Report of the National Science Foundation Workshop on Water- and Energy-efficient Food Production: *Solutions for America's Bread Basket*

November 19 – 20, 2015

Manhattan, Kansas

I. Workshop Participants

The following are the attendees (listed in alphabetical order) of the National Science Foundation (NSF) Workshop on Water- and Energy-Efficient Food Production in the Central Great Plains held in Manhattan, Kansas during November 19 to 20, 2015.

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Contents

II. *Executive Summary*

The NSF workshop on Water- and Energy-Efficient Food Production in the Central Great Plains held in Manhattan, Kansas during November 19 to 20, 2015. This was one of 17 workshops focusing on critical research priorities within the Food-Energy-Water trilemma. This workshop specifically focused on issues relating to the agricultural production of foodstuff within the Central Great Plains region. With workshop participants from across the nation, the group identified several critical barriers to the immediate success of this objective. These include:

- The need to take a systems-approach to this inter-related problem
- Improving efficiency and sustainability of nutrient production and use in agriculturer
- Energy for agricultural machinery
- Modeling and data management
- Optimizing Soil-Health by combining Geo-Eco-Systems in a Biology Approach
- Livestock Systems
- Genetic Improvement and Breeding of Existing and Alternative Crops
- Climate Change and Agroecosystems
- Precision Agriculture and Irrigation
- Water Quantity and Quality

Each of these topics overlaps with one or more of the other topics listed. As such, any concerted effort to create a research portfolio that advances this topic will require a complex portfolio covering all of these topics and perhaps others.

III. *Objectives of the Workshop*

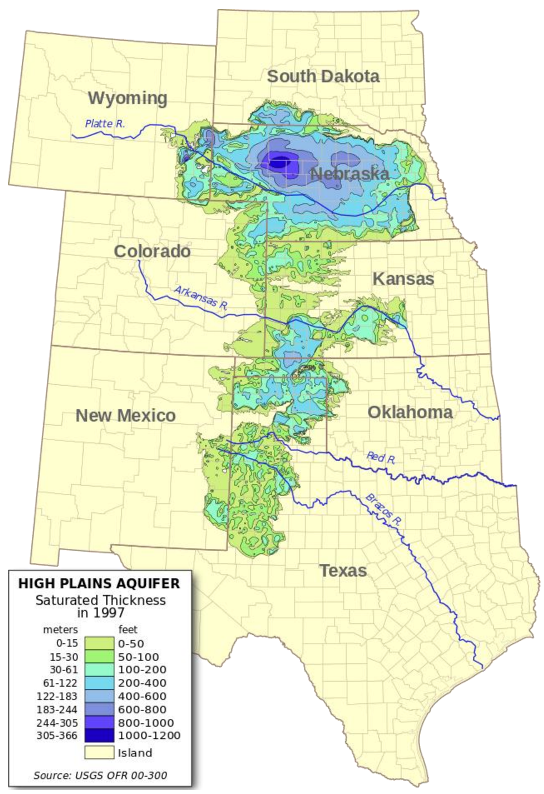
The objective of this project is to host a workshop that will develop research priorities related to water- and energy-efficient food production in the Central Great Plains. The workshop will be attended by researchers, government agencies, producer groups, consumers, and policy makers. The Central Great Plains (CGP) produces wheat, barley, canola, corn, cotton, sorghum, and soybeans for consumption in the US and international markets. The CGP consists of a region roughly bounded by the Missouri River on the east and the Rocky Mountains on the West with Canada's Parkland Belt on the north and Texas's Edwards Plateau on the south. The region is an agricultural powerhouse fueled in part by the great tracks of aquifer water that provide irrigation in the otherwise semi-arid region. As the temperature in the region raises, rainfall declines or holds steady, and the aquafer resources are depleted, it will be necessary to develop new crop varietals, water and fertilizer technologies, and policies to ensure the continued production of food in a changing environment. We propose to use this workshop to prioritize the research tasks to be completed to ensure food availability in the future *AND* to strengthen research team development to respond to these challenges. The workshop will address six topical deemed critical for system success.

Expected Outcomes

- A white paper that identifies the priority research areas for addressing the specific question of how to achieve water- and energy-efficient production of food in the CGP,
- Identification of the start-of-the art in computational modeling, technology, and societally-accepted practices,
- A structure that supports interaction and collaboration of researchers, and
- Increased public awareness of the inter-relation of food, energy, and water issues in the central Great Plains.

IV. Importance of Food Production and the Energy-Water-Food nexus in the Central Great Plains

World food demands will sharply increase by 2050. The world's population is expected to increase from currently 7.4 billion to 9.7 billion people by 2050.[i] This represents a 30% increase over the current levels. Additionally, as the wealth of the world increases, the expectations for high-protein food increase as well. The land and water required to produce protein (meats) is greater than that for grains, so the tensions for food production will accelerate. During this period, the arable land available for agriculture is expected to remain largely unchanged.[ii] Thus, to meet the expected demands, the productivity of significant agricultural areas such as in the central great plains must be significantly increased.



The Central Great Plains are special. The map to the right[iii] provides an overview of the central Great Plains with the Ogallala Aquifer overlaid. The Central Great Plains (CGP) produces wheat, barley, canola, corn, cotton, sorghum, and soybeans for consumption in the US and international markets. The CGP consists of a region roughly bounded by the Missouri River on the east and the Rocky Mountains on the West with Canada's Parkland Belt on the north and Texas's Edwards Plateau on the south. The region is an agricultural powerhouse fueled in part by the great tracks of aquifer water that provide irrigation in the otherwise semi-arid region. The region is of great agricultural importance producing the majority of all grains and livestock produced in the USA. Because of this significance, the region has earned the moniker of 'America's Breadbasket'. On the other hand, the region also has very significant renewable energy (wind) and fossil energy (gas, oil) resources.

Agricultural production has relied upon the abundance of historic water within the Ogallala Aquifer. Yet, continued use of this non-renewing resource has resulted in a reduction aquifer's reserves. As the figure at right indicates, the water resource is not uniformly distributed within the region. Areas with high water availability (large saturation depths shown in dark blue) are clearly the 'winners' and those in with little or no aquifer water available are the losers. For communities that have historically had aquifer water but for whom the water is coming to an end, new social and economic models will be required to ensure the survival of these regions.[iv]

Over the next 30 years, the world expects the agricultural producers within the central Great Plains to provide food, feed, fuel, and fiber to meet the ever increasing demands of an expanding population. Each of the factors described so far will influence the likelihood of the region realizing this expectation, Research efforts now will position the region to make wise choices regarding resource allocation and maximize the probability for success.

Water is an essential element in food production. While the precise amount of water required to grow crops or raise livestock is dependent upon many variables, there is unquestionably a positive relationship between the amount of water applied to a crop and the yield of that crop (bushels per acre). Thus, if the productivity of arable land in the future must be significantly increased, it is reasonable to expect that additional water will be used in the process even if modifications of the plants and the practices used in agriculture is taken in account.

Certain crops use water more efficiently than others. The Central Great Plains produces wheat, barley, canola, corn, cotton, sorghum, and soybeans for consumption in the US and international markets. The water efficiency of each of these crops is markedly different. In the CGPs, sorghum is one of the most water efficient commercial crops with a water use efficiency rating nearly 50% higher than corn.[v] Yet, corn remains a focus of production because of consumer preference and public policy (promotion of fuel ethanol). Future research may focus on the development of more water efficient crops and on understanding how to educate the public and the policy makers about water/food/energy tradeoff choices.

Energy is essential for the production of food (more precisely fertilizer) and purified water. Food production requires land, fertilizer, sunlight, water, and energy. The energy spent in agriculture to produce crops (about 2.2 quadrillion BTU per year[vi]) consists of about 67% to operate machinery, 30% for fertilizer, and 3% to produce pesticides and for water pumping[vii].

Energy to operate machinery for agriculture can be addressed by improved the efficiency of internal combustion motors, or conversion to use of renewable energy in form of renewable electricity, or renewable liquid fuels. The central great plains are especially suitable to produce renewable electricity from wind (Class 4 or 5 areas on a scale of 1-7 are found in significant portions of the CGPs[viii]).

Production and application of fertilizer is quite energy intensive. By one estimate[ix], in 2009 nearly 0.5% of all the energy used in the US went to the production of nitrogen-based fertilizers. For perspective, this equates to the total energy used by Nigeria or the total energy consumption for transportation in China during the same period.

Although the overall energy for pumping of water is small compared to other sectors of agriculture, the electrical or fuel energy and costs required for pumping of irrigation water can account for significant reductions in profit for a farmer. If technologies or practices were available that would increase the efficiency of water use and acquisition, pumping costs could be reduced and long-term water availability could be enhanced.

Fertilizers are essential to feed the world's current population. Land use, human nutrition and the carbon cycle form an intricate set of relationships. Healthy plants use carbon dioxide, give off oxygen and increase soil organic matter (OM), thereby enhancing soil fertility. Harvesting of crops removes nutrients in the form of our food and any residues that are removed, wind and water runoff may also remove nutrients, and those nutrients must be replaced to nourish the next crop. For these reasons, soil fertility and fertilizer will remain key components of feeding the world's hungry population. Without the fertilizer industry, food and fiber production per acre could be reduced by as much as half.[x] Thus, about 50% of the food we eat exists only due to natural gas that is used to convert nitrogen from air to ammonia (the most heavily utilized fertilizer).

Nitrogen, phosphorous, and potassium in a bio-available form are the main components in fertilizers. Potassium and phosphorous can be obtained through mining of geological deposits. The invention of the Haber-Bosch process to synthesize ammonia from air at a very large scale and for a reasonable price early in the 20th Century enabled significant population growth and avoided hunger on a global scale[xi]. The Haber-Bosch process keeps about 40% of the world's population alive. About 15 grams of ammonia are needed for a single loaf of white bread. Ammonia synthesis consumes about 5.8 Million tons of natural gas per year in the U.S. alone, for more than 10% of the U.S. total annual natural gas consumption.

The Haber-Bosch process is the only process used to produce ammonia for fertilizers. It has been highly optimized as far as catalyst technology and process technology for over 100 years so that state of the art implementations now operate perhaps 10% above the absolute practical minimum energy demand. Little is to be gained from further process- or catalyst research. Decoupling food from fossil energy can therefore be achieved in two ways: produce the feedstock for the Haber-Bosch process (hydrogen and nitrogen) using renewable energy instead of fossil energy (essentially replacing the "front end" of the process), or use an entirely different process.

Fertilizer overuse and misuse can lead to water pollution issues. In the USA and worldwide, Nitrogen fertilizer is overused by an estimated 30 to 60 percent in intensively managed fields.[xii] Once spread on fields, nitrogen compounds cascade through the environment, altering our world, often in unwelcome ways. Some of the nitrogen washes directly from fields into streams or escapes into the air. Some is eaten, in the form of grain, by either humans or farm animals, but is then released back into the environment as sewage or manure from the world's growing number of pig and chicken farms. Additionally, phosphorus losses of up to 86 % of total mined P input have been attributed to agricultural runoff and erosion and animal processing wastes. [xiii]

Clearly educating farmers as to the benefit of using less nitrogen and phosphorous based fertilizer will be essential to future control methods. Additionally, the development of technologies that efficiently recover fertilizer elements (N and P) from wastes and aqueous streams might allow recycle and reuse of both the water and the fertilizer while minimizing environmental impact unless the energy needed to perform the recovery exceeds the benefits of the recovered materials.

V. Research Priorities Identified

Each of the following sections describes topics identified as important for success in achieving the workshop goal of water- and energy-efficient food production in the Central Great

Plains. Each element is required for the overall success and order of presentation carries no implied prioritization of one topic relative to another.

1. The need to take a Systems-Approach to this inter-related problem

Improving productivity within the context of sustainable services and in the face of future climate change. We acknowledge that there is a need to cross boundaries of disciplines and funding agencies to understand and optimize a sustainable complex system encompassing food production, energy, water use, and conservation. We also acknowledge that water and land resources are increasingly scarce or unpredictable, and that the energy to produce input such as fertilizers needs also to be reduced.

Specific objectives include:

- Develop system based approaches to achieve optimization of inputs and outputs, which includes for example total plant use, landscape consideration, water quality/quantity and sustainability. For example, cropping systems could be paired with the use of sustainably collected stover for cattle feed.
- Develop ecosystem based approaches to crop production where cropping systems and crops also provide regulating services. Cropping intensification methods need to be studied in the context of a system:
  - Tillage methods vs no tillage, double croppings, multicropping, use of buffers, filterstrips and other landscape based crop placement, increase perennial crops on the landscape, and diversify crops using native crops and perennial. Develop and improve perennial crops.
  - Match crops with resources and land forms available. Use landscape ecology principles and science to determine optimal cropping areas on the landscape, at the implementable scale (farm, watershed) and at the planning scale (region, County etc,), based on soil types, location on landscape, climate and water, and other constraining factors such as pollinators, biodiversity, soil fertility, carbon etc.
  - Biomimetic approaches to develop new crops that can grow in extreme environments, For example, research the CAM photosynthetic pathway to understand how succulents/cacti are able to thrive in deserts, and link with genetic improvement theme. Likewise, there are other natural perennial systems which deserve attention: how did prairies achieve high productivity with sometimes limited water and nutrient resources while sequestering C in soil?
  - Increasing the productivity of drylands and low productivity lands will be important because, even if yields are low, they still contribute to a higher output. And through the lens of designing sustainable landscapes, there could be sustainable land uses that will enhance productivity. Also it will be important to work with the soils quality and microbiome research to improve productivity.
- At the field scale

- Optimize nitrogen use efficiency by using rotations and other cropping systems (double croppings, etc) that leverage legumes N fixing ability – explore the opportunity through modeling and experimentation.
- Improve the resiliency and ability to fix nitrogen in legumes
- Understand and improve N and P storage ability in perennials, including endophyte N fixation in native grasses and bioenergy crops.

An overarching concern is that of climate change – understand its impact to crops and cropping systems, understand how temperature shifts and moisture will alter land use changes and rotation shifts, pest threats. Breed for adaptation to climate change and resistance.

2. Improving efficiency and sustainability of nutrient production and use in agriculture

Fertilizer production consumes about 30% of the commercial energy used in agriculture[xiv]. Bioavailable nitrogen, potassium and phosphorous need to be added to soil periodically for sustained crop production since nutrients are constantly removed with the crops and through other mechanisms. The lack of synthetic ammonia threatened the world with mass starvation at the beginning of the 20th century, before the Haber-Bosch process to fix nitrogen from the air as ammonia was invented and implemented on industrial scale world-wide[xv].

Depending on the crop, 30-50% of the yield is only possible through fertilization. The question is therefore not if man-made fertilizers should be used, but to produce and use fertilizers efficiently (smart farming, precision agriculture), with minimum impact on the environment, and producing them in a sustainable way (reducing or eliminating fossil energy). Eliminating man-made fertilizers from agriculture would be catastrophic as it would doom about 45% of the World's current population since there is no alternative to produce sufficient foodstuffs[xvi]. The sheer mass of fertilizer needed to sustain the human population on earth precludes shifting to producing fertilizers based on human or animal wastes, except in niche applications.

The need for fertilization is a common theme in agriculture around the world. Nitrogen fertilizer production consumes about 2% of the world's commercial energy, almost all of this is in form of coal (mainly in China) or natural gas. Options to disconnect fertilizer production from fossil fuels and thereby move towards renewable agriculture are discussed below. Both fossil fuels and abundant wind energy are available in the central great plains, along with a growing capacity for nitrogen fertilizer production. This may offer an opportunity to introduce renewable nitrogen fertilizers.

P and K fertilizer components

The elements N, P, and K are the main components of fertilizers. The energy-intensive synthesis of the N component (ammonia) was discussed above. Potassium and phosphorous-containing minerals are mined (potash and phosphates, respectively) to be added to fertilizers. There is controversy if we are nearing "peak phosphorous" which would greatly endanger sufficient food production in the future[xvii]. P and K bearing minerals are not renewable on human timescales and it is unlikely that they can be recovered at scale from wastes or runoff without spending prohibitive amounts of energy.

The link between fertilizer and water

The direct link of fertilizers to energy and thereby agriculture to energy is clear, but a link from fertilizer to water consumption also exists. Fracking as a source for natural gas especially recently in the U.S. requires significant amounts of water that is not recoverable, thereby contributing indirectly to the water consumption to make ammonia or food. Ammonia facilities like all large energy-consuming industrial facilities thermodynamically require cooling water that is often evaporated to remove waste process heat and therefore is no longer available locally.

A. Improved sustainability of fertilizer production/Renewable fertilizer production

Ammonia as the nitrogen carrying compound of fertilizer is produced industrially from the nitrogen in air and hydrogen from natural gas and water, or from coal and water (mainly China). The energy to produce ammonia for fertilizers is the main focus here as it dwarfs the energy used to mine minerals for fertilizers.

State of the Art is near thermodynamic limits, no need for improved catalysis

The current industrial Haber-Bosch process for ammonia production consumes 600 kg natural gas to supply the hydrogen and energy for 1000 kg ammonia produced. Nitrogen and hydrogen (from natural gas and steam) is reacted to ammonia at about 500°C and 300 atmospheres. All carbon from the natural gas is released as CO_2. A large, inexpensive, and uninterrupted natural gas supply is required to secure the capital layout for a profitable facility (~$1 Billion for 1000 ton ammonia per day capacity). This is reflected in the fact that ammonia production in Africa, where capital layout is often cannot be secure for decades is essentially negligible. This is despite the fact that natural gas would be available.

The Haber-Bosch process was the first large-scale high-pressure industrial process. It is one of the most optimized chemical processes in existence. The heterogeneous catalysts used in the process are no longer a critical issue in efficient Haber-Bosch based ammonia synthesis. While research in heterogeneous catalysis is rich and rewarding, the particular issue of high pressure ammonia synthesis has been recognized as no longer of importance due to the level of achievement. The production of hydrogen and nitrogen as feedstock is instead the important issue in Haber-Bosch technology as pointed out by a leading researcher at the Haber Institute[xviii]. While industry is still actively working on process integration and "upstream" technology, Haber-Bosch catalysis is no longer the focus[xix]. The Haber-Bosch based ammonia synthesis is optimized to near thermodynamic limitations. 24-26 Gigajoule per ton of anhydrous ammonia (natural gas lower heating value) are the state of the art, while the thermodynamic minimum is at 19.2-21.2, depending on discharge conditions of process streams[xx] [xxi]. Summarizing the state of the art in ammonia synthesis

- The industrial scale Haber-Bosch based catalytic process with water-gas shift technology to produce the hydrogen and nitrogen feed for the catalytic step is nearing thermodynamic limits in energy efficiency, further rewards will be small
- The catalytic step in Haber-Bosch synthesis of ammonia cannot contribute to further efficiency increases and is considered optimized for practical purposes
- The opportunities in Haber-Bosch based technology are in hydrogen and nitrogen feedstock production without fossil energy

- A completely different ammonia synthesis principle without fossil fuel and preferably at low pressure would be desirable if economic constraints can be addressed

A practical result of the highly optimized state of the process is that ammonia market prices track natural gas prices closely and are only about 10% above the cost of the feedstock natural gas used to produce the ammonia[xxii].

Path forward for synthetic ammonia decoupled from fossil fuels

Research into alternatives to the Haber-Bosch process is currently limited due to the dominance and efficiency of the state-of-the-art process. However, if the fossil fuel dependency of food production is to be reduced, alternatives become more interesting, especially for fundamental research with significant future impact. Examples are given below

Solar Thermochemical Ammonia Researchers at Kansas State University and elsewhere are developing technology that aims to change the century old fossil-fuel-to-fertilizer-to-food paradigm by synthesizing ammonia without natural gas. Air, water, and concentrated sunlight are process inputs, with ammonia and oxygen as products (Figure 1) in a three-step chemical reaction cycle based on manganese. The process is performed at atmospheric pressure and elevated temperature. The mild pressure enables down-scaling which is essential to produce ammonia for example in Africa where large capital intensive facilities such as traditional Haber-Bosch plants may not be feasible due to political and economical reasons.

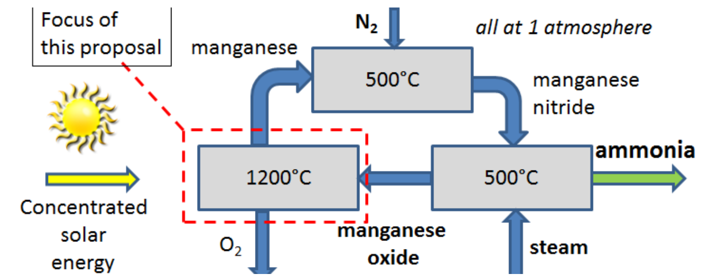


Figure 1: Ideal solar thermochemical ammonia process.

Biomimetic processes attempt to duplicate the ability of some organisms to fix atmospheric nitrogen through enzymatic processes. Enzymatic processes suffer from the fragility and complexity of biological molecules, requiring slow aqueous phase operation near room temperature. The well-known Nitrogenase enzyme requires 8 electrons, 8 protons, and 16 ATP molecules to produce two ammonia molecules from N_2. This chemical and electrical energy demand does not give a promising picture for large scale economic application, even if the biological process is perfectly reproduced. Currently no technical-scale biomimetic process has been conceptually evaluated or proposed.

Electrochemical methods for direct ammonia synthesis require stoichiometric amounts of electrons, resulting in high operating costs compared to non-electrochemical approaches. Trace amounts of ammonia have been produced in electrochemical research with low current utilization. Additional research will be required to promote energy-efficient fertilizer production using this approach.

Accepting Haber-Bosch as the basis, modifications, avenues to quick adoption

The state of the art Haber-Bosch process has a very large installed capital base. This will not change over the next decades and it may be prudent to develop not only replacement processes, but also avenues for incremental change towards renewable ammonia production in existing facilities.

Due to the rapidly falling costs of renewable electricity from wind it could be envisioned to produce hydrogen via electrolysis, and nitrogen with membrane separation of air and trace oxygen removal by chemical means. This could be used as an incremental or additional capacity option for existing Haber-Bosch facilities, particularly in the Great Plains where wind energy is relatively abundant.

An advanced reactor that would operate at Haber-Bosch conditions with the optimized existing catalysts can be envisioned. If ammonia as the reaction product could be rapidly and selectively removed from the reaction mixture without cooling or other changes then a significant improvement in single-pass conversion would result. Recycling of unreacted hydrogen and nitrogen is a significant energy consumer in the Haber-Bosch process since only about 10% of the feedstock is converted in the Haber-Bosch reactor in a single pass. This is another example where process research is beneficial while catalyst research would not.

Opportunities summarized

High-impact research opportunities to decouple fertilizers and thereby food production from fossil fuels can be summarized:

- Efficient ammonia synthesis with processes substantially different than Haber-Bosch (ammonia is not to be formed from highly purified hydrogen and nitrogen over a catalyst at high pressure)
    - Atmospheric pressure thermochemical reaction cycles instead of ammonia
    - Electrochemical synthesis
- Haber-Bosch synthesis
    - produce hydrogen from water using renewable energy (electrolysis, thermal)
    - produce nitrogen from air using renewable electricity, via membrane separation
    - dynamic techno-economic modeling for integration with renewable energy production
    - a high temperature/high pressure ammonia-selective membrane reactor to house the Haber-Bosch catalysis and significantly improve conversion through reaction product removal

B. Nutrient recovery and recycling from nontraditional sources

Significant amounts of nutrient (P, N, and K) inputs are lost to the environment through point sources - agricultural and food wastes, wastewaters, and byproducts streams- and non-point sources – agricultural runoff. This can adversely affect environmental (air and water) quality and is an economical loss to farmers. Reduction of losses would lead to reduced environmental impact and improved economics for farms.

.Phosphorus (P) in fertilizers is critical for ensuring a sustainable food supply for the growing global population. It is a finite resource that uses energy-intensive processes for mining and production, which also generate harmful emissions and wastes. However, almost half of P applied in fertilizers is lost to runoff. P in runoff is mostly associated/bound to suspended particulates in runoff. These particulates are transported through streams and settle out in major surface water bodies. The eventual release of bound P, from these settled sediments has been recognized as a major cause of eutrophication, toxic algal blooms, and overall deterioration of water quality. Groundwater quality can be affected as well. On the other hand, runoff particualtes represent an untappped source of P that could potentially reduce the demand for mined sources. Recovery of P from runoff will be a significant step toward closing the loop for nutrient sustainability in addition to protecting our nation's water resources and ecosystems. The biggest challenge in recovering P in runoff particulates is its highly periodic but large discharge volumes. The energy demand to recover P from non-point sources is critical since excessive cost may prohibit P recovery due to unrealistic economics. Research areas include:

- Recovery of nutrients from municipal waste, animal wastes (manures), food-processing wastes.
  - Anaerobic digestion to release bound nutrients to solubilize nutrients
  - Speciation, characterization of bioavailable nutrient species.
  - Robust Anaerobic digestion process efficiency improvements – effects of contaminants
- Recovery of phosphorus from agricultural runoff
  - Methods for rapid and efficient capture and immobilization of runoff particulates.
  - Benign and efficient biochemical and physicochemical methods of extraction, separation, recovery, and concentration of phosphorus species from captured runoff particulates.
  - Understanding the dynamics of speciation and supramolecular bonding of phosphorus species in runoff particulates and their transformations and transport properties as they are being transported across watershed tributaries leading to major surface water bodies.
- Sustainable use of recovered products.

C. Improved sustainability and efficiency of fertilizer/nutrient use/management

The science of nutrient movement from application through the environment is highly complex. Dynamic systems of sources, sinks, and reservoirs are coupled and interact in feed-forward and feed-backward loops, with a wide range of characteristic time constants, and the impact of climate and weather. Some research topics may include:

- Understanding dynamics of nutrients in soil and the environment
- Understanding nutrient cycling dynamics in soil and water – for timed application/release of nutrients, reduce loss, reduce over fertilization
- Develop low cost fast acting sensors (remote sensors) – sensing technology for nutrient tracking
- Develop mathematical models for automated guidance of precision nutrient application Develop precision application technologies
- Improving fertilizer use efficiency
  - Developing improved scientific application rate recommendation.
  - Improved application timing
  - Improved application methods

3. Energy for Agricultural Machinery

Over 60% of the commercial energy expended to produce agricultural crops is to operate machinery. Most of this is petroleum-based fossil fuel used for internal combustion engines. Reducing the energy use of agriculture in this area can be separated into several areas:

- improved engines
- improved agronomic practice, such as links to "big data" weather reports etc., precision farming
- replacing manned machinery with lighter robotic/artificially intelligent units

A separate approach is to work towards replacing fossil fuels with renewable fuels. Renewable wind electricity is becoming abundant and inexpensive in the Great Plains and could be used to operate some machinery, similar to increasing electrification of transportation[xxiii]. Other examples are renewable electricity, "bridge fuel" natural gas with reduced pollution, renewable liquid fuels from biomass, and hydrogen or ammonia from excess wind energy.

Decentralized production of bio-oil to replace petroleum diesel would be advantageous in an area such as the CGP where biomass may be available but the users of the fuel and biomass sources are geographically dispersed. Significant research has been done to make bio-oil viable both technically and economically, with conditioning such as hydrogenation still posing significant obstacles.

Summarizing potential research areas for fossil fuel replacement in agriculture

- electrification of agricultural machinery to use wind energy
- renewable fuels from biomass (cellulosic ethanol, bio-oil for diesel replacement), especially decentralized production
- hydrogen or ammonia[xxiv] generation from wind energy as fossil fuel replacements

4. Modeling and Data Management

Modeling of food production systems ranges from world-wide logistics and transportation to the fundamental interactions of organisms like bacteria or plants with their surroundings. The length scales, time constants, and multiple interactions of sub systems are exceptionally challenging to the development of integrated models. However, dynamic modeling could improve and optimize current practices or uncover non-obvious approaches to issues in the food-water-energy area.

Collecting data at the level of the dynamics of interactions of soils, water, and organisms is highly challenging since model systems are often not useful if they neglect potentially unklnown real-world complexities. Time consuming field work may be needed due to growth cycles and weather impact.

Modeling

To meet INFEWS objectives models are needed that combine biophysical aspects of agricultural production with water, energy, and socio-economic components. The needed characteristics of these models are

- They must be multi-sectoral (e.g. crops and livestock) to be able to mimic vertically integrated production systems;
- They need to have spatial extent so as to mimic situations arising from soil variability within a field or differences in aquifer depth across a water management district;
- They must be dynamic – that is they must be grounded in the behaviors of relevant processes over time rather than simply solving for endpoints or equilibrium conditions; two particular temporal processes that must be supported are:
    - Different estimated rates of genetic gain;
    - Different assumptions about the adoption curves for relevant technologies.
- While many different model applications can be envisioned, two critical bookend benchmark uses that bracket this range are real-time, on-farm decision support and policy analysis.

The needs in this area can be framed in form of research questions:

- How to assemble and integrate the various types of information needed to formulate model described above
- How to construct modeling frameworks that allow one to swap in and out alternative model formulations so as to:
    - Support testing of different model assumptions;
    - Support modeling at different levels of aggregation while maintaining scientific consistency;
    - Support different output interfaces to meet the needs of particular audiences. A specific example of the latter is immersive environments[xxv] which have knowledge transfer applications ranging from research visualization, to education, to generation of materials for public presentations, to role playing games for stakeholder groups.
- How to meet computational needs for model use which will be highly intensive as most questions of interest will involve hundreds to millions of model executions[xxvi].
    - A question of pressing interest is how to partition model-related computations between processors on-board field equipment and cloud-based supercomputing. This also entails communications issues.

Data Management

Agricultural production systems are complex and dynamic, and the decision making by individual farmers, ranchers, and institutions requires data (and information) from various components at near-real time to real time, including weather, climate, soils, plants, livestock, market, etc. Multi-scale observations and monitoring of agricultural production systems, which is essential for sustainable agricultural production, will generate "big" data, in the range of terabyte to petabyte. Producers and researchers need to quickly analyze and evaluate the observation data, and model data to make choices about which actions to take or move forward in an effort to optimize the food/water/energy trade-off and efficiency.

1. As a programmatic recommendation there is a great need for Critical Zone Observatories that focus on agricultural systems, as opposed to LTER- and NEON- and CZO-type facilities, whose aims target natural systems such as forests, grasslands, and lakes. It would be appropriate to establish Integrated Agroecosystem Observation sites. Agro-ecosystems need to be added as part of NSF's scope for long-term and integrated basic research, which is a key component for landscape-, watershed- and macro-scale biological systems.
2. Driven by needs and opportunities ranging from high throughput phenotyping to precision agriculture there is a major shift underway in the mechanisms by which large data sets are collected. In the past such efforts have been conducted by public agencies. However, in the very near future such collection will be done in the private sector by actors ranging from individual farmer to major agribusinesses and/or combinations of both of them. This is raising often contentious public debates about data ownership, allowable uses, disclosure requirements, proper remuneration schemes, etc. Researchable questions include:
    - What are the implications of alternative policies
    - Data ownership and access
    - Are there cybersecurity technologies that exploit unique features of agricultural data to enable high levels of protection within scenarios that arise in that debate.
3. There is currently intensive research underway in the areas of ontologies, etc. to describe and standardize meaning across databases. But there is also research needed on cyberinfrastructure to manage and distribute data to the points where computation occurs. This interacts both with the last point in the preceding topic as well as the cybersecurity issues just presented.
    - Standardize meaning across databases
    - Data distribution to point of use
4. While there are many types of data to be utilized, finding integration schemes that bridge across the following categories while maintaining temporal consistency would be particularly helpful:
    - Historical data
    - Near real-time data
    - Real-time data
    - “Future data” – e.g. climate model outputs

5. Optimizing Soil-Health by combining Geo-Eco-Systems in a Biology Approach

There is a need to increase sustainability of physical-chemical-and biological soil properties supporting plant productivity to supply food and fuel to a growing world production. To date we recognize that below ground biodiversity (roots, vertebrates, invertebrates, and microorganisms) impacts physical and chemical structure of soil to support plant productivity. Microbial communities (microbiome) have been described to play a significant role in soil health and plant productivity. While an effort is ongoing to characterize the microbiomes of soil and plants efforts are limited to description based on taxonomy. However taxonomy alone does not predict the physiological role or functional link of the microorganism to soil or plant health. The use of culture-independent (meta-omic) approaches can help identify the functional role microorganisms play is important. In the event of unannoted gene sequences these approaches will also need to be combined with physiological and enzymatic studies from culture-dependent approaches in order to demonstrate a genetic link to a function in the soil environment.

Native plant species including grasses have adapted to drought tolerance and have direct impacts on water retention, soil stabilization, and primary productivity. We need to understand the micro-macrofauna interface in these natural systems to provide a foundation for development of technology of native plants play in maintaining soil health. Alternative approaches can then be developed to promote soil microbial community growth or genetically modifying plants to recruit specific groups of microorganisms facilitating water retention, nutrient cycling or increasing nutrient availability.

There is a need to identify how land use practices (e.g., irrigation strategy, chemical inputs) influence the microbial community structure in soils and rhizosphere and the subsequent impact on biogeochemical function including weathering reactions at varying spatial and temporal scales. Differences in land use are recognized to impact soil water retention and carbon storage. The impact on long term soil weathering is poorly understood. Transport of agrichemicals into the subsurface from the soil could also impact subsurface weathering decreasing groundwater (irrigation) water quality, ie., salinization, pH, alkalinity. Applications of poor quality irrigation water will thus have negative consequences to sustainable soil health. What other negative impacts could result such as arsenic and uranium mobilization? What impact does this have on food quality?

There is a need to link the geological, microbiological, and plant systems into an integrated model to predict how soil heterogeneity contributes to microbial metabolism and growth influencing soil and pore water chemistry below ground over a spatial and temporal scale with the implications towards plant productivity. This would allow for the integration of relationships between plant genetics/physiology, macrofauna, microbial genetics/physiology, and soil and water chemistry across time scales.

6. Livestock Systems

- Improve livestock genetics (include dairy operations)
- Identify more sustainable forage crops such as perennial grasses and alfalfa, encourage grass fed cattle, use less grain and fewer antibiotics for healthier human diets. Understand the LCA implications of perennial grass fed vs grain fed livestock (energy, GHG emission, inputs etc,)
- Explore digestibility of agricultural residues such as corn stover for livestock feed, so that grain can go to human nutrition.

7. Genetic Improvement and Breeding of Existing and Alternative Crops

- Improving crop growth and yields under drought, temperature stress
- Improving water (and nutrient acquisition, nitrogen fixation), utilization efficiency, root architecture
- Breeding for growth in marginal soils and environmental stresses such as salinity and alkalinity
- Low input agriculture
- Improve crop nutritional value so that lower yields still can deliver required nutrition

Genomic breeding to improve rates of genetic gain

Motivation: traditional breeding cannot achieve the rate of genetic improvement necessary to meet the demands for future development and the future global demands for food and feed.

State of the art: epigenetics, gene editing,

- Genomic selection, genome x environment interactions and plasticity, and understanding the genomics of local adaptation
- Bioinformatics, sequencing platforms and technologies for long reads
- Breeding for climate adaptation in new crops and taking advantage of natural variations especially of wild types
- New biological pathways
- Perennialize annuals.

High throughput phenotyping and sensing

Conventional breeding cannot achieve the rate of genetic improvement necessary to meet global demands for food, feed, and energy feedstocks. Genomics-assisted breeding has great potential, but current models are ill-equipped to address novel environments, epistasis, or genotype-by-environment interactions. Therefore, genomic selection approaches based on statistical genetic models must be integrated with other more mechanistic approaches, such as systems biology and ecophysiological modeling. Traditional varieties and wild relatives harbor an abundance of natural variation for adaptive traits, but the diversity overwhelms crop improvement methods, including genomic selection. To take advantage of this diversity, we need a better fundamental understanding of molecular and ecophysiological mechanisms of stress tolerance, the genomic basis of local adaptation, and structure of the genome-phenome map in crop plants.

High throughput methods for the phenotyping and sensing of variables related to crop productivity such as biotic and abiotic stresses, drought, temperature, nutrient stress, salinity and alkalinity are desirable. This needs to be connected with microbiome research to understand soil-plant interactions, increase yields, increase stress tolerance and adaptation to climate stresses.

Specific objectives are:

1. *Dissect mechanisms of crop productivity under drought and temperature stress*

- Identify novel dynamics in plant-water relations (e.g. transpirational and osmotic regulation)
- Develop new phenomics methods to quantify physiological performance under field conditions
- Map metabolomic networks (e.g. lipid and carbohydrate remodeling) linking genome to phenome

2. *Integrate genetic and ecophysiological models to predict plant response to stress*
    - Improve frameworks for integration genetic factors into ecophysiological models
    - Use models to identify optimal plant architecture and phenology for stress environments
    - Develop new genomic selection methods leveraging phenomic data and ecophysiological models
3. *Navigate genotype-by-environment interactions to enhance crop nutritional quality under stress*
    - Map the genomic basis of stability nutritional and functional traits in crop plants
    - Elucidate the genetic and physiological mechanisms impacting nutritional and functional quality
    - Investigate the role of grain secondary metabolites (e.g. polyphenols, carotenoids) in stabilization of nutritional value

8. Climate Change and Agroecosystems

The role of climate change effects on agroecosystems has already become more pronounced over the last several decades and is expected to have even greater impacts in the future. As atmospheric CO_2 concentrations increase from 400 ppm to predicted levels of 700-1000 ppm by the end of this century, average global temperatures are expected to rise by 4 and 8 °C. Therefore, our understanding of a number of responses and feedbacks of agroecosystems to these changes will be essential. Therefore, we divide research objectives under the climate change realm into three main areas: (1) Enhancing our understanding of the responses of agroecosystems to climate change, (2) Increasing our knowledge of how agricultural practices feed back to influence climate change and how greenhouse gas emissions can be reduced in agricultural practices, and (3) clarifying our vision of how climate change effects on agroecosytsems will influence human-based economic markets, intrinsic behavior, and overall health. We do this to illustrate both the impacts of climate change on ecosystems as currently predicted, as well as feedbacks at the levels of technology and human behavior that could mitigate such responses.

1. Enhancing our understanding of the responses of agroecosystems to climate change

Although the understanding of molecular, organismic, and ecosystem processes have received attention over the last several decades with substantial progress, there are several areas that remain unclear or unknown altogether. It is key that agroecosystem responses to climate change be more fully understood in order that we are not surprised by future changes (i.e., tipping points) and that we can react with developments to reduce negative impacts.

A. Identify thresholds (tipping points) that may impact crop developmental responses to climate change (e.g., flowering time, pollen viability (gametic viability), meristem responses). *For example, we know little about the mechanisms that control flowering time responses to elevated* CO_2.

B. Identify thresholds where plant-pollinator interactions may be altered in response to climate change

C. Better determine how below-ground processes (nitrogen fixation, mycchorizal) will be impacted by climate change and extreme events. This area may greatly benefit from continued use of emerging -omics capabilities (including microbiome work)

D. Identify physiological and developmental responses of crops to extreme conditions (heat stress, drought, etc.)

E. Continue to elucidate the effects of interacting climate change factors on crops that may produce emergent stress responses

F. Continue to determine the genetic and physiological mechanisms that control crop responses to the environment, specifically with respect to climate change parameters (molecular, physiological, organismal, and ecosystem scale); this knowledge then needs applied to crop timing behaviors (planting, harvesting, etc.) to inform agricultural practices from a mechanistic perspective

G. Determine how changing climate patterns influence the invasion of insect pests (and other crop diseases), as well as range expansion/contraction of these pests

H. Form long-term research groups with molecular through ecosystem-level expertise (along with modelers) in order to better scale these responses in agricultural systems

2. Increasing our knowledge of how agricultural practices feedback to influence climate change and how greenhouse gas emissions can be reduced in agricultural practices

In addition to being impacted by climate change, agricultural practices can also contribute to climate change through greenhouse gas emissions and other land use change practices. Therefore, we propose further study in these areas. Such work will require a strong inter-disciplinary focus to conduct the proper scaling to increase our understanding in this critical research area.

A. Better understand the level that agricultural systems serve as sources (or sinks) for greenhouse gases
B. Enhance the use of renewable energy sources into agricultural practices, and contribute to adopting these approaches in agricultural practices, machinery, and operations
C. Advance interactions between climate modelers and scientists studying climate change effects on agroecosystems
D. Inform modelers of potential shifts in agricultural land use for future models

3. Clarifying our vision of how climate change effects on agroecosytsems will influence human-based economic markets, intrinsic behavior, and overall health

Human response to climate change in the agricultural realm will have key effects on the levels of climate change that eventually come to fruition, the behavior and vulnerability of human populations, as well as impacts on human health. Thus, we propose key research areas in the social sciences, education, economics, and human nutrition

A. Determine the potential for human migrations and vulnerabilities due to reduced agricultural lands and productivity and reduced food security

B. Determine the influence of changes in crop nutritional levels in response to climate change on human diets and health (e.g., higher C/N ratios in food at elevated CO_2)

C. Understand the vulnerabilities of African populations and other markets where climate change effects may be most severe

D. Improve our economic understanding of how climate change will affect socio-economic status of communities, nations, and global markets

9. Precision Agriculture and Irrigation

Irrigation is needed to supplement low and sporadic rainfall to meet a growing demand for high quality food. With declining availability and cost of fresh water for irrigation, more precise water and nutrient delivery (spatially and temporally) plays a critical role in meeting irrigation requirements. Precision management optimizes conversion of limited resources into marketable crops, economically, environmentally, and agronomically. The result is less waste of inputs and greater overall productivity. More precise (or efficient) use of water and nutrients also results in reduced energy need for food production. Relieve need for over-exploitation of marginal lands for food production. Precise input management aids in adaptation to and risk management associated with climate change. Precision application of water and nutrients is a tool for sustainable intensification of food crops, thereby allowing prolongation of supplies of basic inputs and economic viability of the farming unit.

A. State of the Art in this field
   1. Irrigation scheduling based on:
      a. Evapo-transpiration-driven water balance
      b. Soil and crop water-status sensors
      c. Remote sensing of crop and soil water status by satellite and unmanned aerial vehicles.
   2. Microirrigation including as drip systems
   3. Variable rate irrigation by variable pivot speed and variable nozzle control.
   4. Remote sensing to characterize soil and vegetative cover.

B. What is needed?

1. Identify economic and cultural barriers to adoption of more efficient irrigation practices and facilitate the overcoming of such barriers.

2. Increase efficiency of water, energy, soil resources by adoption of high-efficiency systems, interpretation of sensed data, and coordinating their management.
   Corollary:

   a. Facilitate the coupling of soil and plant sensing technologies with advanced micro-irrigation systems.

   b. Integrating real-time weather data with soil and plant water status at varying spatial and temporal scales.

3. Decision-support for producers to utilize data-intensive sensing and precision agriculture platforms, i.e. close the gap between data acquisition and short-range decision making. Real-time, near real-time, historical data, and future-time data.

4. Improve food security through efficient use of water and energy by linking precision irrigation and nutrient management.

5. Understanding response and adaptation of plants to water-limited environments to enhance crop water productivity and economic sustainability.

10. Water

Water Quantity (Availability)

1. Aquifer storage and recovery: Motivation/broader impacts

Aquifer storage and recovery (ASR) is a tool to store water during times of plentiful flow (usually runoff in streams) or process wastewaters from many sources (treated effluent, oil and gas production, etc. to augment water supplies). These waters are captured, treated, and stored in aquifers for eventual recovery when water is not plentiful or as augmentation of exiting supplies. Challenges for making ASR a viable long-term strategy for water supply include:

- economic cost/benefit analysis of construction and operation of facilities in comparison to the quantity of water that can be captured;
- economic viability and energy requirements associated with treating saline or other low quality waters
- quantitative modeling of water quantity and quality limits of treatment;
- engineering design of capture systems for sufficient quantities of water during the short periods of time it is available;
- treatment of water to prevent degradation of the water quality in the receiving aquifer;
- geochemical compatibility of treated recharge water with receiving aquifer quality and interactions with the aquifer materials;

- possible changes in the physical properties of the aquifer material caused by artificial water

State of the art in this field:

Work in this field is well summarized elsewhere[xxvii] [xxviii] [xxix] [xxx] [xxxi]. Research on a new approach utilizing small-diameter direct-push wells for recharge for ASR is described in the literature[xxxii].

What is needed?

Additional research is needed on understanding the biochemical processes controlling clogging of the bottoms of recharge basins and trenches and the screens of injection wells used in ASR under different conditions, including the chemical and physical characteristics of basin and subsurface sediment, the chemistry and microbiology of recharge water and receiving groundwater, and variations in weather. This research should be aimed at supplying information that will help in the development of remedies to clogging issues. Additional work on small diameter wells and direct-push installation technology is needed for improving and assessing this potential approach as an alternative to large diameter wells typically used in groundwater recharge.

Research Priorities

a. Develop geochemical monitoring tools and novel geochemical modeling techniques to predict and characterize problems involved with aquifer storage and recharge. For example, develop coupled quantity and quality models like PHAST and improved models of geochemical interactions (PHREEQC). Apply and enhance current tools and techniques[xxxiii].

b. Develop and improve new methods for aquifer storage and recharge, such as direct push wells.

c. Determine the limitations of water quality and bacteria content on water injection and develop methods to handle this issue such as how to best utilize soil to filter recharge water.

d. Develop modeling tools to quantify quantities of surface water and groundwater quantities to assist in economic viability of recharge.

e. Develop modeling tools to quantify required treatment and energy requirements to sufficiently treat water quality to the point where recharge water is compatible with receiving aquifer quality.

2. Dynamics of aquifer systems: Motivation/broader impacts

The aquifers of the central Great Plains, primarily the High Plains aquifer that covers parts of eight states, provide water for irrigation and livestock that comprise a substantial portion of the food produced in the U.S. Declines in aquifer storage, along with changes in climate, are forcing alterations in the amounts of water that can be pumped and will be needed for future food production. Many different factors affect the amount of groundwater available from storage, including the heterogeneity of the aquifer sediments (e.g., differences in the transmissivity of strata and variable rates of drainage as water tables decline), changes in the rates and spatial distribution of recharge (including the impact of climate change), and modification of groundwater flow rates and direction due to non-uniform drops in water tables and potentiometric surfaces. The dynamics of these factors need to be well understood for accurate prediction of future groundwater supply and appropriate adjustments in aquifer management to provide water supplies for agriculture, as well as other uses, in the future.

State of the art in this field

The main assessment of groundwater available from the High Plains and other aquifers in the central Great Plains involves the annual winter measurement of water levels in a large number of wells. Individual states or the U.S. Geological Survey conduct these surveys. Advances in the measurement programs in some states include GPS and on-site electronic data entry and transmission. Various simple, first-order, but fact-based approaches and more complex computerized process modeling are used for assessing current rates of aquifer storage changes and temporal and spatial predictions of future aquifer resources. The simple approaches allow rapid assessment and communication of conditions, as well as being readily usable by management entities, whereas the process models allow more comprehensive consideration of multiple factors. An example of an advance in the first-order approaches is the application of correlations among water-level changes, pumping, and climate indices[xxxiv]. An example of process modeling is the Groundwater Availability Model (GAM) program of the Texas Water Development Board[xxxv] that covers the major and minor aquifers of Texas. A recent development in process modeling is the integration of groundwater models with other models, including climate models, and with remotely sensed data such as is being conducted by Michigan State University[xxxvi]. An advance in water measurement is the application of satellite gravity data to the determination of water stored in both the saturated and unsaturated sediments of the High Plains aquifer[xxxvii], although the method currently provides too large a regional picture to be applicable for groundwater management at the subregional or local scale. Microgravity methods have been applied to characterize groundwater storage changes in an aquifer outside the central Great Plains

What is needed

Continued development of both first-order approaches and comprehensive process modeling coupled with other models, especially climate models, is needed for understanding the dynamics of aquifer systems in response to changes in pumping, land and water use, and climate across the central Great Plains. The first-order approaches provide better understanding of the main variables that the process models should simulate without being black boxes, whereas the process models improve predictions based on the integration of all the significant factors controlling water inputs and outputs in the aquifer system. An example of an improvement for process models is the correct simulation of delayed drainage from infiltration of water from the land surface and from lower permeability units below which groundwater levels have dropped in response to pumping. Although these processes have recently been incorporated in a groundwater model for a region of the High Plains aquifer[xxxviii], additional study is needed for confirming the approaches used. Selected processes of the dynamics of the High Plains aquifer that need additional field study include differences in infiltration and effective recharge from focused recharge zones, particularly ephemeral stream valleys and playas, e.g., the effect of different playa and interplaya conditions such as farmed versus unfarmed. Improvements in satellite gravity measurements (GRACE) to provide assessment of water at smaller spatial scale, if possible, as well as better microgravity application for local studies of water in unsaturated and saturated sediments of the High Plains aquifer would be valuable.

Research Priorities

Determine how aquifer water availability changes occur in aquifer systems by inflow/recharge, storage redistribution, and outflow through hydrogeological, geochemical, and geophysical (GRACE and microgravity) methods. For example, how is inflow changing though time and how will this affect water availability in the future.

3. System model uncertainties: Motivation/broader impacts

System models built for predicting the efficiency of water and energy use for future food production and the impact of external forcing such as climate change are only as good as the limit of their accuracy. Determination of the uncertainties in the models is important to evaluate how good they are for future applications. In addition, determination of the variables that contribute the greatest amount of uncertainty in models will point out where additional efforts need to be placed in improving the amount and/or quality of the data used for those variables.

State of the art in this field

Information on the national program of the USGS on modeling and uncertainty of complex groundwater systems and subsequent work is available[xxxix] [xl]

What is needed?

An understanding of uncertainties in different models is needed for better comparison of the projections and forecasts of models. This understanding is also needed across the range of models of different complexity. An emphasis on models that require colossal computational demands that have greater uncertainty than less complex, faster running models, may not be justified if their uncertainties are greater than the less complex models. The very complex, computationally intensive models may also have uncertainties involved with their being more nonlinear and discontinuous than the real world. The USGS web site above also describes some of the fundamental problems related to determining system model uncertainties. These include determining the proper use of models in testing theories and calibration, numerical problems and limitations of forward models, resolving errors in estimated parameter estimation, and evaluation of multiple alternative models to assess uncertainties from different approaches.

Research Priorities

a. Determine uncertainties in models of differing complexity to evaluate whether models of great complexity that require very large computational resources and time are justified.

b. If complex models are needed, determine the uncertainties involved with the processes and data inputs to assess where work should be focused to improve the models.

a. Improve forward ground-water modeling capabilities to resolve existing numerical problems and limitations that prohibit accurate simulation of realistic situations.

b. Develop inverse modeling methods to make this technology more readily accessible and to resolve remaining difficulties such as the estimation of insensitive parameters.

c. Investigate constraining models using more sophisticated data and analyses.

d. Use the insight provided by inverse models to determine improvements needed for data quantity and quality, develop data collection techniques for better data, design and interpret laboratory experiments for better understanding of processes used in models, and evaluate the importance of the water and energy systems and principles involved in models.

4. Reservoir sedimentation: Sediment source and deposition: Motivation/broader impacts

Sedimentation in reservoirs in the central Great Plains is substantially reducing the volume of surface water storage. For example, six of the 24 federal reservoirs in Kansas have already lost more than a third of their storage capacity. Some of this storage is used for agricultural food production. In addition, reduction in future storage could potentially reduce the flow of downstream river water during droughts that interacts with alluvial groundwater resources pumped for irrigation and other agriculture uses, thereby adversely affecting agricultural production.

State of the art in this field

Some of the states in the central Great Plains have programs to assess the loss of reservoir storage to sedimentation. For example, the Kansas Biological Survey at the University of Kansas has a reservoir assessment program in which acoustic echosounding technology is being used for bathymetric mapping, sediment thickness estimation, and bottom sediment type classification [xli]. Coring of bottom sediments is used to determine their thickness and physical and chemical characteristics. Predictions of sedimentation rates and time for infilling of reservoirs are then made based on the data. Another state example is the program of the Texas Water Development Board for surveying reservoir capacity [xlii]. Other types of studies have focused on the source and nature of upstream sediment sources and their control[xliii]. National programs of the USGS include monitoring, transport, and modeling of sediment in streams [xliv] [xlv]. The USGS has also been involved in reservoir sediment studies in Kansas[xlvi].

What is needed?

Substantial funding is being spent on methods to reduce erosion from fields and stream banks. However, additional research is needed on determining the percentage of the sources of most of the sediment entering reservoirs from streams, especially during high flow events when most of the sediment transport occurs. Concomitant with this research is the need to quantify how effective are current practices to reduce sediment erosion. Better quantification of the net sediment trapping in reservoirs would be valuable (i.e., the amount entering and being deposited minus the amount leaving in outflow, particularly during high flows. Current sediment removal methods are very costly. More cost efficient approaches are needed for managing and removing sediment from reservoirs.

Research Priorities

a. Quantify the effectiveness of sediment reduction practices (e.g. streambank stabilization) to better manage fluxes to reservoirs.

b. Advance the fundamental understanding of sediment erosion processes and transport.

c. Measurement uncertainty is between 10-20%. Techniques are needed to better manage sediment and through flow in reservoirs using real-time flux measurements, including measurement of bedload transport.

d. Develop and improve engineering systems to move sediments through the reservoir using routing techniques—siphon approaches among others.

5. Real-time data monitoring and transmission/communication: Motivation/broader impacts

Data and modeling are needed on temporal and spatial scales that meet the requirements to most efficiently use the nutrient or water resources and result in real-time adaptive management techniques.

What is needed?

Further development of "portals" such as available from agriculture related departments of universities, natural resource agencies of states, and federal agencies such as the USGS[xlvii] [xlviii] [xlix] [l] and the National Weather Service (for climate data) are needed that meld all different types of information that are desired for managing and effectively enhancing agricultural production. All types of data need to be joined – water use, water levels, water quality, climate data, nutrient data, crop growth/status information, etc.

Research Priorities

a. Determine methods for enhanced rainwater capture.

b. Develop better weather predictions.

c. Determine the effect shifting from irrigation to rain-fed agriculture thereby reducing stored water consumption by crops.

d. Centralize water data sharing/exchange, especially web data that communicates real-time monitoring. Develop artificial intelligence systems that can repackage data so that assumptions associated with data do not change but only data changes.

e. Develop near real-time monitoring of food and water production data to enhance information technology for energy-food-water nexus.

f. Develop real-time modeling of water and food production systems.

6. Interstate issues and water systems: Motivation/broader impacts

Most of the states in the central Great Plains have interstate compacts related to surface water, which also inherently involves stream-aquifer interactions, whether or not groundwater is specifically included in the compacts. These include the Upper Niobrara Compact (Wyoming, Nebraska), South Platte River Compact (Colorado, Nebraska), Republican River Compact (Colorado, Nebraska, Kansas), Big Blue River Compact (Nebraska, Kansas), Colorado-Kansas Arkansas River Compact, Kansas-Oklahoma Arkansas River Compact, Canadian River Compact (New Mexico, Oklahoma, Texas), and Red River Compact (Oklahoma, Texas, Arkansas, Louisiana). Water supplies from many of these rivers or from aquifers impacted by the surface-water flow are used for food production or in energy generation facilities.

State of the art in this field

Legal issues related to the interstate issues are actively being addressed by the compact states, as well as the Supreme County when disputes arise. Various models have been developed by the states to simulate river flows and stream-aquifer interactions; the models have then been modified to produce a regional model accepted by all of the states within a compact.

What is needed?

One of the most important future issues for interstate water systems is the effect of climate change on the temporal and spatial variability in precipitation and temperature that will affect water supplies and therefore food production. A critical need in this area is the appropriate and correct consideration of climate change in interstate basin models and the uncertainties involved in climate predictions and the water system models. Another need is a better understanding of how socioeconomic factors related to water, energy, and food production in individual states will affect the interstate issues involved in compacts.

Research objectives

a. Develop climate change models that are appropriate for interfacing with interstate water system models and adapt the water system models to appropriately incorporate the climate change models. This includes steps to address the individual issues of states that may have different views of how climate change should be included in the interstate compact models.

b. Determine the impact of socioeconomic issues in the different states of interstate water compacts on the interstate issues and water systems of the entire compacts.

Water Quality

Agricultural and industrial practices discharge large volumes of water. In agriculture, this includes irrigation runoff and liquid waste from animal feeding operations, as well as other sources. Industrially, waster is used for cooling or process fluid and is frequently discharged at slightly elevated temperatures or with increased concentration of process chemicals. Recently, in the Central Great Plains, there has been an increase in the discharge of water from hydraulic fracturing operations. In almost all cases, the discharged water contains low-levels of organic and inorganic chemicals. The presence of these chemicals can reduce the suitability of the water for human consumption or irrigation. Thus, technology that could efficiently and economically remove these contaminants to an acceptable level. Additional details are provided in Recommendation #2 of this report in the section relating to Nutrient Runoff and Recovery.

I. REFERENCES CITED

[i] United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.241

[ii] FAO, Global agriculture towards 2050, (2009) accessed at: www.fao.org/fileadmin/templates/wsfs/docs /Issues_papers/HLEF2050_Global_Agriculture.pdf

[iii] "Ogallala saturated thickness 1997-sattk97-v2" by Kbh3rd - Own work. Licensed under CC BY-SA 3.0 via Wikimedia Commons . commons.wikimedia.org/wiki/File:Ogallala_saturated_thickness_1997-sattk97-v2.svg#/media/File:Ogallala_saturated_thickness_1997-sattk97-v2.svg

[iv] B. Brown, The Last Drop: America's Breadbasket Faces Dire Water Crisis, NBC News, (2014) accessed at http://www.nbcnews.com/news/us-news/last-drop-americas-breadbasket-faces-dire-water-crisis-n146836

[v] Sruthi Narayanan, Robert M. Aiken, P. V. Vara Prasad, Zhanguo Xin, and Jianming Yu, Water and Radiation Use Efficiencies in Sorghum, Agronomy Journal, 105 (2013) 649-656

[vi] USDA ERS, "Energy Use in the U.S. Food System", ERR-94, 2010
vii Stout, B.A., Handbook of Energy for World Agriculture, Pergamon, 1990 (1986 FAO data)
[viii] U.S. DOE, National Renewable Energy Laboratory, Wind Energy Resource Atlas of the United States, DOE/CH 10093-4, October 1986, http://rredc.nrel.gov/wind/pubs/atlas/titlepg.html
[ix] Nathan Kelischek , Energy budget of nitrogen use in the United States, Journal of Student Research in Environmental Science at Appalachian, 1 (2011) 32-35

[x] F. West, Fertilizer feeds the world, accessed at: http://www.fertilizer101.org/about/.

[xi] REF
[xii] D. Charles, Fertilized World, The National Geographic Magazine, (May 2013) available online at: http://ngm.nationalgeographic.com/2013/05/fertilized-world/charles-text

[xiii] Rittmann, B. E., Mayer, B., Westerhoff, P., and Edwards, M. (2011). Capturing the lost phosphorus. Chemosphere, 84(6), 846–853.
[xiv] Stout, B.A., Handbook of Energy for World Agriculture; 1986
[xv] Hager, T., The Alchemy of Air, Random House Inc., 2008
[xvi] Smil V., Nitrogen cycle and world food production. World Agriculture 2:9-1, 2011

[xvii] Cordell, D., Drangert, J. O.; White, S., "The story of phosphorus: Global food security and food for thought". Global Environmental Change 19 (2): 292–305, 2009
[xviii] Schlögl, R., "Catalytic synthesis of ammonia – a "never ending story?" ", Angew. Chem. Int. Ed., 42, 2004-2008, 2003
[xix] Ammonia, ThyssenKrupp Industrial Solutions (formerly Uhde), Company brochure, 2009, http://www.thyssenkrupp-uhdemexico.com/fileadmin/documents/brochures/0a2d5391-b166-484d-847d-3cbfd941f06b.pdf, retrieved 12-22-2015
[xx] Moulijn, J.A., Makkee, M., van Diepen, A. E., Chemical Process Technology, 2nd Edition, Wiley, 2012
[xxi] Ullmann's Encyclopedia of Industrial Chemistry, Wiley, 1999-2014

[xxii] Blanco, M., "Supply of and access to key nutrients NPK for fertilizers for feeding the world in 2050", Report, Universidad Politécnica de Madrid (UPM), Department of Agricultural Economics, 2011, http://eusoils.jrc.ec.europa.eu/Projects/NPK/Documents/Madrid_NPK_supply_report_FINAL_Blanco.pdf (retrieved 12-6-2015)
[xxiii] U.S. DOE, "Revolution…Now The Future Arrives for Five Clean Energy Technologies – 2015 Update", November 2015, http://www.energy.gov/sites/prod/files/2015/11/f27/Revolution-Now-11132015.pdf, retrieved 12-22-15
[xxiv] Christensen CH, Johannessen T, Sørensen RZ, Nørskov JK. Towards an ammonia-mediated hydrogen economy? Catalysis Today. 2006;111(1-2):140-4
[xxv] Dede, C. (2009) Immersive interfaces for engagement and learning. Science 323, 66-69.
[xxvi] Several available cites.
[xxvii] https://water.usgs.gov/ogw/artificial_recharge.html
[xxviii] http://ks.water.usgs.gov/equus-beds-recharge
[xxix] http://ca.water.usgs.gov/misc/asr/
[xxx] http://sofia.usgs.gov/sfrsf/rooms/hydrology/ASR/
[xxxi] http://water.epa.gov/type/groundwater/uic/aquiferrecharge.cfm
[xxxii] Liu et al., 2015, *Groundwater*, doi: 10.1111/gwat.12363.
[xxxiii] http://water.usgs.gov/nrp/software.php
[xxxiv] Whittemore, D.O., Butler, J.J., Jr., and Wilson, Blake B., 2015, Assessing the major drivers of water-level declines: new insights into the future of heavily stressed aquifers. *Hydrological Sciences Journal, doi:* 10.1080/02626667.2014.959958
[xxxv] http://www.twdb.texas.gov/groundwater/models/gam/
[xxxvi] Hyndman, D., Kendall, A., Smidt, S., Deines, J., Liu, X., Cotterman, K., and Haacker, E., 2015, H44F-02 Evaluating water sustainability across the High Plains aquifer using remote sensing and process-based hydrology models. AGU Fall Meeting, San Francisco.
[xxxvii] Strassberg, G., Scanlon, B.R., and Rodell, M., 2007, Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains aquifer (USA). *Geophysical Research Letters* 34, L14402, doi:10.1029/2007GL030139.
[xxxviii] Wilson, B., Liu, G., Bohling, G., Whittemore, D., and Butler, J., Jr., 2015, West Central Kansas GMD1 model. Kansas Geological Survey, Open File Report 2015-33.
[xxxix] http://water.usgs.gov/nrp/proj.bib/hill.html
[xl] Hill, M. C., Kavetski, D., Clark, M., Ye, M., Arabi, M., Lu, D., Foglia, L., and Mehl, S., 2015. Practical use of computationally frugal model analysis methods. *Groundwater*. DOI: 10.1111/gwat.12330.
[xli] https://biosurvey.ku.edu/reservoirs
[xlii] http://www.twdb.texas.gov/surfacewater/surveys/survey_methods/index.asp
[xliii] http://fox.okstate.edu/
[xliv] http://water.usgs.gov/nawqa/sparrow/
[xlv] http://water.usgs.gov/nawqa/sparrow/; http://www.usgs.gov/science/science.php?term=1034
[xlvi] http://ks.water.usgs.gov/reservoir-sediment
[xlvii] http://www.waterqualitydata.us/
[xlviii] http://cida.usgs.gov/ngwmn/
[xlix] http://cida.usgs.gov/ngwmn/
[l] http://www.westernstateswater.org/wade/