NSF Food Energy Water

Geographical Sustainability of Agriculture Considering Production, Energy and Water Constraints

The Output of a FEW Workshop

Boulder, Colorado October 21-23, 2015

Summary of Need and Research Issues

It is hypothesized that better understanding of sustainable geography of U.S. agricultural production, considering water and energy constraints and whether migration of agriculture toward this geography might protect the nation's food security. In the last century the geography of the Nation's agricultural production changed dramatically as food and fiber production shifted from the East to the arid West under irrigated agriculture. Similarly, as transportation improved, corn and grain production migrated to deep water-holding soils in a relatively concentrated area of the upper Midwest compared to the distribution of production in 1930. In the meantime, agriculture in the East dropped precipitously. In a positive sense, this migration of agriculture produced a bountiful fare of food at a price affordable to ordinary Americans. However, the present drought in the West, the 2012 Midwest drought and climate change projections perhaps expose the vulnerability of the present geography of U.S. agriculture. Additionally, the shift in agriculture brought about adverse impacts on river ecosystems in the West for the sake of irrigation and the concentration of nutrient export to the Mississippi River. This leads to several strategic questions. Is the geography that evolved in the last century, due to immediate market forces and government investments, sustainable and reliable for the future? Will the geography of agriculture continue to evolve and, if so, can information be developed that can guide future migrations of agriculture toward sustainability? The East lost its agriculture in large part because of drought losses, so bringing agriculture back to the East will require expanded irrigation. Can some portion of the production in the West, now under water stress due to increasing demand from population growth and potential reduction in supply from climate change, be migrated back to the East or northern parts of the Northwest under irrigation? Can grain production be more geographically distributed to avoid the environmental issues (e.g. nutrient run-off) and vulnerability to small regional droughts that the present concentration of grain production in the Midwest entails? This present geography of agricultural production has also affected energy consumption through electrical energy used to move surface water in the West and to pump water in the High Plains. It has created the need for transportation energy to move refrigerated food from the West to the East and grains from the Midwest to the Southeast for consumption by poultry and swine. While transportation energy is generally a small part of total energy in food production, it can have a large impact on final profit. A new migration of agriculture back to the East may engender competition for water for cooling in thermoelectric generation and hydroelectric losses. Is the geography of energy availability consistent with the geography of available water and agricultural production? ***It is felt that defining a sustainable geography for U.S. agricultural production is at the nexus of food, energy and water interactions and important to U.S. food and global security/safety.***

Needed research elements on geographical sustainability include:

1. **Defining Sustainability Metrics and Mapping Geographical Attributes of Agricultural Production –** This would include data and tools to map the economics of agricultural production, water use, energy of production and transportation, and natural resource impacts under scenarios of climate change, population change and energy change.This might also include measures of nutrition and freshness.
2. **Geographical Optimization Models –** This would include developing and testing models and Life Cycle Assessments that might develop optimal geographies of agricultural production including water, energy and natural resource constraints.
3. **Process and Component Models –** This would include developing sub-component models or data needed to capture geographical attributes needed in (1) and (2).

Intellectual Challenges: The main intellectual challenges are defining the geographical metrics defining sustainability and acquiring/creating the data to map these metrics. This is complicated by the fact that the data crosses the science of climate and hydrology with applied economic information in agriculture and energy. It also involves coupling physical (climate and hydrological models) with agricultural and energy use models (e.g. crop models and energy transport models) and optimization methods.

Utility of Outputs: The outputs of the study will be useful for policy makers and the private sector. For policy makers, it can help guide incentive programs and infrastructure investments to move toward a more sustainable geography. For the private sector, it can provide information for making investments in land and irrigation as well as production decisions.

1. Background and Workshop Context

An NSF FEW Workshop was convened in Boulder, Colorado October 21-23, 2015 that brought together hydrologists, agronomists, economists, engineers, climatologists, ecologists, energy experts, lawyers and water resource planners to discuss the vulnerabilities and dynamics of the geography of agriculture in the nation (http://nsstc.uah.edu/few.workshop/index.html). The workshop also discussed whether information might be developed to assess the geography of economic and agricultural sustainability in the future that might guide private sector investments and government policy that is necessary to sustain production in the coming century. The workshop began the process of how the geography of sustainable production might be defined in terms of food, energy, and water metrics. A workshop report ftp://ftp.nsstc.org/outgoing/estesmg summarizes the background on the geography of production and discussions at the workshop. The present whitepaper describes research challenges and needs to address Geographical Sustainability and outlines the major science questions and paths to develop metrics and components to define Geographical Sustainability. In terms of nomenclature, geographical sustainability is used to describe the aggregate of metrics and migration as acting on these metrics.

1.1 Background on the Evolution of the Geography of Production

Agricultural production systems evolve and adapt to climate, soil, markets, economics of production, industry, technology, social, political, and ecological conditions leading to a given geographical state. However, internal, external, natural and manmade disruptions can occur. These perturbations can be climate change, soil degradation, changes in policies or regulations, pests and disease, energy costs, increased populations taking farm land, changes in diet, changes in product or input prices, and change in water supply/drought or conflicts.

In the last century a significant amount of the Nation’s food and fiber production shifted from the East to the arid West due to the establishment of irrigation infrastructure (Effland 2000, Gardner 2002) and improved transportation. Similarly, with transportation improvements corn and grain production became concentrated in deep water-holding soils in the upper Midwest that avoided drought losses occurring in the shallow, poor water holding soils in much of the East (Meyer 1987, Gardner 2002, McNider et al. 2005, McNider and Christy 2007).

A similar shift occurred with cotton, vegetables, and potatoes as irrigated production became concentrated in the river basins of the arid West. The East and especially the Southeast lost a large portion of its row crop agriculture due to poor water-holding soils and short-term droughts. Rain-fed corn farmers in the East could not compete with farmers cultivating in the high water-holding capacity soils of the Midwest or irrigated cotton in the West (Arax and Wartzman 2003, Effland 2000). The shift in production was accelerated by drought conditions in the 1950’s that forced Eastern corn and cotton farmers out of business.

In 1939 Maine, New York and Pennsylvania led the nation in potato production. By the 1950’s, Maine, New York and Pennsylvania lost their historical top rankings in potato production to Idaho and Washington as irrigation projects on the Snake River came on line. Potato farmers in the Northeast and vegetable farmers throughout the East went out of business.

The Northeast lost vegetable production to California and Arizona. At present, California accounts for approximately 25% of the nation's vegetable production including potatoes. For vegetables alone, California accounts for nearly 50% of U.S. production. Wysong et al. (1984) showed that in 1950 the Northeast produced nearly the same percentage (21%) of vegetable production as California does now. However, by 1980 this had dropped to less than 7%.

The shift in agriculture left a swath of poverty in abandoned agricultural areas especially in the South. This poverty persists today and in many areas the economy is dependent on government welfare transfers.

1.2 Vulnerability of the Present Geography and Food Security

The present drought in the West and the 2012 Midwest drought underscore the vulnerability of the present geography of U.S. agricultural production. In the West, burgeoning population growth and environmental restoration are competing with farmers for water supply (Reisner 1986, Postel, 1992; Rosegrant et al., 2002; Gleick et al., 1995, Udall and McCabe, 2013, Overpeck and Udall 2010, MacDonald 2010). The last 100 years in which western irrigated agriculture evolved was likely the wettest in the last 500 years in the Colorado Basin (Pechoita et al. 2004, Vano et al. 2014). The paleo-climate record shows historical multi-year and decadal droughts in the West far exceeding those in the recent past (Cook et al. 2015, Woodhouse and Overpeck 1998). Further, future climate change scenarios generally show drying in the Southwest U.S. and increased risks of decadal and multidecadal droughts but little change or an increase in precipitation in much of the East and South (Cook, et al 2015,IPCC).

The 2012 Midwest drought shows the danger of concentrating so much of the Nation's grain production in one geographical area whose size is less than the synoptic weather scale. Regional droughts are often controlled by the synoptic scale of high pressure persistence. Thus, not distributing production across the synoptic scale can lead to increased vulnerability. In addition to the regional drought, the concentration of grain production in the upper Midwest has overwhelmed the assimilative capacity of its watersheds leading to excessive nutrient export hypoxia in large areas of the Gulf of Mexico (Rabalais et al.2001). Recent policy panels suggest that a significant reduction in nutrient export may be required to alleviate nutrient loading (Rabalais 2011) which may constrain Midwest production and certainly make it more expensive.

Given the climate of North America there is a huge variation in available water for consumption. National maps (Kenny et al 2005, Caldwell et al. 2012, McNider et al. 2015) show that many areas of the west are currently consuming large fractions of the available water. In fact, Sabo et al. (2010) calculate that humans now appropriate the equivalent of 76% of the West's streamflow for agriculture, domestic use, and other purposes.

Perhaps of greater concern from the discussions above is that both climate change scenarios (IPCC) and paleo-climate data (Piechota et al. 2004) indicate that the West is likely to experience greater reductions in available supply. IPCC consensus of precipitation models under climate change scenarios show that conditions are likely to exacerbate further the existing difference in water supply with the West becoming drier and the East and Southeast in large part showing no change or an increase in water supply. Can western agriculture be substantially maintained with less water likely in the future? In the recent California drought, in the face of significant surface water reductions, agricultural production was maintained by increased ground water pumping (Howitt et al. 2014, Howitt et al. 2015); however many feel this is unsustainable (Famiglietti et al. 2011).

On the other hand, in the East in most watersheds, only a small fraction of the water is actually withdrawn and used (see Kenny et al., 2005, Caldwell et al. 2012, McNider et al. 2015 with less than 5% consumed in most watersheds. In the past 100 years the U.S. has migrated agriculture away from the most abundant water resources, taking advantage of the drought mitigating aspect of the irrigated agriculture common to the West and the plentiful class A soils found there. Balancing the generally more plentiful freshwater supplies in the eastern states, are the preponderance of shallow/poor water-holding soils. This renders rain-fed agriculture susceptible to yield reductions and even crop failure during short-term growing season droughts common to the region. This is why irrigated area has expanded greatly in the Mid-South and is expanding in a number of Southeastern and Midwestern states as well as along the Atlantic seaboard (Vories and Evett, 2014). Additionally, the East and Southeast are not immune to drought (Seager et al. 2009). The 2000 and 2006-2007 droughts are recent examples, so that consideration of drought conditions especially hydrologic drought must be considered in examining the limits on expanded irrigation in the East. However, even during severe Eastern droughts over 100cm (40 inches) of precipitation still falls.

As discussed below while the East likely has available water for irrigation in most places, consideration must be given to ecosystem requirements. Also, pest, fungus and soil erosion as well as legal constraints may inhibit eastern production.

1.3 Strategies for Sustaining Agricultural Production

Sustaining the country’s extraordinary agricultural production in the face of population growth, water use, environmental, energy and climate challenges will be difficult in the 21st Century. There have been at least three major climate adaptation paths proposed for sustaining food supply in the U.S:

1. Water conservation (e.g. reduction in flood irrigation, use of conservation tillage, low pressure nozzles, improved irrigation application methods and scheduling (O’Neill and Dobrowolski, 2005)
2. Additional large water projects to store or deliver water to agriculture (e.g. projects proposed in California (Bureau of Reclamation 2014) or moving water vast distances from the Northwest or the East).
3. New drought, heat and salt tolerant hybrids through genetics.

Given the relatively rapid (about 30 years 1950-1980)) geographical shift in agriculture in the last century, it is proposed that consideration of a fourth strategy (in addition to those above) - a geographical positioning or distribution of agriculture to where it may better face the challenges enumerated above.

The migration that occurred in the last century was initiated by federal policy that led to market forces which changed production geography. In the West it began with the Homestead Act of

1862, followed by the Reclamation Act of 1902 and the Enlarged Homestead Act of 1909. Although private irrigation projects had already expanded irrigated area in the western states, the Reclamation Act began a period of rapid expansion of irrigated area in the western states during which irrigated area expanded from 8 million acres in 1900 to 55 million acres in 2000, mostly in the western 17 states. With this new highly productive competition, eastern rain-fed farmers faced market forces that drove them out of business. Similarly in the Midwest, government policies that improved transportation, especially locks and dams, enabled Midwest farmers to expand their market footprint.

The geography that evolved in the last century was largely driven by a search for consistent water for agricultural production – through irrigation in the west and deep water holding soils in the Midwest. Thus, increased production in other areas will require increased irrigation in the Midwest, Mid-South and Eastern states (Vories and Evett, 2014).

Though the new geography that evolved due to market forces provided abundant food and fiber production, non-market forces such as the environmental costs, or the subsidized cost of water, or future costs of water or the sustainability of production, or future energy costs were not fully considered in this geographical shift.

While many have voiced concerns about vulnerabilities of agriculture to future climate change (Schneider 1989, CCSP 2008, Mearns et al 1999, Melillo et al. 2014), little has been discussed about geographical changes in U.S. agriculture in the last century that make it more vulnerable to climate. Also, these geographical changes may be more vulnerable to competing demands on water resources and the energy required for effective distribution of food to population centers.

Is the geography that evolved in the last century, due to government policy promoting homesteading, immediate market forces and government investments, sustainable and reliable for the future? Will the geography of agriculture continue to evolve and, if so, can information be developed that can guide future migrations of agriculture that can provide food security sustainably?

1.4 Research Challenges to Define Geographical Sustainability

In order to address the research challenges in geographical sustainability it is necessary to build tools and information that can help define a geography of agricultural production that maintains economically competitive agricultural production in the U.S. but considers its sustainability in terms of natural resource and energy factors. The challenges have three main components:

(1) **Defining Metrics and Mapping Geographical Attributes of Agricultural Production –** This would include data and tools to map the economics of production, water availability, energy production and transportation and natural resource impacts under scenarios of climate change, population change and energy change.

(2) **Geographical Optimization Models –** This would include developing and testing models that might produce optimal geographies of agricultural production including natural resource constraints.

(3) **Process and Component Models –** This would include developing sub-component models or data needed to capture geographical attributes needed in (1) and (2).

The main intellectual challenges are defining the metrics for sustainability and acquiring/creating the data to map these metrics. This is complicated by the fact that the data crosses the science of climate and hydrology with applied economic information in agriculture and energy.

2. Defining Geographical Sustainability

While there have been many NSF and USDA activities examining the potential impact of climate change on agricultural production, it is felt that there has not been as much attention to the relative geography of production related to climate, transportation energy, soils and water availability. There are two strategic questions – (1) Is the geography of agricultural production that evolved in the last century sustainable and reliable for the future? (2) Will the geography of agriculture continue to evolve and, if so, can information be developed that can guide future migrations of agriculture?

2.1 Defining and Mapping Geographical Attributes of Agriculture

Research is needed to develop data and modeling tools that can map metrics that define the food production economics, energy transport, water resource availability (that is the Food Energy Water-FEW nexus) and environmental attributes that characterize a sustainable geography.

Production Metrics: First order metrics would be crop yield, water use efficiency, energy use and net profit. While government investments and transportation perhaps initiated the shift in agriculture in the last century, its maintenance was dependent on the new geography being more profitable. Midwest grain farmers, largely insulated from short-term droughts by deep water-holding soils, drove competitors out of business by delivering grains at prices that other rain-fed regions could not match. Western potato and vegetable farmers delivered quality and price that could not be matched by Eastern producers. However, some of the costs of production are changing such as increased costs of water in the West or new costs of dealing with nutrient loading in the Midwest.

Thus, the first metrics that need to be produced are maps of yield, water use efficiency, energy use and net profit for various crops. These production maps would now consider the new costs of water, potential increased costs of energy for pumping and transportation, and costs of implementing reduced nutrient loading. The production maps would also consider irrigated production in parts of the East and costs of pesticides/herbicides/fungicides. The yield information to construct these maps would likely come from crop models that reflect soils, water availability, cultivars and weather. Energy costs and use can be determined by energy projection models (EIA 2015). Data driven statistical models of crop yields might also be used in creating the maps.

To understand the future resilience of the geographical production system, these crop yield/profit tools would need to be coupled to external physical factors such as climate change or paleo-climate scenarios and to external global food and energy scenarios.

Climate Scenarios: At the Boulder Workshop it was emphasized that both climate change scenarios and paleo-climate scenarios represented threats to agricultural production. Consideration of historical information and paleo-climate may be especially important for evaluating resilience in the East since climate change scenarios often show little change or increases in precipitation in the region. However, the East and Southeast do suffer from drought (e.g. Seager et al. 2009) so long-term simulations and paleo-reconstructions must be used to evaluate the sustainability of Eastern irrigation. Blended climate change/paleo scenarios have been developed in the past. See for example Yates et al. 2009.

Energy Use Scenarios: The production maps would also need to consider energy price scenarios. Energy availability and price impact of pumping costs for irrigation and transfer of water. Energy prices also impact transportation costs for delivering food and grains. While final transportation costs are generally a small part of the total energy in producing a crop, transportation costs can be a major factor in final net profit. McNider et al. (2015) showed that reduced transportation costs made irrigated corn profits in the Southeast competitive with Midwest profits. Heller et al. (2001) also showed in a study of the optimal geography of dairy herds that, because some energy costs of production are inelastic by region (e.g. all fertilizer input may be nearly the same by region), transportation cost can determine the final net profit.

Energy Production Scenarios: In addition to the impact energy has on production and delivery of crops, is the impact on ethanol production. While ethanol is still a small and controversial part of U.S. energy production, it is critical as an octane booster in gasoline for automobiles. The concentration of corn production in the Midwest makes this supply vulnerable. Refineries may not be able to find other short-term options. Soy diesel production is also concentrated in the Midwest. Electric energy production is also dependent on water. Food and energy are essential to modern life so consideration of water available for irrigation and its competition for production should considered.

Water Scenarios: Water availability is not only dependent on precipitation and evaporation from climate scenarios but also on anthropogenic demands. In the West, other uses of water for public water supply and energy compete with agriculture, potentially increasing the costs of water. While the Southeast has potentially similar competition, the baseline starts with much smaller fractions of the available water than the West. The challenge should consider population change scenarios in both the East and West in terms of impact on water prices for agriculture and competition with use by the energy sector.

Global Agricultural Production Scenarios: While the focus is on the geographical economic and environmental metrics in the U.S., the backdrop of global food production must be considered. It is envisioned that the U.S. mapping of metrics might be carried out at a resolution that could not be replicated for the globe due to data availability. However, global production and global needs for food can impact price, imports and exports. It is felt that global agricultural scenarios can be applied as boundary conditions on price and demand for the U.S. profit metrics. Defining these global externalities and their impact on U.S. and global production will be challenging and require consider of downstream impacts such as nutrition. The U.S. extraordinary food production currently supports food needs for the world. Given, the global growth in food needs and potential threats to agricultural production, it may be critical for the U.S.to maintain its production.

Environmental Resource Metrics: As noted above, the shift in agriculture in the last century largely ignored the costs of environmental externalities such as the ecological costs of riverine streams depleted for the sake of irrigation or reduction of flows into coastal zones or the impact of nutrient loading on freshwater and marine ecosystems. However, today it is recognized that such costs need to be considered as part of sustainability. While it is sometimes difficult to place an absolute economic value to these impacts, relative measures of impact can be defined. The following gives some possible environmental metrics, although part of research challenge is the development of new environmental/natural resource metrics.

Fraction of Water Resource Used: Hydrologic models coupled with models of irrigation demand and other anthropogenic withdrawals and consumption rates can be used to calculate the fraction of the water resource used (see Kenny et al. 2005). Examples of a national maps of water demand to water supply from the WaSSI model are provided in Caldwell et al, 2012 and McNider et al. 2015. Gollehon 2012 noted that the reduction in water used per acre in irrigation in recent years was in large part due to an eastward migration of irrigation where water needs were less.

Limits on Watershed Withdrawals: In looking back at the evolution of irrigated agriculture in the last century, there were never quantitative calculations of the limits to irrigation that might be sustainably carried out based on ecosystems needs and competing demands. Using hydrologic models, coupled with irrigation demand models and specification of environmental flow attributes to be protected, one can make calculations of how much land can be irrigated and still protect ecosystems. Srivastava et al. (2010, 2011) provided example calculations for a few water sheds in the Southeast where 10-20% of the water shed could be irrigated while still maintaining environmental flow criteria.

Nutrient Export/Concentrations: As noted above, agricultural production in the upper Midwest may be constrained by nutrient export to the Mississippi Watershed. Calculations of nutrient export per hectare or by nutrient concentrations within a watershed would provide some assessment of the relative resource stress.

Pesticide/Herbicide/Fungicide Applied: While western agricultural production may be limited by water pressures, the East may have other negative environmental attributes such as chemical applications. While these are negative in terms of additional cost of production their potential in terms of run-off pollution should also be considered.

Impact on Carbon Sequestration: Additional Eastern agricultural production may come at the expense of forest conversion land back to agricultural land. Calculations of changes in carbon sequestration can be a metric.

2.2 Geographical Optimization Models / Life Cycle Analyses

A second more ambitious challenge would be to develop modeling systems that would theoretically optimize the national geography of agricultural production given water, energy and market constraints. That is, can models that include soils, water, climate, cultivars, agronomic practices (including irrigation), transportation energy, and production energy be used to define an optimal geography which maximizes agricultural output and minimizes natural resource impacts? In California, investigators (see Howitt et al. 2009, Medillin-Azuara et al. 2012) have developed optimization models that consider land, markets and water inputs to determine the optimal production location and crop mix that maximizes the net economic gain to the State. It is interesting that this model foresaw the changes in agricultural production during the current California Drought. For, example rice and grain farmers reduced their acreage and water was transferred to high value crops such as almonds and vine crops.

There have been several funded activities (e.g. Meiyappan et al. 2014, Meiyappan, P. and Jain, 2012) that look to understand changes in the global land use geography and gross agricultural production under climate change scenarios. While there have been large scale attempts at model evaluation of these type models (Meiyappan et al. 2014) it would appear that the dramatic shift in U.S. geography of production driven by water infrastructure development, national policy, market forces and transportation might also be used for smaller scale evaluations. While externalities are sometimes difficult to cost absolutely, one can ask what levels of cost would change the geographical answer. For the future, these models could be used to look at optimal production in the face of climate, population and energy demands.

In addition to optimization models, classes of models referred to as Life Cycle Analyses/Assessments (LCA) (Guinée 2002, Brentrup et al. 2004, Heller and Keoleian, 2000, World Resources 2011) should also be considered as paths to defining optimal geographies. Heller and Keoleian, 2011 provide an example of the optimal location of dairy herds considering water, energy and profit.

3. The Utility of Geographical Sustainable Information for Policy Makers and the Private Sector

It was noted at the workshop that the U.S. does not have a planned agricultural economy and that the government does not tell producers what to grow. What producers decide to grow and where they grow is a free market decision.

However, as noted above the shift in agriculture that occurred in the last century was spurred by government policies and public investment in water infrastructure. The Bureau of Reclamation programs of land grants and low cost water spread agricultural production throughout the West. The locks and dams on the Mississippi, Ohio, Missouri and Tennessee Rivers allowed grain to be shipped out of the Midwest to the Southeast for consumption and for export to the world. Perhaps less well known were programs in Farm Bills which prohibited farmers in protected commodities such as corn, soybeans and cotton from growing vegetables, or policies of the Conservation Reserve Program that accelerated the loss of agriculture in the East. The EQIP programs gave western farmers funds to upgrade irrigation systems but did not allow eastern farmers to invest in new efficient irrigation infrastructure. Information on geographical sustainability would be useful in policy decisions.

Never-the-less, the comments above are on the mark that individual producers select what they grow and they measure the risk involved. It is believed that such risk-reward decisions are best made when good information is available to producers making these decisions. In the last century when Southern agriculture was collapsing, many farmers in the South simply did not have the information to understand that transportation and western irrigation had changed their world. Having farmed for generations and looking at their production costs all they could see was that commodity prices were too low and the weather too bad (especially in the 1950's). Thus, many farmers tried to hang on thinking better prices and good weather would eventually come. In the new world of Midwest grains and irrigated agriculture this simply put Southern rain-fed farmers further in debt and many lost everything.

Providing Macro-information on Water/Energy/Food Production

It is felt that providing understanding of the geography of climate, water, energy and production for the private sector and government useful in making production or policy decisions. Thus, the maps of geographical economics and water availability may provide cues to western producers that their world is changing now (just as Eastern farmer's world changed in the last century). The water that was critical to the success of agriculture in the West may not be available in the future.

For Midwestern farmers the constraints that may be placed on production due to nutrient limitations may increase their costs. Drought losses, with perhaps less protection than presently in Farm Bills may endanger these large investments. This is precisely why irrigated area is rapidly expanding in the Midwest.

The geographical sustainability research products to be produced will be the type of information that farmers and agri-business can use in making key investment decisions. There are currently national farm realty companies that use GIS information to market land based on soils, slope and other physical attributes. Production potential, profit, irrigation demand, energy costs, and transportation costs could be added as attributes to these farm realty information systems.

Irrigation companies are at the forefront of where farmers make long-term investments in irrigation. Information in terms of irrigation demand, water availability, and energy pumping/transfer costs will be the type of data that irrigation companies can convey to farmers for these long-term investments.

Such information can also be used by policy makers in government to make needed infrastructure investments. As mentioned, the West flourished under the investments made by the Bureau of Reclamation and states. If the U.S. wants to sustain its agricultural production in the coming century, investments may need to be made in Eastern agricultural water infrastructure. The information to be developed could determine the economic and environmental sustainability of the creation of such infrastructure.

Role of the Private Sector

As noted above, while government policy decisions can drive crop and production strategies, many of the individual production decisions are based on farmers' understanding of their own capability, factoring in expected costs of production and final product price. While some decisions are year to year, many are long-term such as investing in new farm equipment or irrigation. Agri-businesses play a role by both guiding and responding to changes in long-term trends. As such they must be partners in any strategy to re-distribute the agricultural productivity of the nation.

4. Tools, Geographical Analyses and Processes

There are several tools and approaches that can be used to address geographical sustainability of U.S. agriculture. These are outlined below.

As mentioned above there are three types of research components that can help define geographical sustainability of U.S. agriculture. Examples of tools and approaches are provided below within these categories.

(1) **Defining Metrics and Mapping Geographical Attributes of Agricultural Production:** This would include data and tools to map the economics of production, energy of production and transportation and natural resource impacts under scenarios of climate change, population change and energy change. This would also include Life Cycle Analyses (LCA).

Crop Analyses: Crop models driven by climate scenarios are needed to define the yields and economics of crops grown in different regions.

- Cotton example: One example might be an analysis of cotton grown in New Mexico, Arizona and California compared to Alabama, Mississippi, and Georgia. Metrics might be yields, costs of irrigation, energy use, irrigation demand etc. Environmental metrics might be herbicide or pesticide rates, fraction of available water used etc.
- Vegetable Production: A second example would be an analysis of vegetable production between the West and East. Metrics might include costs of production, transportation energy costs, freshness etc. under different climate and energy scenarios (see Wysong et al. 1984)
- Dairy Herds: A third example, as a Life Cycle Analyses (LCA) approach, may be the positioning of dairy herds. Here transportation energy costs for grain and dairy might be considered as well as costs of local grain production including irrigation costs (see Heller and Keolian 2011).
- Grain Production: A fourth example might be the relative economics of growing rain-fed grain in the Midwest versus irrigated grain in the Southeast (see McNider et al. 2015) Metrics might include net profit, energy used for transportation and energy used for pumping. Climate scenarios emphasizing regional drought in the Midwest or Southeast might be utilized along with boundary conditions on world supply and demand scenarios which would impact price.

Water Quantity / Quality Impact analyses: Regional hydrologic models coupled to anthropogenic withdrawals, including irrigation demand from crop models, might be used to analyze impacts on water availability.

- Changes in the geography of agriculture: One example would be increases in agriculture in the East and increases or decreases in the West. These could be calculated under different climate scenarios. Metrics might include fraction of water supply used, impact on environmental flow criteria, and number of times withdrawals for agriculture might be curtailed due to drought.

- Cost of water infrastructure: The costs of water infrastructure to support irrigated agriculture per hectare in different geographical areas might be calculated using irrigation demand models, storage needs and climate information.
- Changes in water quality nutrient loading due to changing patterns of production (Mirhosseini and Srivastava, 2015). How would a more distributed system of grain production outside of the Mississippi watershed change nutrient input to the Gulf of Mexico?
- Changing from ground water to surface water in the East: Is there a role for the greater use of surface water in areas where ground water is being depleted such as the Mississippi Delta (Arkansas, Mississippi, and Louisiana)? Metrics might include energy requirements for pumping water laterally as opposed to vertically, costs of infrastructure, impacts on surface water of increased withdrawal and impacts on ground water of decreased withdrawal.
- Ground water as a buffer in the West: Can ground water continue to be a critical support for agriculture in California in times of surface water drought?

Energy Impact analyses: Understanding the geography of energy use in agriculture and energy production by agriculture is important to understanding geographical sustainability.

- Geography of energy availability and agriculture. The geography of energy costs/availability for irrigation might be mapped and the impact on cost/availability analyzed for increasing or decreasing agricultural production under climate change and energy pricing scenarios.
- Competition between hydroelectric energy production and agriculture: In the East increased irrigation may use water in basins where the water is used for hydroelectric production. Is the use for agriculture a greater positive economic and societal impact than electricity production? Here LCA approaches might be used.
- Competition between water for thermo-electric cooling and agriculture: In the East and the West water is used for cooling, Is there competition for water and how often might such conflicts arise? How many watersheds might have such competition? Can intermittent withdrawal limits on farmers or utilities during extreme droughts reduce these conflicts?
- Impacts of energy costs on transports of food and grain. The current geography of agricultural production depended on relatively cheap energy for transportation. How might the geography of net profits depend on transport costs?

(2) Geographical Optimization Models – There is a need for developing and testing models that might develop optimal geographies of agricultural production.

Optimization methods have long been used in economic analyses, of energy production evaluation, and water use in agriculture (Mullin et al. 2003, Medellin et al. 2012). In these optimization models a cost function is chosen to be minimized or maximized.

In macro-agricultural economic terms, the problem of what crops are best grown where is an optimization of profit problem (Howitt, 1995). With the assumption that a crop region having the greatest net profit in connected markets will, through improved price taking capability, eventually drive other regions out of the crop. In its simplest schematic form the optimized net profit is

$$\text{Max}\ [\text{Yield (i) x Price (i)} - \text{Cost of Production (i)}] \qquad (1)$$

For a specific crop at location i then the region with the greatest net profit would ultimately prevail. For example, if one returns to the last century and takes corn as the crop then two regions (Iowa and Alabama) can be compared in terms of competitiveness. Iowa yields are higher because their deep water-holding soils reduce drought losses suffered by the Alabama rain-fed farmer. In 1925 before transportation improvements, the price received in Alabama was much greater than in Iowa because yields were low but these low yields coupled with local demand dictated a higher price. In Iowa yields were high but farmers rapidly saturated the local market producing a low price. However, as transportation improved so that Iowa could sell corn into the Alabama market, the Iowa farmer eventually gained a higher price while Alabama farmers faced a lower price. The lower yields and lower price received reduced the net profit to the point that the Alabama farmer was driven out of business. This is the economic model that supported the migration of corn from the East and Southeast to the upper Midwest. Transportation energy costs enter through the price term as opposed to the cost term since the offering price (the basis difference from the Chicago price) depends in part on the delivery point of the grain from Iowa. Similar mathematics faced Southern rain-fed cotton farmers competing with Western irrigating cotton farmers whose yield and quality were higher, resulting in a migration of cotton production from the South to the High Plains, California, Arizona and New Mexico.

Today the contributing terms of equation (1) for cotton and corn have changed. For cotton in the West the effective Cost of Production has increased due to the value of water for irrigation. In the South irrigation has the potential to increase yields both for cotton and corn but at the expense of cost of production. Midwest costs of production have increased due to the price of land and potentially increased production costs due to new regulations on nutrient export. However, transportation costs are now in the SE favor since the grain is consumed locally.

Use of Optimization Models for Determining the Optimal Geography of Production: It is envisioned that spatial optimization models could be tested against the last century's large migration of agriculture for different crops. While equation (1) is conceptually a simple equation, it is complicated because of weather and climate. Yields are dependent on weather as is the cost of irrigation which in the East depends on how much natural rainfall occurs. Transportation distance/cost to consumption also influences the net profit.

Crop models using climate scenarios could be used to predict yields, irrigation demand and nutrient inputs to be used in equation (1) for yields and production costs. Models to determine the costs of environmental externalities could also be added as production costs. Once tested, these spatial optimization models could then be used to define the optimal geography of future production given future scenarios of climate, cost of water, energy cost for pumping, energy costs for transportation, etc. Spatial optimization models have been used in California and have shown skill in predicting the locations and specific crops that have been fallowed in response to drought (Medillin-Azuara et al. and Howitt et al. 2015)

There are also other approaches, though not full optimization models, which fit into this category such as Life Cycle Analyses. As mentioned above, these tools can address the spatial advantages to production. An example above was the geographical placing of dairy herds.

(3) Process and Component Models – While complex multi-component synthesis models as envisioned in (1) and (2) above are needed to examine the geography of production and it sustainability, there is also a need for process and component model development and application. These process studies and component models could eventually be used in the mapping of the geography or in the optimal geography models. Examples of these process or component models are given below.

A. Nutrient Export: There is a need to be able to quantify nutrient export in different geographic regions under both rain-fed and irrigated conditions and/ or to couple existing nutrient export models to crop models or regional hydrologic models. What will be the costs to Midwest farmers for complying with new nutrient regulations? While one goal of migration might be reduced nutrient loading on the upper Mississippi, are there other issues with nutrient loading in other locations? What are the differences in the nutrient transport processes/systems in the Midwest and Southeast? While decreased loading may reduce hypoxia in the one part of the Gulf of Mexico, will additional loading in other river systems create similar problems in other marine/coastal zones?

B. Cultivars suited to Eastern Production: Because of the dominance of the West in vegetable production, cultivars have been honed for that environment. The Eastern Broccoli Project (Björkman et al. 2012) is an example of developing cultivars that do well in Eastern climate and pest environments. Eastern production protects against cost increases to the consumer if water prices for agriculture increase in the West, but have additional positive benefits by increasing freshness and nutrition for Eastern consumers.

C. Carbon Sequestration: While the loss of agriculture in the East was an economic blow, the return of agricultural land to forests has been part of increased carbon sequestration that has in fact been used in carbon budgets. What impact might increase agriculture in the East have on carbon sequestration?

D. Economic costs of environmental externalities: While agricultural profit as a geographic metric is complicated by weather, costs of energy, external markets and demand, it is at least definable. In characterizing geographic optimality, determining the external costs to the environment will be less straightforward. What are the costs due to reduced flows in rivers or the costs of added nutrients to aquatic or marine ecosystems? Process studies that attempt to quantify these costs are needed.

E. Energy Pricing: Part of the current geography of agricultural production was built upon transportation energy costs that allowed food and grains to be delivered vast distances. What might be the impact of higher transportation energy costs? What are relevant models for projecting future energy costs for agriculture?

F. Legal Impediments to Migration of Agriculture: The Riparian Rights Doctrine governing water policy in most of the East restricts the use of surface water to land owned next to streams (Dellapenna 2004). Thus, legal policy may be an impediment to providing renewable water for expanded irrigation in the East. It may also be an impediment to relieving pressure on ground water in places like the Mississippi Delta. Joint legal, crop irrigation and hydrologic studies may be needed on ways to allow sustainable use of water on non-riparian land and have systems in place to protect the other part of the Riparian Doctrine which is not harming a current riparian downstream user. Also, water policies can have unintended consequences (Whittlesey and Huffaker, 1995) and impede conservation efforts in the West (Huffaker et al. 2000).

G. Vegetable Models: Crop models for grains and other commodities have been used widely in looking at the impact of climate change on food production. However, there are fewer models of vegetable production that include quality and impact of pests and disease (reference – vegetable modeling workshop in Davis). Can new crop models for vegetable production be developed to be used in different geographical settings?

H. Nutrition: As noted above, since California controls the current market for many vegetables, if water is not available rather than a reduction in vegetable production, prices may go up. What will be the impact of higher fruit and vegetable costs on nutrition?

I. Limits on Irrigated Production: In the West, watersheds became oversubscribed by not looking ahead to how much irrigation might be supported without harming the ecosystems of the streams. The hydrologic and crop models can be coupled to determine these limits in other regions.

J. Societal Impacts: As mentioned above, the shift in agriculture in the last century left a swath of poverty in abandoned agricultural areas. Research on societal impacts of future changes need to be considered.

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APPENDIX A

WORKSHOP RESEARCH ISSUES / QUESTIONS DEFINED

Workshop Discussion on Research Questions

On the final day of the workshop a session was held to define the overarching questions related to understanding geographical sustainability and its role as a tool in migration of agriculture to maintain production. The following attempts to classify and categorize the major research questions and sub-questions.

The Boulder FEW Workshop was built around three overarching questions.

1. **Should the geographical positioning of agriculture be considered as a path to sustain agricultural production in the U.S.?** This would be an additional path for coping with climate, water, energy and environmental pressures on agricultural production. Previously discussed paths have been conservation, genetics (drought and salt tolerant cultivars) and additional water infrastructure (storage and transfer).
2. **How can geographical sustainability be defined; that is what metrics need to be considered?** Example economic metrics might be yield, profit, etc. Environmental metrics might be water availability, nutrient export, etc. Societal metrics might be rural poverty, unemployment etc.
3. **Of what use would be the geographical information to policy makers and the private sector?**

These general questions were part of the program and presentations made. **Given, the interest and response to the workshop and the discussions at the workshop there is a consensus among the participants that consideration of understanding of geographical sustainability is a worthwhile goal of NSF's research challenge.**

In addition to these overarching questions there was consideration of sub-questions that need to be answered to address geographical sustainability. The following lists and discusses these questions.

1. Economics

What are the economic metrics to be produced? Examples discussed at the workshop included profit, yield, gross production (e.g. Gross Agricultural Impact including costs of production and economic multipliers).

How can agro-economic analyses be constructed that demonstrate competitiveness of agricultural systems in the Southeast with the West and world? While the emphasis and details of geographic assessment must be made at the national and regional level, it is imperative that global agricultural production be included at least through boundary conditions that impact supply, demand and price.

Do we need to focus on national or regional economics or both?

What is the integrated balance between food, fiber, feed and fuel?

2. Environmental

While one goal of migration might be reduced nutrient loading on the upper Mississippi are there other issues with nutrient loading in other locations? What are the differences in the nutrient transport processes/systems in Midwest and Southeast?

While decreased loading may reduce hypoxia in the one part of the Gulf of Mexico, will additional loading in other river systems create similar problems in other marine/coastal zones?

Can we evaluate the limits of irrigated agriculture in the face of other demands, so we don't over subscribe the system?

What are the sustainability boundaries or ecological limits of various hydrological alterations?

How can we create maps on smaller watersheds to see how irrigation increases ET for the entire region?

3. Climate

The current western drought and the Midwest 2012 drought exposes the geographical vulnerability of the present production system. Can future climate scenarios be developed to test future geographies? As discussed at the workshop this will likely require blending of climate change and paleo-climate scenarios to examine future resilience.

What is the role of changing extremes in adaptation and the benefits and limits of equilibrium based approaches? This is an important question in that while movement of agricultural production to the Southeast may reduce pressures on water in the West, it may open up vulnerability to other parts of the climate system such as hurricanes, floods and storms.

What other approaches can we develop that account for volatility in a system? Climate will not be the only stressor.

4. Energy

Is migration sustainable given energy demands? The current geography of energy for water and agriculture has evolved over the last 50 years. Will a new geography of agricultural production be compatible with the existing geography of energy availability?

One of the goals is to make agriculture energy self-sufficient. Is this an issue that should be part of geographical sustainability?

What impact will migration have on CO2 emissions or other greenhouse gases such as methane?

Will conversion of forest lands back to agricultural lands in the East impact strategies for carbon sequestration?

What impact will energy pricing have on migration scenarios? As noted worldwide energy use has grown exponentially. Can the relatively low prices for pumping and transportation which supported the current geography be maintained in the future against the backdrop of increased energy requirements?

Most ethanol/biofuel plants are in the upper Midwest. Would a more distributed system of production of grains require a new geography of biofuel facilities?

Would a more distributed grain production – help ameliorate competition between food and energy for fuel stocks?

What will be the competitiveness of nutritious food production within the migration concept?

5. Societal

What is the uniformity of impact among the populace of the increase in GDP associated with migration of agricultural production? That is, even if agricultural production is maintained of what economic value is this to local populations? Will only a few profit and others be negatively impacted by the associated negative impact of agricultural production?

How can those areas which may lose agricultural production be protected?

What changes in water policy framework are needed to provide incentives for further migration?

What is the importance of crop and water insurance, intermittent regulations, and financial services to make migration work?

What are the diets of the future? This is important. It is not only climate that changes but also the type foods. In the last century diets in the U.S. changed dramatically to a higher meat and prime cut diet. Will the world follow this path or will the U.S. return to a greater grain/vegetable diet?

What is the potential for urban agriculture to address food security? At the present there are the beginnings of a buy local movement – will this persist or is it a fad?

What is the influence of the rural to urban interface on food supply, and water and energy footprints to transport food to consumers?

6. Programmatic

How can a FEW Program coordinate and foster the disparate pieces of the overall long-range goal of developing information to guide geographic production?

How can we craft collaborative data frameworks between remote sensing and management for information services to support adaptation in a changing environment?

How can Earth System models and integrated system models be effectively applied to study the FEW nexus?

How can we determine the optimal methods to use for life cycle analysis to analyze tradeoffs? Heller made a compelling presentation that life cycle tools and analyses may be key to carrying out geographic sustainability analyses.