposures to agricultural climate risk.

5. Conclusions

To prepare for increasingly severe agricultural risks in the future potentially amplified through extremely efficient and therefore fragile, intensely interconnected food systems, scientific, business, civil society, national and global governance communities will need to work together. This scenario suggests that significant multiple-crop agricultural production shocks are plausible and could have major impacts upon society. The scenario is structured to push industry and academia to more rigorously evaluate current understanding and management of agricultural climate risk, recognize exposure to those risks, and to incentivize risk mitigation. The insurance sector is in a strong position to expand the recognition of agricultural climate risks to society as a whole far beyond the traditional narrow frame of crop insurance, and to offer metrics and tools to begin to account for interacting and more systemic risks and uncertainties. Improved reflections of these vulnerabilities, will be essential for more timely and accurate responses to food system shocks, and the ability to make better decisions, especially in an anticipatory mode, concerning food system risk. Agriculture and therefore humanity faces unprecedented challenges at extreme scales in the next several years to decades. The scientific community, along with all industries and stakeholders who are vulnerable, should prioritize improved capacity to characterize and manage agricultural climate risk and its humanitarian, economic and environmental dimensions.

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References

Adams, R.M., Chen, C.-C., McCarl, B.A., Weiher, R.F., 1999. The economic consequences of ENSO events for agriculture. Clim. Res. 13, 165–172.
Adams, R.M., Hurd, B.H., Lenhart, S., Leary, N., 1998. Effects of global climate change on agriculture: an interpretative review. Clim. Res. 11, 19–30.

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M., Vazquez-Aguirre, J.L., 2006. Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res. 111, D05109. http://dx.doi.org/10.1029/2005JD006290.

Andelman, S.J., Bowles, C.M., Willig, M.R., Waide, R.B., 2004. Understanding environmental complexity through a distributed knowledge network. Bioscience 54, 240–246. http://dx.doi.org/10.1641/0006-3568(2004) 054[0240:UECTAD]2.0.CO;2.

Arrouays, D., Grundy, M.G., Hartemink, A.E., Hempel, J.W., Heuvelink, G.B.M., Hong, S.Y., Lagacherie, P., Lelyk, G., McBratney, A.B., McKenzie, N.J., Mendonça Santos, M.L., Minasny, B., Montanarella, L., Odeh, I.O.A., Sanchez, P.A., Thompson, J.A., Zhang, G.-L., 2014. Chapter three – GlobalSoilMap: toward a fine-resolution global grid of soil properties. In: Sparks, Donald L. (Ed.), Advances in Agronomy. Academic Press, pp. 93–134.

Athanasiadis, I.N., Rizzoli, A.-E., Janssen, S., Andersen, E., Villa, F., 2009. Ontology for seamless integration of agricultural data and models. In: Sartori, F., Sicilia, M.A., Manouselia, K. (Eds.), Metadata and Semantic Research, Proceedings. Springer-Verlag Berlin, Berlin, pp. 282–293.

Challinor, A.J., Simelton, E.S., Fraser, E.D.G., Hemming, D., Collins, M., 2010. Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. Environ. Res. Lett. 5, 034012. http://dx.doi.org/10.1088/1748-9326/5/3/034012.

Clarke, D.J., Mahul, O., Rao, K.N., Verma, N., 2012. Weather Based Crop Insurance in India Policy Research Working Paper No. WPS5985. The World Bank Financial and Private Sector Development Vice Presidency Non-Banking Financial Institutions Unit & South Asia Region Finance and Private Sector Development Unit.

Collins, F.S., Morgan, M., Patrinos, A., 2003. The human genome project: lessons from large-scale biology. Science 300, 286–290.

Comenetz, J., Caviedes, C., 2002. Climate variability, political crises, and historical population displacements in Ethiopia. Global Environ. Change B 4, 113–127.

Cook, B.I., Ault, T.R., Smerdon, J.E., 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Sci. Adv. 1, 1–7. http://dx.doi.org/10.1126/sciadv.1400082 e1400082.

Coumou, D., Rahmstorf, S., 2012. A decade of weather extremes. Nat. Clim. Change 2, 491–496. http://dx.doi.org/10.1038/nclimate1452.

Coumou, D., Robinson, A., Rahmstorf, S., 2013. Global increase in record-breaking monthly-mean temperatures. Clim. Change 118, 771–782. http://dx.doi.org/10.1007/s10584-012-0668-1.

Dai, A., 2011. Drought under global warming: a review. WIREs Clim. Change 2, 45–65. http://dx.doi.org/10.1002/wcc.81.

Dai, A., Trenberth, K.E., Qian, T., 2004. A global dataset of palmer drought severity index for 1870–2002: relationship with soil moisture and effects of surface warming. J. Hydrometeorol. 5, 1117–1130. http://dx.doi.org/10.1175/JHM-386.1.

Devarajan, S., 2013. Africa's statistical tragedy. Rev. Income Wealth 59, S9–S15. http://dx.doi.org/10.1111/roiw.12013.

Dilley, M., Heyman, B.N., 1995. ENSO and disaster: droughts, floods and El Niño/Southern Oscillation warm events. Disasters 19, 181–193. http://dx.doi.org/10.1111/j.1467-7717.1995.tb00338.x.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., Mearns, L.O., 2000. Climate extremes: observations, modeling, and impacts. Science 289, 2068–2074. http://dx.doi.org/10.1126/science.289.5487.2068.

Ermolieva, T.Y., Ermoliev, Y.M., Havlik, P., Mosnier, A., Leclere, D., Kraksner, F., Khabarov, N., Obersteiner, M., 2015. Systems analysis of robust strategic decisions to plan secure food, energy, and water provision based on the stochastic GLOBIOM model. Cyber. Syst. Anal. 51, 125–133. http://dx.doi.org/10.1007/s10559-015-9704-2.

Fedoroff, N.V., Battisti, D.S., Beachy, R.N., Cooper, P.J.M., Fischhoff, D.A., Hodges, C.N., Knauf, V.C., Lobell, D., Mazur, B.J., Molden, D., Reynolds, M.P., Ronald, P.C., Rosegrant, M.W., Sanchez, P.A., Vonshak, A., Zhu, J.-K., 2010. Radically rethinking agriculture for the 21st century. Science 327, 833–834. http://dx.doi.org/10.1126/science.1186834.

Fegraus, E.H., Andelman, S., Jones, M.B., Schildhauer, M., 2005. Maximizing the value of ecological data with structured metadata: an introduction to ecological metadata language (EML) and principles for metadata creation. Bull. Ecol. Soc. Am. 86, 158–168. http://dx.doi.org/10.1890/0012-9623(2005)86[158:MTVOED]2.0.CO;2.

Fraser, E.D.G., Mabee, W., Figge, F., 2005. A framework for assessing the vulnerability of food systems to future shocks. Futures 37, 465–479. http://dx.doi.org/10.1016/j.futures.2004.10.011.

Friedman, J.H., 1984. A Variable Span Smoother LCS Technical Report No. 5. Stanford University Lab For Computational Statistics.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818. http://dx.doi.org/10.1126/science.1185383.

Goodwin, B.K., Hungerford, A., 2015. Copula-based models of systemic risk in U.S. agriculture: implications for crop insurance and reinsurance contracts. Am. J. Agric. Econ. 97, 879–896. http://dx.doi.org/10.1093/ajae/aau086.

Groisman, P.Y., Knight, R.W., Easterling, D.R., Karl, T.R., Hegerl, G.C., Razuvaev, V.N., 2005. Trends in intense precipitation in the climate record. J. Clim. 18, 1326–1350. http://dx.doi.org/10.1175/JCLI3339.1.

Hansen, J., Sato, M., Ruedy, R., 2012. Perception of climate change. PNAS 109, E2415–E2423. http://dx.doi.org/10.1073/pnas.1205276109.

Hansen, J.W., Hodges, A.W., Jones, J.W., 1998. ENSO influences on agriculture in the Southeastern United States. J. Clim. 11, 404–411. http://dx.doi.org/10.1175/1520-0442(1998) 011<0404:EIOAIT>2.0.CO;2.

Headey, D., 2011. Rethinking the global food crisis: the role of trade shocks. Food Policy 36, 136–146.

Headey, D., Fan, S., 2010. Reflections on the Global Food Crisis: How Did It Happen? How Has It Hurt? And How Can We Prevent the Next One? (No IFPRI Research Monograph 165). International Food Policy Research Institute (IFPRI), Washington, D.C.

Headey, D., Fan, S., 2008. Anatomy of a crisis: the causes and consequences of surging food prices. Agric. Econ. 39, 375–391. http://dx.doi.org/10.1111/j.1574-0862.2008.00345.x.

Heath, C., Campbell, J., Clarke, D., Farr, D., Hosken, G., James, G., Newman, A., Simmons, D., Van Rensburg, H., n.d. What is a 1-in-200? Presented at GIRO 2009.

Hill, H., Pittman, J., 2012. Agriculture and Disaster Risk Reduction Draft contributing paper submitted to the UNISDR's GAR 13. Unpublished Manuscript. Agriculture and Agri-Food Canada, Saskatoon, Canada.

Jayanti, H., Husak, G., 2013. A probabilistic approach to assess agricultural drought risk. In: Background Paper Prepared for the Global Assessment Report on Disaster Risk Reduction 2013.

Jerven, M., 2014. The political economy of agricultural statistics and input subsidies: evidence from India, Nigeria and Malawi: political economy of agricultural statistics and input subsidies. J. Agrarian Change 14, 129–145. http://dx.doi.org/10.1111/joac.12025.

Joseph, R., Nigam, S., 2006. ENSO evolution and teleconnections in IPCC's twentieth-century climate simulations: realistic representation? J. Clim. 19, 4360–4377. http://dx.doi.org/10.1175/JCLI3846.1.

Juroszek, P., von Tiedemann, A., 2013. Plant pathogens, insect pests and weeds in a changing global climate: a review of approaches, challenges, research gaps, key studies and concepts. J. Agric. Sci. 151, 163–188. http://dx.doi.org/10.1017/S0021859612000500.

Kamenidou, S., Jain, R., Hari, K., Robertson, J.M., Fletcher, J., 2013. The microbial rosetta stone central agricultural database: an information resource on high-consequence plant pathogens. Plant Dis. 97, 1097–1102. http://dx.doi.org/10.1094/PDIS-03-12-0263-RE.

Klein Tank, A.M.G., Peterson, T.C., Quadir, D.A., Dorji, S., Zou, X., Tang, H., Santhosh, K., Joshi, U.R., Jaswal, A.K., Kolli, R.K., Sikder, A.B., Deshpande, N.R., Revadekar, J.V., Yeleuova, K., Vandasheva, S., Faleyeva, M., Gomboluudev, P., Budhathoki, K.P., Hussain, A., Afzaal, M., Chandrapala, L., Anvar, H., Amanmurad, D., Asanova, V.S., Jones, P.D., New, M.G., Spektorman, T., 2006. Changes in daily temperature and precipitation extremes in central and south Asia. J. Geophys. Res. 111, D16105. http://dx.doi.org/10.1029/2005JD006316.

Kraemer, M.N.L., 2014. Climate Change is a Global Mega-Trend for Sovereign Risk. S&P Rating Direct.

Lobell, D.B., Field, C.B., 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2, 014002. http://dx.doi.org/10.1088/1748-9326/2/1/014002.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science 333, 616–620. http://dx.doi.org/10.1126/science.1204531.

Luck, J., Spackman, M., Freeman, A., Trębicki, P., Griffiths, W., Finlay, K., Chakraborty, S., 2011. Climate change and diseases of food crops. Plant Pathol. 60, 113–121. http://dx.doi.org/10.1111/j.1365-3059.2010.02414.x.

Lybbert, T.J., Smith, A., Sumner, D.A., 2014. Weather shocks and inter-hemispheric supply responses: implications for climate change effects on global food markets. Clim. Change Econ. 5, 11.

Macario, C.G.N., Medeiros, C.B., 2009. A framework for semantic annotation of geospatial data for agriculture. Int. J. Metadata Semant. Ontol. 4, 118–132. http://dx.doi.org/10.1504/IJMSO.2009.02626.

Madin, J.S., Bowers, S., Schildhauer, M.P., Jones, M.B., 2008. Advancing ecological research with ontologies. Trends Ecol. Evol. 23, 159–168. http://dx.doi.org/10.1016/j.tree.2007.11.007.

Maynard, T., Smith, N., Gonzalez, S., 2013. Feast or Famine: Business and Insurance Implications of Food Safety and Security. Lloyd's of London.

Maynard, T., 2015. Food System Shock: The Insurance Impacts of Acute Disruption to Global Food Supply. Lloyd's of London.

McElroy, M.B., Baker, D.J., 2014. Climate extremes: recent trends with implications for national security. Vermont J. Environ. Law 15, 727–803.

Mearns, L.O., Katz, R.W., Schneider, S.H., 1984. Extreme high-temperature events: changes in their probabilities with changes in mean temperature. J. Climate Appl. Meteorol. 23, 1601–1613.

Meehl, G.A., Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305, 994–997. http://dx.doi.org/10.1126/science.1098704.

Michel-Kerjan, E., Morlaye, F., 2008. Extreme events, global warming, and insurance-linked securities: how to trigger the "tipping point". Geneva Papers Risk Insur. Issues Pract. 33, 153–176.

Michener, W.K., 2006. Meta-information concepts for ecological data management. Ecol. Inf. 1, 3–7. http://dx.doi.org/10.1016/j.ecoinf.2005.08.004.

Miranda, M.J., Glauber, J.W., 1997. Systemic risk, reinsurance, and the failure of crop insurance markets. Am. J. Agric. Econ. 79, 206–215. http://dx.doi.org/10.2307/1243954.

Müller, C., 2011. Agriculture: harvesting from uncertainties. Nat. Clim. Change 1, 253–254. http://dx.doi.org/10.1038/nclimate1179.

Natalini, D., Jones, A.W., Bravo, G., 2015. Quantitative assessment of political fragility indices and food prices as indicators of food riots in countries. Sustainability 7, 4360–4385.

Naylor, R.L., Battisti, D.S., Vimont, D.J., Falcon, W.P., Burke, M.B., 2007. Assessing risks of climate variability and climate change for Indonesian rice agriculture. PNAS 104, 7752–7757. http://dx.doi.org/10.1073/pnas.0701825104.

Nelson, G.C., Valin, H., Sands, R.D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Lampe, M.V., Lotze-Campen, H., d'Croz, D.M., van Meijl, H., van der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A., Willenbockel, D., 2014. Climate change effects on agriculture: Economic responses to biophysical shocks. PNAS 111, 3274–3279. http://dx.doi.org/10.1073/pnas.1222465110.

Parthasarathy, B., Sontakke, N.A., Monot, A.A., Kothawale, D.R., 1987. Droughts/floods in the summer monsoon season over different meteorological subdivisions of India for the period 1871–1984. J. Climatol. 7, 57–70. http://dx.doi.org/10.1002/joc.3370070106.

Porter, J.H., Parry, M.L., Carter, T.R., 1991. The potential effects of climatic change on agricultural insect pests. Agric. For. Meteorol. 57, 221–240. http://dx.doi.org/10.1016/0168-1923(91)90088-8.

Postel, S.L., 1998. Water for food production: will there be enough in 2025? Bioscience 48, 629–637. http://dx.doi.org/10.2307/1313422.

Roberts, Michael J., Tran, Anh Nam, 2013. Did Rapid Growth of Ethanol Production in the US Affect Global Food Price Volatility? OreCal Issues Brief No 010.

Ropelewski, C.F., Halpert, M.S., 1987. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. Mon. Weather Rev. 115, 1606–1626. http://dx.doi.org/10.1175/1520-0493(1987) 115<1606:GARSPP>2.0.CO;2.

Rosegrant, M.W.IMPACT Development Team, 2012. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). International Food Policy Research Institute, Washington, D.C..

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. PNAS 111, 3268–3273. http://dx.doi.org/10.1073/pnas.1222463110.

Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P.R., Chivian, E., 2001. Climate change and extreme weather events; implications for food production, plant diseases, and pests. Global Change Hum. Health 2, 90–104. http://dx.doi.org/10.1023/A:1015086831467.

Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P., Antle, J.M., Nelson, G.C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G., Winter, J.M., 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): protocols and pilot studies. Agric. For. Meteorol. 170, 166–182. http://dx.doi.org/10.1016/j.agrformet.2012.09.011.

Rosenzweig, C., Tubiello, F.N., Goldberg, R., Mills, E., Bloomfield, J., 2002. Increased crop damage in the US from excess precipitation under climate change. Global Environ. Change 12, 197–202. http://dx.doi.org/10.1016/S0959-3780(02)00008-0.

Ruiz, J.J., Ariza, F.J., Ureña, M.A., Blázquez, E.B., 2011. Digital map conflation: a review of the process and a proposal for classification. Int. J. Geog. Inf. Sci. 25, 1439–1466. http://dx.doi.org/10.1080/13658816.2010.519707.

Rurinda, J., Mapfumo, P., van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R., Giller, K.E., 2014. Sources of vulnerability to a variable and changing climate among smallholder households in Zimbabwe: a participatory analysis. Clim. Risk Manage. 3, 65–78. http://dx.doi.org/10.1016/j.crm.2014.05.004.

Sachs, J., Remans, R., Smukler, S., Winowiecki, L., Andelman, S.J., Cassman, K.G., Castle, D., DeFries, R., Denning, G., Fanzo, J., Jackson, L.E., Leemans, R., Lehmann, J., Milder, J.C., Naeem, S., Nziguheba, G., Palm, C.A., Pingali, P.L., Reganold, J.P., Richter, D.D., Scherr, S.J., Sircely, J., Sullivan, C., Tomich, T.P., Sanchez, P.A., 2010. Monitoring the world's agriculture. Nature 466, 558–560. http://dx.doi.org/10.1038/466558a.

Schoemaker, P.J.H., 1995. Scenario planning: a tool for strategic thinking. Sloan Manage. Rev. 36 (2), 25.

Seaman, J.A., Sawdon, G.E., Acidri, J., Petty, C., 2014. The household economy approach. Managing the impact of climate change on poverty and food security in developing countries. Clim. Risk Manage. 4–5, 59–68. http://dx.doi.org/10.1016/j.crm.2014.10.001.

Selvaraju, R., 2012. Climate risk assessment and management in agriculture. In: Building Resilience For Adaptation to Climate Change in the Agriculture Sector: Presented at the Joint FAO/OECD Workshop, Rome, pp. 71–90.

Sheffield, J., Wood, E.F., 2007. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim. Dyn. 31, 79–105. http://dx.doi.org/10.1007/s00382-007-0340-z.

Smillie, A., Epperlein, E., Pandya, T., 2014. Use of stress scenarios in market risk economic capital. J. Risk Manage. Financial Inst. 7, 85–92.

Sutherst, R.W., 1991. Pest risk analysis and the greenhouse effect. Rev. Agric. Entomol. 79, 1177–1187.

Trenberth, K.E., 2012. Framing the way to relate climate extremes to climate change. Clim. Change 283–290. http://dx.doi.org/10.1007/s10584-012-0441-5.

Trenberth, K.E., Fasullo, J.T., 2012. Climate extremes and climate change: the Russian heat wave and other climate extremes of 2010. J. Geophys. Res. 117, D17103. http://dx.doi.org/10.1029/2012JD018020.

Turner, A.G., Annamalai, H., 2012. Climate change and the South Asian summer monsoon. Nat. Clim. Change 2, 587–595. http://dx.doi.org/10.1038/nclimate1495.

Vaysse, K., Lagacherie, P., 2015. Evaluating Digital Soil Mapping approaches for mapping GlobalSoilMap soil properties from legacy data in Languedoc-Roussillon (France). Geoderma Reg. 4, 20–30. http://dx.doi.org/10.1016/j.geodrs.2014.11.003.

Veen, L.E., van Reenen, G.B.A., Sluiter, F.P., van Loon, E.E., Bouten, W., 2012. A semantically integrated, user-friendly data model for species observation data. Ecol. Inf. 8, 1–9. http://dx.doi.org/10.1016/j.ecoinf.2011.11.002.

Von Bomhard, N., 2010. The advantages of a global solvency standard. Geneva Papers Risk Insur. Issues Pract. 35, 79–91.

Von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., van Meijl, H., 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agric. Econ. 45, 3–20. http://dx.doi.org/10.1111/agec.12086.

Whitcraft, A.K., Becker-Reshef, I., Justice, C.O., 2015. A framework for defining spatially explicit earth observation requirements for a global agricultural monitoring initiative (GEOGLAM). Remote Sens. 7, 1461–1481. http://dx.doi.org/10.3390/rs70201461.

Wright, B.D., 2009. International Grain Reserves and Other Instruments to Address Volatility in Grain Markets (Policy Research Working Paper No. 5028). The World Bank Europe and Central Asia Region, Agricultural and Rural Development Unit Development Research Group, Trade and Integration Team United Nations, Food and Agriculture Organization.

Xu, W., Filler, G., Odening, M., Okhrin, O., 2010. On the systemic nature of weather risk. Agric. Finance Rev. 70, 267–284, doi:http://dx.doi.org.ezproxy.library.wisc.edu/10.1108/00021461011065283.

Zubair, L., 2002. El Niño–southern oscillation influences on rice production in Sri Lanka. Int. J. Climatol. 22, 249–260. http://dx.doi.org/10.1002/joc.714.