Pharaoh's Dream Revisited: An Integrated US Midwest Field Research Network for Climate Adaptation

DAVID GUSTAFSON, MICHAEL HAYES, EMILY JANSSEN, DAVID B. LOBELL, STEPHEN LONG, GERALD C. NELSON, HIMADRI B. PAKRASI, PETER RAVEN, G. PHILIP ROBERTSON, RICHARD ROBERTSON, AND DONALD WUEBBLES

We're being warned of future grain failures—not by the dreams of a biblical Pharaoh, but by modern computer model predictions. Climate science forecasts rising temperatures, changing rainfall patterns, and episodes of increasingly extreme weather, which will harm crop yields at a time when the world's growing population can ill afford declines, especially in its most productive areas, such as the US Midwest. In order to adequately prepare, we call for the establishment of a new field research network across the US Midwest to fully integrate all methods for improving cropping systems and leveraging big data (agronomic, economic, environmental, and genomic) to facilitate adaptation and mitigation. Such a network, placed in one of the most important grain-producing areas in the world, would provide the set of experimental facilities, linked to farm settings, needed to explore and test the adaptation and mitigation strategies that already are needed globally.

Keywords: climate change, sustainability, water resources, agriculture production, genetics

Managing agriculture to adapt to weather variability has been a challenge since humans began growing crops. Four thousand years ago, in Egypt, Joseph interpreted a pharaoh's dream of impending famine and initiated a science-based policy change: Store 20% of the grain harvest from seven good years to cover shortfalls during seven bad years. Famine was averted, and Egypt became a grain exporter. We still use storage and trade to manage local and global availability: Markets currently store 15%–25% of global annual production (FAO 2015).

Across the US Midwest, as in Egypt in the time of Pharaoh's dream, all seems well for now, and productivity is as high as ever. Record amounts of corn (14.4 billion bushels, 366 million metric tons) and soybeans (3.96 billion bushels, 108 million metric tons) were harvested in 2014 (USDA 2015) across the United States, with record high average yields of 173 bushels per acre (10.9 metric tons per hectare) for corn and 47.5 bushels per acre (3.2 metric tons per hectare) for soybeans. But unlike the situation Joseph confronted, we do not need dreams to foretell our food future. Global populations and affluence are growing, and climate science forecasts a shift toward higher temperatures punctuated by unpredictable episodes of extreme weather, with increasing frequency and intensity globally, in the United States and in the US Midwest (Melillo et al. 2014). To date, Midwest farmers have largely avoided climate-induced losses experienced elsewhere in the world, partly as a result of a geographic "hole" in overall global warming for portions of the Midwest (Lobell et al. 2011), and partly by changes in crop management, such as shifting planting dates to earlier in the spring (Melillo et al. 2014).

What happens to Midwest farmers affects the world. Midwest farmers produce the dominant share of US contributions to the global corn (35%) and soybean (30%) traded volumes (USDA 2015). To improve climate resilience, farmers have increased their use of in-field drainage to reduce water logging from early season rains; adopted new seed treatments to extend the viability of planted seeds through wet periods; expanded irrigation to better withstand droughts; reduced tillage to increase soil organic matter and reduce erosion; and purchased larger field equipment to allow for faster planting during favorable weather— the entire Iowa corn crop, for example, can now be planted in seven days (Takle et al. 2013).
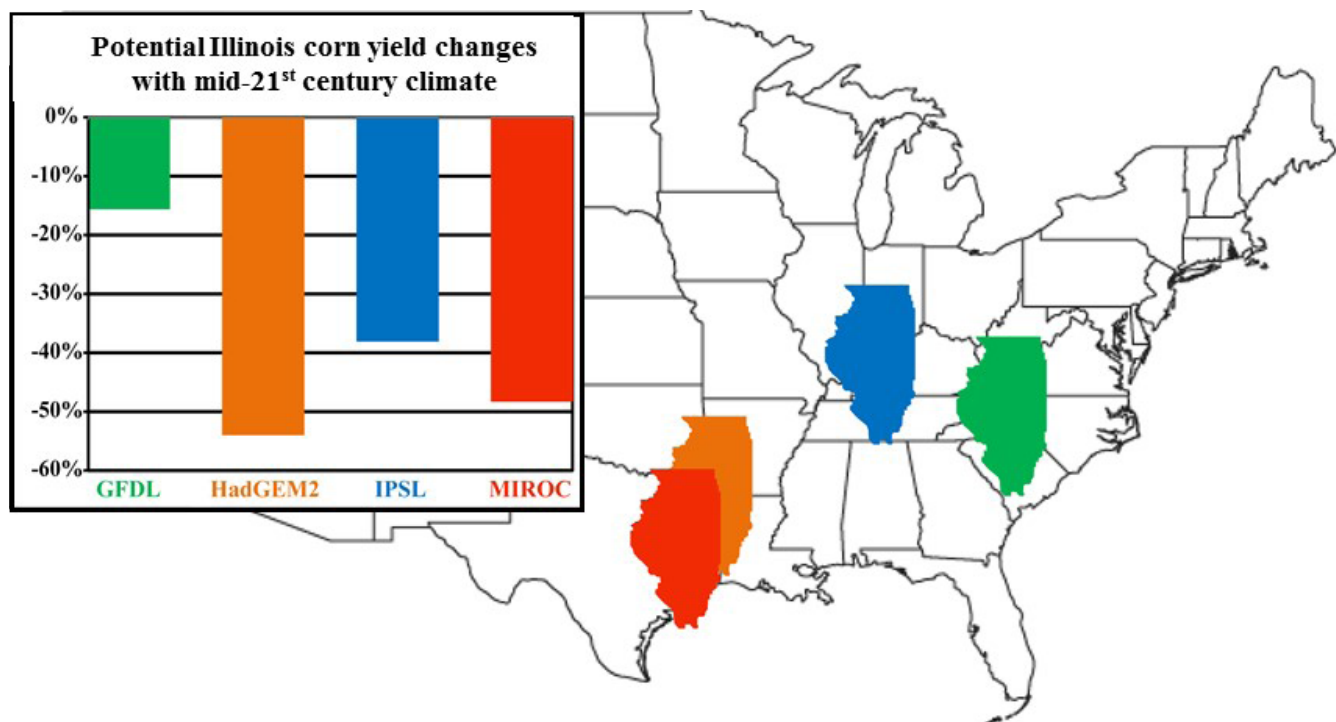
Figure 1. The US map shows projections for where Illinois weather will have "moved" by the 2035–2065 period, relative to 1971–2000, based on changes in warm-season (May through September) average daily temperature and precipitation from four Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models run using the Representative Concentration Pathways (RCP) 8.5 (high emissions) scenario (IPCC 2013). The bar chart shows the corresponding potential climate change effects on average Illinois corn yields using the Decision-Support System for Agrotechnology Transfer (DSSAT) CERES model (Jones et al. 2003), holding all parameters at current values except for climate.

However, such adaptations are unlikely to be sufficient in the future. Temperatures will continue to rise, precipitation patterns will become more variable, more extreme weather will occur, and pests and pathogens are on the move (Melillo et al. 2014). By midcentury, temperatures in Illinois will likely be closer to those of today's mid-South, and precipitation will range somewhere between that of today's East Texas and that of the Carolinas (figure 1). Vapor-pressure deficits, a measure of the atmosphere's drying power, are responsible for significant yield losses in corn (Lobell et al. 2014) and will also increase, potentially constraining future rates of yield gain (Ort and Long 2014).

This is all challenging news for Midwest farmers: As we show in figure 1, current corn varieties could see yield reductions of more than 25% with the climate predicted for 2050 (Takle et al. 2013). Nor will warmer temperatures farther north offset lost Midwest yields: Poor soils, low rainfall, or both will constrain productivity in those regions (Rosegrant 2012). Qualitatively, then, these threats have the potential to reduce global food security. But by how much? Recent predictions of global food price increases due to climate change through 2050 range from negligible to more than 60% (Nelson et al. 2014), reflecting a host of climate- and food-production-modeling uncertainties that must be addressed.

These challenges have led to calls for aggressive increases in agricultural research spending, thus far largely unheeded. Kennedy (2014), for example, recently asked in *Science*, "If we want to combat new strains of pests that destroy crops, find new crop varieties enriched in nutritional value, improve yields, develop resistance to disease and drought, and provide environmentally sensitive cultivation practices, then agricultural research must be a priority. Why isn't it?" (p. 13).

We believe that this need is particularly acute for the Midwest. Intensifying climate change in the face of a growing global demand for more nutritious and more sustainably produced food, together with the increasing prevalence of biotic stressors (weed, insect, and microbial pests), all combine to compel the United States to take a vastly more proactive approach to help Midwest farmers successfully adapt to a very challenging future. Furthermore, because the Midwest has extensive infrastructure and is a major source for crops grown around the world, it is an ideal setting to explore and test climate mitigation and adaptation strategies that could be implemented globally. Finally, the design and implementation of the network itself could serve as a model for the establishment of similar systems in other world regions.

An integrated field research network

We call for the establishment of a new network of field research sites where precise data on the performance of current and future crops and cropping systems and farm level management practices in the US Midwest could be gathered. For efficiency and continuity with current research activities, we propose that the existing public agriculture research infrastructure within this region could form the core of the new network, which would include both public- and private-sector collaborators. The USDA Midwest Climate Hub would be another important public-sector partner, as would the many land-grant universities and their associated extension systems across the region. Private-sector partners would include farmers, as well as the companies that provide agronomic inputs and services and purchase farm outputs.

Such a network, placed in one of the most important grain-producing areas in the world, would provide the set of experimental facilities needed to explore and test the adaptation and mitigation strategies that already are needed globally for similar agroecosystems. Given current cropping patterns and investments, the initial focus should be on major current grains—corn, soybean, and wheat—with effort also directed toward crops novel to the region that might become more important under altered climates. It should also experiment with crops that are currently minor in the area but that could become important in future climate and market environments. To be clear, a significant adjustment of specific US Midwest corn and soybean strategies would be required before they could be applied to other regions and crops, but the integrative approach proposed here, including systematic data collection and management, should have broad applicability in other regions. Individual sites might include experiments such as the SoyFACE field study, established in central Illinois and elsewhere in the early part of this century (Ort et al. 2006), which enabled *in situ* alterations of various atmospheric constituents (e.g., carbon dioxide, CO_2; ozone, O_3). Sites would also include the capability to evaluate cropping-system and farmer responses to altered temperature and precipitation and would provide the knowledge to support a suite of potential adaptation and mitigation approaches involving crop improvement, emergent pest and disease threats, sustainable agricultural practices, and innovative IT strategies (Arbuckle et al. 2013, Haigh et al. 2015). The network would be designed to include farmer-managed fields that capture on-farm decisionmaking and farm-level experiments with potential new technologies.

One of the unique aspects of this network might be its operation through a new public–private partnership involving the direct participation of individual grower–producers, similar to another recently launched initiative focused on soil health (Soil Health Partnership 2015). An advantage to this strategy is the previously reported finding that most farmers support actions to protect farmland (Arbuckle et al. 2013), suggesting that this is as an effective way to achieve both adaptation to and mitigation of climate change. It will also ensure that the research carried out across this network will be of immediate relevance and practical applicability to farmers.

Understanding farmer response to climate change is a key element of the proposal. Social-science research would be integrated into this network at the outset to capture the existing interactions between biology and human behavior and provide guidance on the direction of future research. Studies of climate adaptation suggest that science and technology are most useful when they are fully integrated into social, economic, and political systems that are capable and ready to integrate them (Melillo et al. 2014).

An *integrated* network is needed because existing empirical data provide only a very limited basis for understanding the impacts of future weather, CO_2, O_3, and biotic stressors on crop production, nutritional makeup, socioeconomic factors (e.g., farm incomes, prices, and land values), and sustainability outcomes (e.g., greenhouse gas emissions, soil degradation, and water quality). Recent field studies in which some of the biological factors have been experimentally manipulated (Leakey et al. 2012) have demonstrated our inability to extrapolate growth-chamber and greenhouse results to field situations. For example, whereas crop models based on *in vitro* experiments universally predict a positive response to increasing CO_2, *in situ* experiments show these predictions are either overly optimistic or unfounded—compromising predictions of future cropping-system performance. Systematic and integrated field studies are needed in strategic locations across a range of soil and climatic conditions. Our vision is for a network of such sites, fully integrated with research teams focused on each of several adaptation and mitigation approaches, as we describe briefly below.

Our vision emphasizes the integration of interdisciplinary research to bolster a systems-level understanding, which is crucial but currently far from realized (NSF 2015). Existing field research networks, such as the Long Term Agricultural Research Network (LTAR), the Soil Climate Analysis Network (SCAN), and the Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network (GRACEnet), tend to be focused on relatively narrow climate-related topics. We propose that only an integrated interdisciplinary program can address these broad enterprise-level challenges by having the direct, coordinated engagement of researchers and other individuals with highly diverse but relevant expertise, including agribusiness, agronomists, bioinformaticists, biologists, climatologists, economists, environmental scientists, farmer–producers, hydrologists, information technologists, modelers, plant breeders, and policy experts. Engineering has long recognized the necessity of designing industrial processes from a systems perspective: the need to anticipate how a change in one component can create unwelcome surprises elsewhere, affecting input costs, expenses, and outcomes that can affect the entire system. Applying this approach in agriculture has thus far failed because of lack of integration. Cropping

systems are rarely researched from genome to landscape by multidisciplinary teams working in concert (Robertson et al. 2004). Therefore, we've failed to discover many of the tradeoffs and synergies (socioeconomic and environmental) that result from poorly explored or unknown interconnections. Achieving an integrated interdisciplinary understanding of crops and cropping systems and making accurate predictions of the impacts of climate change demand a network of sites at which such experiments can be deployed. We describe below four areas in which integration—both within and among—is crucial for the design of ever more productive and climate-resilient cropping systems.

Improving crops. Genetic variation is the basis for improved crops and is achieved by traditional breeding and advanced breeding technologies, including genetic engineering. However, not enough is known about natural variation; how variation is expressed in response to high temperature, O_3, CO_2, pests, and disease; and how all of these factors might influence the yields and nutritional content of the harvested crop. That crops fall short of the theoretically attainable yield because of increased CO_2 (Leakey et al. 2012) makes this knowledge gap especially noteworthy as ambient CO_2 levels continue to rise. Modern breeding methods make rapid adaptation to new climates possible and should be used to improve crop performance as the climate changes.

In parallel, molecular tools should be exploited to better understand the mechanisms of response in these crops to changes in environment. Genomewide association study (GWAS), advanced imaging, and transcriptomics may be especially important for understanding heat-wave effects on ovule fertilization and possibly photosynthesis, the failure or partial failure to respond positively to rising CO_2, and the mechanisms of damage and resistance to O_3. Understanding the gene networks underlying these responses will greatly speed the development and selection of variants that thrive under adaptive conditions. At the same time, synthetic-biology approaches should be explored, with RNAi or manipulations to up- or down-regulate genes.

Another particularly promising area of biological research is on the so-called "plant–soil microbiome": understanding the many crucial roles played by the hundreds of billions of microbes that live in soil and within plants themselves (Smith 2014). Multiple distinct microbial communities live within the various regions of this biome, possessing a genetic diversity that dwarfs their plant hosts. Biologists are just beginning to comprehend the capacity for these microbes to provide plants access to nutrients and help suppress disease. Microorganisms may provide the means for combating plant disease faster than breeding and genetic modification do, and they could also help improve the efficiency of fertilizer use. Each of these areas of research has direct relevance to either climate adaptation or mitigation—or both.

Adapting to emerging pest and disease threats. A changing climate means increased vulnerability to existing threats and to novel pests and diseases that invade newly vulnerable regions, including the movement of tropical and subtropical pests into the Midwest. Monitoring alone is only the first step to stemming new threats. Innovative and sustainable methods of crop protection require identifying new sources of disease resistance and modifying strategies for integrated pest management (IPM) across a distributed network to ensure that crop yields and quality are maintained without sacrificing the biodiversity services provided by noncrop plants, beneficial insects, and other taxa. Integrating pest and pathogen dynamics into landscape and cropping system models (Rosenzweig et al. 2013) will be especially important.

Improving sustainable agricultural practices. Agricultural activities themselves contribute to global greenhouse gas emissions and other environmental harms, including impacts on soil health, surface- and groundwater quality, biodiversity, and groundwater supply. As Midwest farmers continue to increase production in response to global food demand, environmental sustainability must be improved. New practices based on emerging technologies and an improved understanding of ecosystem service trade-offs (Robertson et al. 2014) offer much promise. Winter cover crops, precision agriculture, improved decision-support systems, conservation tillage, improved knowledge of favorable and unfavorable soil and plant microbiomes, advanced fertilizer formulations, real-time crop sensing, variable rate planting, fertilizing, and spraying technologies are but a few of the tools now or soon to be available. Although some of these are already widely practiced (e.g., conservation tillage), faster adoption of the newer ideas would be accelerated by providing more information to farmers and integrating new big-data generators such as drone-based sensors. And regular surveys of farm practices in response to changing biological and socioeconomic conditions would inform the potential priorities of research activities. By including experiments replicated across the new research network with comprehensive data collection, clearer guidance can be given on the sustainability outcomes associated with such practices. A key part of this effort must be to evaluate the short- and long-term economic benefits to famers of the range of potential practices.

Deploying innovative IT capabilities. Unless a modern-day Joseph appears, computer models are the only tool that can provide plausible forecasts of future climate, crop, and economic responses. However, the models must be improved, and the key to crop- and economic-model improvement is better data. There is a growing range of efforts to make existing public- and private-sector data open and more widely available. This includes the president's new Climate Data Initiative (White House Press Office 2014), as well as commitments by the private sector to release crop-breeding trial data through open data portals (Gustafson et al. 2014). But new data-collection efforts are also essential, and we believe it is essential that all data generated through the new

network be publicly available in order to accelerate the pace of innovation.

An integrated network will allow field researchers to team directly with those involved in data science, simulation modeling, and other modern IT capabilities (e.g., sensors, precision agriculture, smart-phone apps, and citizen-science efforts) to explore innovative adaptive strategies. The recent explosion of private-sector investment in applications of data science to Midwest cropping operations (as was typified by the purchase of The Climate Corporation by Monsanto) suggests that the pace of future advancements will be rapid. It will be important for the public sector to engage in appropriate policy responses to ensure maximum public good is realized as these developments unfold. The field research network we are proposing would make this possible and would also help to provide the fundamental knowledge on which proprietary advances are based.

Next steps

The initiative described here will require a major investment in financial resources, human capital, and institutional innovation. In order to be cost effective, we propose that these investments come in a coordinated manner from a combination of public- and private-sector sources. The 2014 Farm Bill created an instrument to fund just such endeavors: The Foundation for Food and Agricultural Research (FFAR), announced by USDA Secretary Tom Vilsack in June 2014, will "leverage public and private resources to increase the scientific and technological research, innovation, and partnerships critical to boosting America's agricultural economy." The integrated field research network we envisage here would be an ideal project to begin realizing the FFAR vision. It would also become a significant global resource for developing and testing the integrated adaptation strategies that will be needed to help all of the world's farmers confront the challenges of increasing climate change.

As was detailed in both the Third US National Climate Assessment (Melillo et al. 2014) and in the more recent report on food-system resilience to extreme weather (UK Global Food Security Programme 2015), dramatic changes (both socioeconomic and climatic) are coming at local, national, and global scales that are likely to profoundly affect farmers in the US Midwest and beyond. The network we propose will provide a tremendous boost to the quantity and quality of information needed to inform the policy and investment decisions that must be made in the face of a rapidly changing climate—in order to avoid the more dire outcomes that await if we fail to plan appropriately. Merely expanding existing research networks and doing things the way we've always done them will be insufficient. Only by having an integrated interdisciplinary network in place will we be able to address with agility the complex interactions between climate science, biology, information technology, and human behavior that will inform both better decisions and more beneficial ultimate outcomes.

References cited

Arbuckle JG, Prokopy LS, Haigh T, Hobbs J, Knoot T. 2013. Climate change beliefs, concerns, attitudes toward adaptation and mitigation among farmers in the Midwestern United States. Climatic Change 117: 943–950.

[FAO] Food and Agricultural Organization of the United Nations. 2015. FAO Food Price Index. (3 May 2015; *www.fao.org/worldfoodsituation/foodpricesindex/en*)

Gustafson DI, et al. 2014. Climate adaptation imperatives: Untapped global maize yield opportunities. International Journal of Agricultural Sustainability 12: 471–486. doi:10.1080/14735903.2013.867694

Haigh T, Takle E, Andresen J, Widhalm M, Carlton JS. 2015. Mapping the decision points and climate information use of agricultural producers across the US Corn Belt. Climate Risk Management 7: 20–30.

[IPCC] Intergovernmental Panel on Climate Change. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jones JW, Hoogenboom G, Porter C, Boote K, Batchelor W, Hunt L, Ritchie J. 2003. The DSSAT cropping system model. European Journal of Agronomy 18: 235–265.

Kennedy D. 2014. Building agricultural research. Science 346: 13.

Leakey A, Bishop KA, Ainsworth EA. 2012. A multi-biome gap in understanding of crop and ecosystem responses to elevated CO_2. Current Opinion in Plant Biology 15: 228–236.

Lobell DB, Schlenker W, Costa-Roberts J. 2011. Climate trends and global crop production since 1980. Science 333: 616–620.

Lobell DB, Roberts MJ, Schlenker W, Braun N, Little BB, Rejesus RM, Hammer GL. 2014. Greater sensitivity to drought accompanies maize yield increase in the US Midwest. Science 344: 516–519.

Melillo JM, Richmond TC, Yohe GW, eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. US Global Change Research Program. doi:10.7930/J0Z31WJ2

Nelson GC, et al. 2014. Climate change effects on agriculture: Economic responses to biophysical shocks. Proceedings of the National Academy of Sciences 111: 3274–3279.

[NSF] National Science Foundation. 2015. NSF FY 2016 Budget Request to Congress. NSF. (3 May 2015; *www.nsf.gov/about/budget/fy2016/pdf/01_fy2016.pdf*)

Ort DR, et al. 2006. SoyFACE: The effects and interactions of elevated CO_2 and O_3 on soybean. Pages 71–86 in Nosberger J, et al., eds. Managed Ecosystems and CO_2: Case Studies, Processes, and Perspectives. Springer.

Ort DR, Long SP. 2014. Limits on yields in the Corn Belt. Science 344: 484–485.

Robertson GP, Broome JC, Chornesky EA, Frankenberger JR, Johnson P, Lipson M, Miranowski JA, Owens ED, Pimentel D, Thrupp LA. 2004. Rethinking the vision for environmental research in US agriculture. BioScience 54: 61–65.

Robertson GP, Gross KL, Hamilton SK, Landis DA, Schmidt TM, Snapp SS, Swinton SM. 2014. Farming for ecosystem services: An ecological approach to production agriculture. BioScience 64: 404–415.

Rosegrant MW. 2012. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) Model Description. International Food Policy Research Institute.

Rosenzweig C, et al. 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agricultural and Forest Meteorology 170: 166–182.

Soil Health Partnership. 2015. Soil Health Partnership: A Project to Make Agriculture More Productive and Sustainable through Improved Soil Health. National Corn Growers Association. (2 September 2015; *http://soilhealthpartnership.org*)

Smith PA. 2014. Untapped plant microbiome could help feed billions. Scientific American. (6 November 2015; *www.scientificamerican.com/article/untapped-plant-microbiome-could-help-feed-billions*)

Takle ES, Gustafson DI, Beachy R, Nelson GC, Mason-D'Croz D, Palazzo A. 2013. US food security and climate change: Agricultural futures. Economics (art. 2013-34). doi:10.5018/economics-ejournal.ja.2013-34.

UK Global Food Security Programme. 2015. Extreme Weather and Resilience of the Global Food System. UK–US Taskforce on Extreme Weather and Global Food System Resilience.

[USDA] US Department of Agriculture. 2015. World Agricultural Supply and Demand Estimates Report (WASDE. USDA Office of the Chief Economist. (3 May 2015; *www.usda.gov/oce/commodity/wasde*)

White House Press Office. 2014. Fact Sheet: Empowering America's Agricultural Sector and Strengthening Food Resilience through the President's Climate Data Initiative. Office of the Press Secretary. (3 May 2015; *www.whitehouse.gov/the-press-office/2014/07/29/fact-sheet-empowering-america-s-agricultural-sector-and-strengthening-fo*)

David Gustafson is affiliated with the Center for Integrated Modeling of Sustainable Agriculture and Nutrition Security, ILSI Research Foundation, in Washington, DC. Michael Hayes is with the National Drought Mitigation Center at the University of Nebraska, in Lincoln. Emily Janssen, Stephen Long, Gerald Nelson, and Donald Wuebbles are affiliated with the University of Illinois, in Urbana-Champaign. David B. Lobell is with the Center on Food Security and the Environment at Stanford University, in Stanford, California. Himadri B. Pakrasi is with the International Center for Advanced Renewable Energy and Sustainability at Washington University, in St. Louis, Missouri. Peter Raven is affiliated with the Missouri Botanical Garden, in St. Louis. G. Philip Robertson is with the WK Kellogg Biological Station at Michigan State University, in Hickory Corners. Richard Robertson is affiliated with the International Food Policy Research Institute, in Washington, DC.