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RESEARCH INTRODUCTION

The science of variable climate and agroecosystem management

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Highly variable climate presents uncertainty and risk challenges to managing water and soil resources in agricultural landscapes. The Third National Climate Assessment documents increased climate disruptions to agriculture in the United States over the past 40 years and projects accelerated impacts in the next 25 years (Melillo et al. 2014). Loss and degradation of soil and water assets due to increasing extremes in precipitation (figure 1) are identified as key concerns to both rainfed and irrigated agriculture. The 2014 North America Regional Aspects Report by the Fifth Intergovernmental Panel on Climate Change cites rising temperatures and carbon dioxide (CO_2) concentrations, high vulnerability to climate extremes, increased wildfire activity, regional drought, pest infestations, land use changes, and pollution as stressing North American ecosystems (Romero-Lankao et al. 2014). The report further notes that water resources are already stressed by non-climate change anthropogenic factors, and effects of temperature and climate variability on yields of major crops have been observed.

Corn or maize (*Zea mays* L.), rice (*Oryza sativa*), soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.) provide 75% of the world's caloric intake. These are but four of the 17 principal cultivated crops planted on 131.4 million US ha (324.8 million US ac) in 2013 (USDA NASS 2014). Corn, the most widely produced grain in the United States, provides the main energy ingredient for livestock feed and is processed into a wide range of food and industrial products, including fuel ethanol, with approximately 20% of US corn exported to other countries (USDA ERS 2014). Planted on 38.4 million ha (95 million ac), the 2013 corn crop yielded 353 million t (13.9 billion bu) grain valued over US$63.7 billion with more than 70% grown in the upper Midwest. United States soybean production, often part of the corn rotation, was planted on 30.8 million ha (76 million ac) and yielded a total of 89 million t (3.3 billion bu) valued at US$41.8 billion in 2013. Wheat, planted on 22.7 million ha (56 million ac) during this same period, yielded 57 million t (2.1 billion bu) valued at US$14.4 billion (figure 2).

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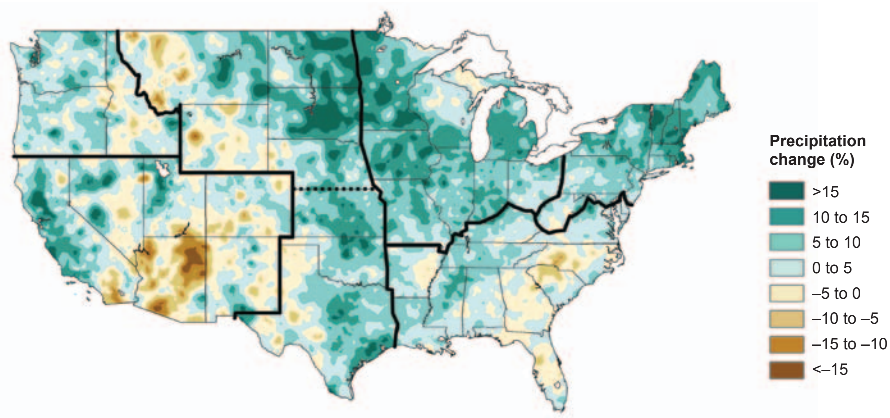
Figure 1

Observed US precipitation change. Annual total precipitation changes for 1991 to 2012 compared to 1901 to 1960 average (Melillo et al. 2014).



These highly productive, intensively managed cropping systems have been developed and cultivated to respond to historical precipitation and temperature patterns where they are regionally grown. They often represent a low diversity of land use, and even without a changing climate, have a history of unintended consequences on soil conditions, water quality, and water supplies. Increasing future climate variability is predicted to heighten temperature effects and the uneven distribution of excess water and water deficits that are likely to make these crops vulnerable in known and unknown ways. As agriculture adapts to these spatial and temporal changes, land cover and use shifts will also occur. Crop production may decline in some areas and expand in others. Changes in temperature patterns can alter accumulation of growing degree units; growing season length; and precipitation amount, intensity, and distribution (Johnson et al. 2010). For example, soil temperature regimes (figure 3) will influence where row crop production may expand to meet demands for corn, wheat, and other crops. Expansions of corn, wheat and forage production have currently been observed in the frigid temperature regime of North and South Dakota with increases in temperature and precipitation. Without careful management, a changing climate and land cover and use adaptations will (1) exacerbate soil erosion, transport, and sediment deposition in streams, lakes, and rivers; (2) increase off-field and off-farm nutrient losses which pollute water; and (3) threaten limited water supplies.

A wide variety of adjustments, adaptations, and mitigation of these conditions must occur if we are to successfully address short and long-range challenges to the resilience of these cropping systems and the larger agricultural landscape. The papers in this volume represent research that is underway to better understand how the distribution and timing of precipitation and temperature, management practices, and human perceptions of and responses to risk affect the vulnerability of production systems and water and soil assets. One group of papers focuses on research design and methods, the development of sampling protocols, and the creation of large shared databases to better detect changes in soil and water and document the impact of climate change on crops. A second set of papers examines intersections among specific cropping practices, soil organic carbon (SOC) retention or sequestration, greenhouse gas (GHG) production, tillage, drainage management, water quality, drought, and productivity. The last category of papers takes a closer look at farmers themselves—how they define climate change, perceptions of anthropic and natural sources of climate change, and attempts (or not) to mitigate climate change by altering management practices.

This science is critical if agriculture is to continue to innovate, adapt, and thrive under changing conditions. These scientific findings are complemented by a number of essays that offer valuable insights into ways farmers are responding to changing conditions, public investments in climate and agriculture, project structures that enable science to be translated and effectively applied to managing cropping systems, methods for training and mentoring next generation scientists, and industry perspectives on capacities to realize important sustainability goals.

SCIENTIFIC METHODS AND DATABASE MANAGEMENT

The research design and methods scientists use to answer questions are critical if science is to "get right" the coupled human-natural system relationships associated with agriculture. In the tradition of Thomas Kuhn (1962), several papers represent important paradigm shifts in opening new approaches to understanding scientific knowledge. One of these approaches, the combining of field measurements and model predictions offers a powerful way to advance knowledge more rapidly (Anex 2014) with transformative potential to move agricultural science beyond linear accumulation of new knowledge. In their paper, Necpalova et al. (2014) integrate project field data across several states and study sites with statistical and biogeochemical modeling to determine how many replications over a certain time period are needed to detect a change in soil carbon (C) stocks. They explore how high natural variability in SOC within field and across the landscape creates a measurement problem that often leads to experimental designs with low statistical power to detect differences. Of concern is the potential of type II errors that falsely declare there is no difference when one actually exists. The power analysis and dynamic modeling used by Necpalova et al. (2014) demonstrate how the minimum detectable difference (MDD) in SOC var-

Figure 2

Acres planted and production of major US cultivated crops from 1929 to 2013 (USDA Nass 2014).

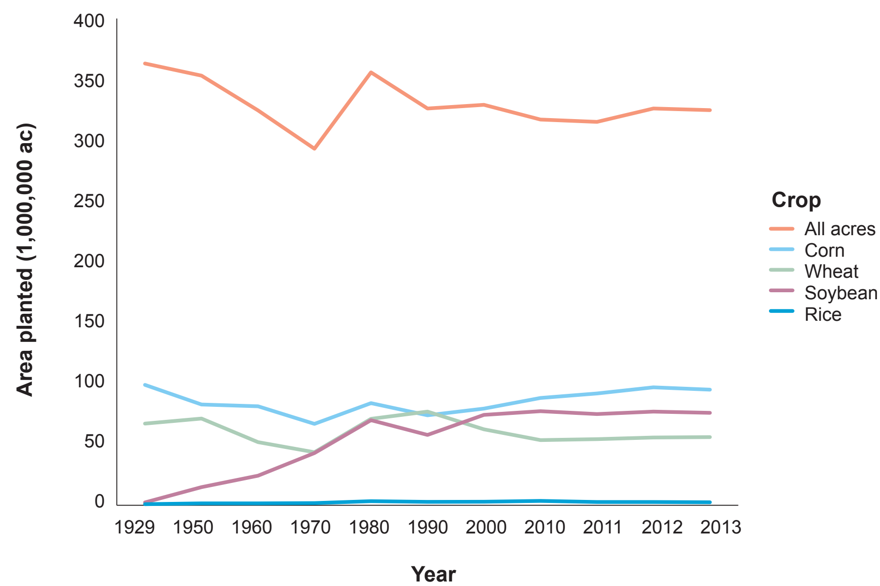
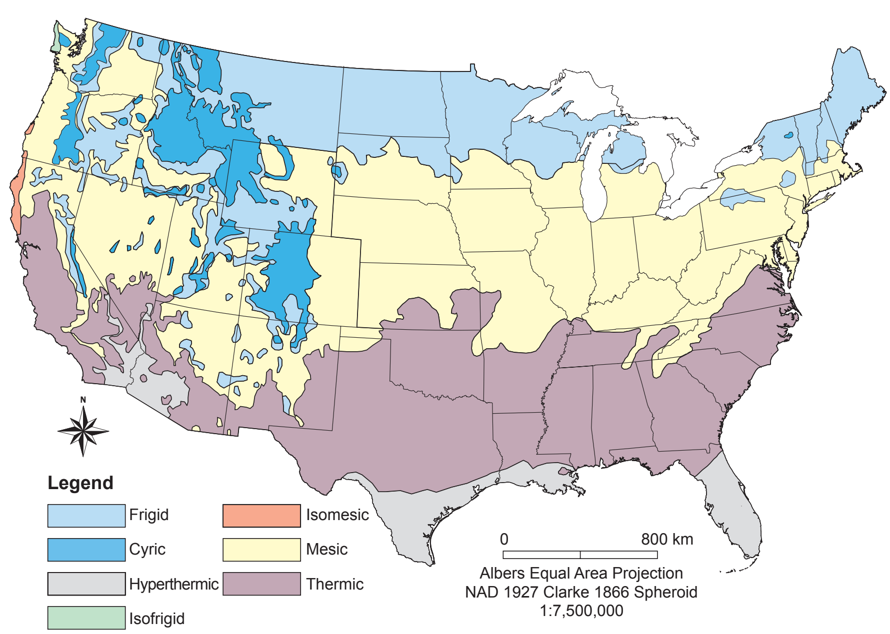


Figure 3

Mesic-frigid boundary in the United States. Map by Mic Greenberg based on USDA Natural Resources Conservation Service soil temperature regimes of the contiguous United States.



ies with soils of the North Central region, and how the length of the experiment required to observe the MDD varies with productivity as well as soil properties. The combination of empirical data and modeling suggests general principles that can guide the design of experiments and the planning of regional comparison studies.

Although not a central premise in their paper evaluating the effects of cover crops on soil moisture, Daigh et al. (2014) offer a side note that also acknowledges the problem of having enough experimental treatment replications and the costly nature of equipment and time. They write that to precisely estimate soil water storage depth in the soil profile, a great quantity of sensors and data logger equipment is required to gather volumetric soil water measurements on daily, hourly, or finer time intervals, and these in-field equipment needs limit the number of treatment replications possible for research sites. They further explain that the limitation to number of treatment replications results in "an unknown degree of precision…lost for estimating treatment means and the experimental error variance; thereby also limiting the ability to detect differences among treatments." This suggests that here also is an opportunity to combine field data with modeling to advance agricultural science.

A second paradigm shift in research design and methods is the development of standardized research protocols that enable data from many different experimental sites and different types of data to be integrated into a single large database for synthesis and analyses. Kladivko et al. (2014) offer detailed research protocols used to standardize the types of measurements taken in a large coordinated agricultural project involving 35 research sites. They note the challenge of building consensus concerning every detail of field measurement protocols among 30 principal investigators, each with their own disciplinary expertise, ranging across agronomy, soil fertility, soil physics, hydrology, engineering, soil biology, cropping systems, GHGs, integrated pest management, and other related areas. These protocols include baseline measurements of soil and water properties prior to the start of the experiments to measure change in corn-based cropping systems' C, nitrogen (N), and water footprints. Necpalova et al. (2014) and Olson et al. (2014a) similarly assert that baseline measurements are necessary to monitor and verify net change in SOC stock under different tillage experiments at different depths to determine if SOC was sequestered, retained, stored, or lost under different tillage treatments.

Claims that reduced tillage can sequester SOC in soil and reverse historical patterns of SOC loss continue to be a difficult and complex issue, confounded by the highly dynamic nature of climate and agroecosystems, writes Olson et al. (2014b). In this paper, the paired comparison method to determine SOC sequestration rates is examined. The basis for this work is a refinement on the definition and measurement of SOC sequestration. These authors specify that changes in SOC levels as a result of management practices (e.g., tillage) must result in greater SOC stock than the pretreatment baseline SOC levels in the same land unit and result in a net depletion of atmospheric CO_2. Thus, claims of SOC sequestration must evidence atmospheric CO_2 transferred into the soil humus through land unit plants, plant residues, and other organic solids (Olson 2013; Olson et al. 2014a). Olson et al. (2014b) offer several recommendations congruent with Kladivko et al. (2014) and Necpalova et al. (2014) papers: (1) protocols for measuring SOC sequestration should be standardized; (2) sequestration rates over a period of time should be measured and compared to the pretreatment baseline over regular intervals during the study; and (3) external already stored C inputs into the land unit must be accounted for to assure SOC sequestration and SOC net gain, i.e., SOC is sequestered or stored in the land unit from the atmosphere rather than redistributed from previous stores in another land unit.

A New Biology for the 21st Century articulates the need for integration of knowledge across disciplines to better monitor, understand, and make predictions about our ecosystems at increasingly finer temporal and spatial scales (NAS 2009). This will require data-intense (spatial, temporal, and human institutions) science from which to build process-based ecosystem models that more accurately reflect current conditions and increase capacity to extrapolate out to future conditions. Future agricultural and natural ecosystems research, analysis, and interpretation are dependent on a data rich environment, which includes the retrieval of historical data sets along with those produced from current research programs. A centralized data infrastructure for unifying and structuring data can accelerate data synthesis, systems mapping, and scientific power to draw conclusions and make predictions. Kladivko et al. (2014) discuss how the collected data must be brought together in a way that can be stored and used by persons not originally involved in the data collection, necessitating robust procedures for linking metadata with the data and clearly delineating rules for use and publication of data from the overall project. Herzmann et al. (2014) illustrate how this centralized database and purposeful infrastructure might be achieved by showcasing the research and project management databases created by the USDA National Institute of Food and Agriculture Sustainable Corn Coordinated Agricultural Project. These two structures (1) enable accountability and communication within the team and externally to funding sources and (2) house primary and secondary data for data synthesis, interpretation, and modeling across multiple data sets.

PRODUCING AGRICUTLURAL CROPS UNDER A VARIABLE CLIMATE

Greenhouse Gas Production. The general circulation of the atmosphere, that is the large-scale movement of air over the earth, is the cause of all climate and weather. The distribution of thermal energy creates patterns of temperature, humidity, atmospheric pressure, wind, and precipitation that over long periods of time become the climate of any given locale. The climate of the earth and specific regions is influenced by complex feedback loops—with multidirectional impacts as agricultural production systems interact with the earth's terrain and nearby water bodies and their currents. One of the energy sources that warms the earth's surface is the downward radiation emitted from the atmosphere based on the amount of GHG present (Arritt 2012). Global temperature increases are mainly attributed to GHG accumulating in the atmosphere. Agriculture worldwide supplies 3% to 4% of anthropogenic CO_2, 30% to 80% of nitrous oxide (N_2O), and 10% to 60% of methane (CH_4) emissions to the atmosphere, according to Campbell et al. (2014).

Major factors influencing soil GHG fluxes in cultivated systems are temperature, moisture, and depth of tillage, with temperature a leading factor. Undisturbed soils in no-till (NT) systems have been found to retain SOC and reduce soil CO_2 fluxes. Kumar et al. (2014) explore relationships of tillage and poorly drained soils and their effects on GHG fluxes in corn-based systems. They conclude that subsurface drainage in NT has potential to emit lower GHG compared to tilled soils with no drainage. However, they report that differences in GHG fluxes among treatments were not always significant and call for additional long-term monitoring of fluxes under diverse cropping systems in poorly drained soils to better understand moisture, drainage, and tillage relationships.

Campbell et al. (2014) also examine tillage and crop rotation impacts on GHG fluxes. They find that NT in a corn–soybean (C-S) rotation yielded lower CO_2 and N_2O emissions than continuous corn (C-C). They speculate the difference is due to less total N fertilizer input in C-S than C-C rotations. Fertilizer N recovery efficiency and N_2O emissions in cereal grain production is also an area of study for Basche et al. (2014). They note the episodic nature of N_2O emissions associated with precipitation and soil moisture and offer a synthesis of 26 peer reviewed articles encompassing 106 observations of cover crop effects on N_2O. They report mixed results with 40% of their studies finding that cover crop treatments decreased N_2O and 60% of the studies finding that cover crop treatments increased N_2O. Nitrogen application rates explained more of the cover crop response rate variability than other factors, but many studies also revealed significant interaction between N rate and tillage systems.

Water. A changing climate directly affects the hydrological cycle. This means that efforts undertaken to contain GHG emissions could help to stabilize rainfall patterns and mitigate the extreme water events that many regions worldwide are already experiencing (Gorbachev 2014). Managing the hydrological cycle is a unifying water security challenge that variable climate presents across regions and nations. Water security encompasses (1) water disasters such as flooding and drought, (2) water quality affected by agricultural nutrient pollution (hypoxia conditions in bays and gulfs) and chemical contamination, and (3) water quantity characterized by competing sectors needing access to limited water supplies (Morton 2014).

The close relationships among land use, water, and climate are particularly evident in historic and current hypoxic conditions of downstream estuaries, bays, and gulfs and are projected to become even greater problems in areas experiencing increased precipitation. Panagopoulos et al. (2014) cite high levels of nitrate (NO_3) and total phosphorous (P) load deliveries to the Gulf of Mexico originating from unmanaged runoff in Upper Mississippi River Basin corn–soybean intensive rotations. These coauthors use the Soil and Water Assessment Tool to estimate landscape and in-stream water and pollutant yields under a variety of cropping and management strategies and varying climatic conditions. Models simulate physical processes associated with water and sediment movement, crop growth, and nutrient cycling in subbasins coincident with US Geological Survey 12-digit hydrologic unit code watersheds and specified management practices parameters by specific dates. Combined with downscaled, bias-corrected Global Climate Model projections across a dense grid overlaid on the Upper Mississippi River Basin study region, this modeling effort reports three management strategies (NT; extended five year rotation of corn, soybean, and three years of alfalfa [*Medicago sativa* L.]; and winter cover crop) that, if widely adopted, could reduce erosion and nutrient loadings to surface water bodies.

Daigh et al. (2014) use the 2012 drought as a natural experiment to evaluate effects of cover crops on soil moisture. In this research they propose to quantify differences in soil moisture due to rye (*Secale cereal* L.) cover crop in C-S rotations. They build on the literatures which find that soil moisture conditions that restrict seasonal evapotranspiration in corn as little as 4.2 cm (1.7 in) can reduce grain yields by 25% to 50% if water-limiting stress occurs before or at anthesis when total water use is greatest. A live growing cover crop has potential to reduce soil water content and soil water storage available for emerging and young cash crop growth in years when water stress is high. They find the use of rye cover crop in C-S rotations did not significantly lower soil water conditions. Further, temporal variations of soil moisture by date contributed the greatest (>72%) of the total observed variability for all sites, soil depths, and observation periods.

Williams et al. (2014) place the context of their study on winter wheat and soil erosion in the regional shift to warmer winters and a corresponding shift in timing of precipitation in the Pacific Northwest. They call attention to the high level of susceptibility to soil loss on steep slopes as unprotected soil moves downslope in absence of rainfall when the top 3 to 4 cm (1.2 to1.6 in) of soil thaws and becomes a viscous, flowing slurry. They cite annual soil losses due to overland flow ranging from 3 to 50 Mg ha^{-1} y^{-1} (1.35 to 22.30 t ac^{-1} yr^{-1}) with mean soil loss estimated at 24.5 Mg ha^{-1} (10.93 t ac^{-1}) between 1939 and 1972 in wetter parts of the region; this exceeds established USDA soil loss tolerance limits of 2.2 to 11.2 Mg ha^{-1} y^{-1} (0.98 to 5 t ac^{-1} yr^{-1}) for sustained economic productivity. Their research examines crop residue accumulation in NT and its capacity to physically protect the soil surface from raindrop impact, increase water infiltration, and reduce rill erosion. They find that variability in regional weather conditions and soil erosion events are highly related with three events responsible for 60% to 70% of total soil erosion in one study. In general they report that (1) when the crop has sufficient residue covering, the soil resists rill development and (2) if runoff is not concentrated in flow paths, the soil will slowly be redistributed from backslopes to toe slopes before moving into and through drainage bottoms.

Soil Organic Carbon. Good soil structure tolerates different wetting conditions, improves air and moisture exchange between roots and soil, and affects susceptibility to water, wind, and equipment traffic over time. Al-Kaisi et al. (2014) explore the stability and formation of soil aggregates in C-S rotations and ask how the increase in SOC influences the stability of soil aggregates over time when soil is subjected to continuous and high intensity rain for extended periods of time. They test five tillage systems using a continuous wetting experiment intended to mimic the volatility of rain intensities and durations. They report that NT showed the highest aggregate stability of all five tillage treatments with increases in SOC associated with greater soil aggregate stability. Lal (2014), in his value of soil C paper, reminds readers that soil organic matter is essential to ecosystem function and must be protected by conservation policy to assure future crop productivity. He speculates that C farming could become the new agriculture where either industry would buy soil or tree C just as it buys other farm produce or farmers would be compensated for provisioning of ecosystem services (mitigation of climate change) through C sequestration in agroecosystems.

THE HUMAN FACTOR

Land management decisions always involve both facts and values (Dietz 2013), and farmer willingness to adapt to changes in long-term weather patterns well illustrates how intertwined facts and values are. Arbuckle et al. (2014) use a random sample 2012 survey of Corn Belt farmers to model farmer beliefs about climate change, personal experiences with climate-related risks, confidence in technology, and perceptions of their own skills to address risks and hazards to better understand differences among farmers and their willingness to put in place adaptive management and mitigation strategies. The variation among farmers is striking with 39% concerned or uneasy about climate change and its potential impacts; 25% not certain but supportive of adaptation and mitigation; and 37% who tend not to believe that climate change is occurring, express low concern about potential risks, are fairly confident in their capacity to adapt, and are not as likely to support action. Those farmers who were unconvinced climate change is a problem tended to report very little experience with adverse weather-related impacts on their farm operations over the previous five years.

CONCLUSION

Soil, water, climate, and human management are central factors in agricultural productivity and the coproduction of ecosystem services. This collection of papers highlights the different scales of geography and time that the scientific community must reconcile as they anticipate a changing climate while recognizing that global climate patterns may not be the same patterns farmers are experiencing in their own locales. The reevaluation of scientific methods to strengthen the integration of field measurements and predictive modeling will require investments in data infrastructure, cross-disciplinary and trans-disciplinary platforms, and willingness to learn and try again when we don't quite get it right (Eigenbrode et al. 2014). The land grant university system, with research, extension, and education missions, is well suited to create new scientific knowledge needed for agriculture to innovate, adapt, and mitigate into the next century and yet provide practical adaption guidance that starts where people are right now. The really big challenge to agriculture is to find strategies that will sustain and increase productivity while protecting ecosystem integrity (Blesh and Drinkwater 2013).

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