Food, a Global Product: An Enhanced FEW Nexus Approach

by

Mukunth Natarajan

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved June 2019
Graduate Supervisory Committee:

Mikhail Chester, Chair
Benjamin Ruddell
Jose Lobo
Andrew Fraser

ARIZONA STATE UNIVERSITY

August 2019

ABSTRACT

Sustainable food systems have been studied extensively in recent times and the Food-Energy-Water (FEW) nexus framework has been one of the most common frameworks used. The dissertation intends to examine and quantitatively model the food system interaction with the energy system and the water system. Traditional FEW nexus studies have focused on food production alone. While this approach is informative, it is insufficient since food is extensively traded. Various food miles studies have highlighted the extensive virtual energy and virtual water footprint of food. This highlights the need for transport, and storage needs to be considered as part of the FEW framework. The Life cycle assessment (LCA) framework is the best available option to estimate the net energy and water exchange between the food, energy, and water systems. Climate plays an important role in food production as well as food preservation. Crops are very sensitive to temperature changes and it directly impacts a crop's productivity. Changing temperatures directly impact crop productivity, and water demand. It is important to explore the feasibility of mitigation measures to keep in check increasing agricultural water demands. Conservation technologies may be able to provide the necessary energy and water savings. Even under varying climates it might be possible to meet demand for food through trade. The complex trade network might have the capacity to compensate for the produce lost due to climate change, and hence needs to be established. Re-visualizing the FEW nexus from the consumption perspective would better inform policy on exchange of constrained resources as well as carbon footprints. This puts the FEW nexus research space a step towards recreating the FEW nexus as a network of networks, that is, FEW-e (FEW exchange) nexus.

DEDICATION

I dedicate this dissertation first to my family. The love, guidance, and life lessons my parents provided me made this journey possible. You are my ultimate role models. I had the opportunity to share this journey with some excellent individuals and met amazing people along the way. This made this gruesome journey possible. For all the happy memories and support during the tough times, I dedicate this to my friends

ACKNOWLEDGEMENT

I am grateful to all of those with whom I have had the pleasure to work during this and other related projects. Each of the members of my Dissertation Committee has provided me extensive personal and professional guidance and taught me a great deal about both scientific research and life in general. I would especially like to thank Dr. Mikhail Chester, the chairman of my committee. He gave me the chance, something that not everyone does. As my teacher and mentor, he has taught me more than I could ever give him credit for here. He has shown me, by his example, what a good scientist (and person) should be. Nobody has been more important to me in the pursuit of this dissertation. than the members of my family. I would like to thank Dr Benjamin Ruddell for pushing me to take that one extra step towards a better model. Dr Andrew Fraser provided me with the grounding and timely and critical feedback necessary to navigate the problem I was trying to address. Last and most definitely not the least, I would like to thank Dr Jose Lobo again for pushing me to see the whole picture, and that any solution that we might propose cannot exist in isolation.

This work would not have been possible without the financial support of the ASU Global Institute of Sustainability. I am especially indebted to Dr. Mikhail Chester, Associate Professor, School of Sustainable Engineering & the Built Environment, Dr. Jose Lobo, Associate Research Professor, School of Sustainability, who have been supportive of my career goals and who worked actively to provide me with the necessary avenues to achieve these goals. They placed their complete trust and in and I thank them for their confidence. I would also like to thank Dr Braden Allenby for the guidance during my early doctoral phase, for the excellent and thought-provoking discussions and

conversations. And finally, I would like to thank Dr Claudio Stockle and Mr Roger Nelson, from Washington State University for taking time off from their busy schedules to guide me through the crop growth simulation modeling process in a short period of time.

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CHAPTER 1 A CRITICAL REVIEW OF THE FEW NEXUS

1.1 Introduction

Food security is a humanitarian crisis and a ‘wicked’ problem. To be food secure, a population, household or individual must have access to adequate food at all times, which refers to both availability and the accessibility of food . Resources need to be expended to make food available and accessible. The Food and Agricultural Organization (FAO) has projected a need for a 60% increase in food production to meet food requirements of the population in 2050. It is projected that 50% increase in irrigated food production to meet the increase in future demand, but the amount of water withdrawn for agriculture can increase only by 10%. This water constraint poses a problem for food security, over which there are energy related inter-system dependencies, and externalities such as climate and trade that make the food system more vulnerable.

Making food available involves the production, transport, and storage before it is processed. The food system thus interacts with infrastructures such as dams, roads, manufacturing plants, warehouses, power plants etc., highlighting the extent of inter-system dependencies. The inter-dependencies between the food system and the infrastructure can be characterized as the interaction between the food, energy and water systems. There is resource use as well as environmental impact, like greenhouse gases, associated with the interactions between these systems. There is clearly a need to characterize these interactions in a detailed manner. The Food-Energy-Water (FEW) nexus is an emerging framework to structurally represent the dependencies between food, energy, and water systems as well as quantify these interactions. In this manner the FEW nexus is the core framework used to address the complex problem of food security from the resource management perspective.

Agriculture is an important industry in the US – it feeds people, generates revenue and jobs, but at a cost. The agriculture industry generates $828 billion annually, contributing 5.5% to the 2010 US GDP (U.S. Bureau of Economic Analysis, 2017). Agriculture and its related industries accounted for more than 1.5% of US employment (Caruso, 2015). There is a resource cost associated with the generation of this revenue. In 2010, the total water withdrawals for irrigation amounted to 115 billion gallons per day (Maupin, et al., 2014), while 1600 trillion BTUs of energy were used on US farms (Beckman, Borchers, & Jones, 2013). Most of this energy and water use is concentrated in the American Midwest and the American Southwest, since they are regions where agriculture is a major industry. When it comes to nexus studies, the American Southwest has been a region of interest due to its severe water constraints. Crop cultivation has always been a water intense process. Given that the American Southwest is one of the centers of food production in the US, it is essential to thoroughly understand the interactions between the food system, the energy system, and the water system. These interactions keep changing, they can change artificially though technology and policy, or naturally due to changes in climate. With climate expected to change, it is essential to understand this dynamic between climate and technology with regards to productivity. Even if productivity levels drop drastically due to climate change, demand for crops can be managed through the crop trade network. Crop production tends to be clustered around few regions but demand for food is dispersed across the US, which highlights the fact that food moves across both regional and international boundaries. The US is primarily an exporter of agricultural produce. It exported $116 billion and imported $82 billion in the year 2010 (USDA ERS, n.d.). Thus, a large portion of the food produced is exported and the rest is moved domestically either to storage destinations or consumption destinations. This creates a network of flows of food between regions which leads to movement of critical water resources. Apart from the water exchange, there are carbon impacts which are difficult to account for due to the movement of crops. Establishing these flows of food is crucial to understand exchange of water and energy through food. This would give insight on the flow of water from water constrained regions as well as carbon footprint of food. Since agricultural produce is the focus of this dissertation, the terms ‘food’ and ‘crop’ are used interchangeably.

1.2 Literature Review

The FEW nexus emerged from the Energy-Water (EW) nexus. Energy-Water interactions are the most established work in the nexus research space . The EW research first established the idea of a nexus by discussing the codependence of the water and energy systems. There are many EW nexus work that has focused on the American Southwest, because of the energy demand to pump and move water from both above ground and underground sources. Arizona is a prime example of a state which depends these various sources of water. Arizona gets its water from surface water sources (54%) and groundwater sources (43%) . Colorado River water delivered to customers is pumped from Lake Havasu by lifting it by nearly 2900 feet (U.S. Department of Interior - Bureau of Reclamation, 2013). Ground water is typically pumped and the depth at which water is found varies drastically across Arizona. Given the water quality requirements in the US, energy is expended to treat surface and ground water. Energy is also required for the treatment of both pre-consumer water and post-consumer water. Drinking water, also known as potable water, is treated extensively to remove disease causing micro-organisms while maintaining aesthetic characteristics such as transparency and smell. Stringent regulation helps maintain the quality of water applied on crops to avoid food borne illnesses. Residential households are also heated with hot water. On the post-consumer end, wastewater from residences, industry, and agriculture need to be treated for dangerous chemicals and pathogens before they are responsibly released into the environment. The wastewater treatment process is energy and chemically intense . Just as energy is needed to make water available, water is required to produce energy. Water is consumed in the extraction and production of energy sources such as coal and crude oil . Even in the case of renewable energy, water is required to produce the equipment, such as solar panels and wind turbines . The production of electricity itself is water intense. Fuel is burned in thermal power plants to convert water to steam to rotate the blades of a turbine, a typical mechanism to convert mechanical energy to electrical energy. Hydro power, a major source of renewable energy in the US, requires moving water to produce electricity. In all, EW studies for a specific region is based on the uses of energy and water.

Agriculture is a major consumer of water and consumes significant amounts of energy both directly and indirectly. This is especially true in arid regions that require water conveyance infrastructure and ground water pumping infrastructure, like the American Southwest. Agricultural production from the American Midwest is far greater in number when compared to the American Southwest. Though more food is produced, the presence of the Great Lakes reduces the constraint issues surrounding resource management in the region. The EW studies based out of the American Southwest are more interesting due to the water constraints in the region. Arizona and California, specifically, have large agricultural industries that depend on water that needs to be brought in from the Colorado river via dams and canals. Water conveyance and water pumping for agriculture thus becomes a large contributor to energy consumed in the American Southwest. But energy consumption is not limited to water conveyance, energy is needed in the form of fuel, fertilizer, and electricity to produce, transport and store crops.

Since the FEW nexus is a conceptual framework for sustainable development this framework needs to address food security by assessing the interaction between various infrastructures that enable agricultural production and make crops available for consumption. Resource constraints as well as the heavy dependence on irrigation (water, energy), fertilizer (energy, water), farm equipment (energy), storage equipment (energy), and freight transportation (energy) drive food security concerns around meeting local and global demands for food. From a resource management perspective, it is essential to evaluate the interdependence between the food, energy and water systems. A large portion of the FEW literature and reports by international agencies have focused on the production of food though they take a variety of perspectives. Production creates the largest environmental impact as it is the largest consumer of resources. Resource use in agriculture has been a topic of discussion for a few decades. It has been identified that resource efficiency is critical for food security from the food production perspective . But the FEW nexus interdependences extends far beyond the production phase. Transportation and storage of food are critical life phases to make food available for consumption. Without transportation and storage, populations across regions would need to be self-sufficient in terms of food production. The FEW nexus is anthropogenically imprinted due to inseparable linkages between the food system and other infrastructures that make food production and supply feasible. One example is the food system's dependence on the freight infrastructure to deliver food to the consumer. In reality, food is moved via land, air and water. Food, throughout its product-life, moves over long distances. It is known that crop production is concentrated while demand is widely distributed. Existing food miles literature highlight the impact that food transport involves . A large portion of food transport literature deals with the idea of local foods since they eliminate the transportation phase and highlight the quality of food as well as support the local economy . But it is important to remember that all food cannot be grown local in a resource efficient manner. Food mobility is, thus, a critical component to identify food's route but also to inform customers about the origin of the food. Trackability and transparency are important aspects with research showing that millennials are more conscious about their environmental impact . Trackability also ensures that any contaminated food can be immediately removed from the stockpile. Food mobility has been widely used to estimate virtual water flows through food , but there has been little work on virtual energy flows. Food needs to be stored so that consumers get the food in good condition. The food system also depends on the extensive network of warehouses and cold storage units to avoid spoilage. Temperature and humidity as well as avoiding insects and pests are key components to effective storage. Researchers have studied the effects of storage technology so as to keep food safe . Since food is transported and is perishable, storage becomes essential to the FEW nexus and contributes to the energy consumed by the food system. But there has been no work on storage as part of the FEW nexus. In summary, the traditional FEW nexus research focuses largely on food production, and this approach excludes the interaction between the food system and other infrastructures outside the production phase. Since the FEW nexus is primarily used as a resource management tool this approach disproportionately favors water conservation efforts more than energy conservation. Few recent studies have realized this effect and have started to consider the different phases of food . To understand and accurately estimate the net energy and water intensity of food, an approach that considers the direct and upstream investments across the various phases are necessary.

Energy and water intensity of crops are not constant and can vary due to many factors including climate and conservation practices. The energy and water intensity of crops is often expressed as the ratio of total energy or water consumed to the total crops produced. Hence any change in crop yield or changes in energy and water consumed would change these intensities. Temperature has significant impacts on crop growth, thus changing crop productivity levels . Effective application of water and fertilizers through conservation technologies reduces the amount of water and energy used for crop cultivation. Also, conservation technologies have been shown to have positive effects on crop productivity . It is important to understand this dynamic to determine options to reduce energy and water exported through food. The climate impacts on the FEW nexus has been largely approached from the water security perspective (Beck & Villarroel Walker, 2013; The World Economic Forum Water Initiative, 2011) in the literature. There are also studies that examine the extent of crop loss due to climate change which directly impacts the FEW nexus . Most crop productivity studies expect a decrease in productivity due to increasing temperatures, since temperature is thought to be the most influential factor in crop growth. The impact of changes in precipitation on crop productivity are important as well and have been studied, but loss in precipitation can be compensated through irrigation and since the extent of irrigated land has been increasing it is more common to do so. General Circulation Models predict, on average, an increase in temperature and drop in precipitation. But increases in temperature are not consistent across space. For example, Maricopa county in Arizona might experience an average increase of 2^{o}C while Yuma county in Arizona might experience an average increase of just $3^{o}C$. This trend could increase the water and energy embedded in crop production thus increasing the amount of resources exported through food resulting in drastic impacts on resource constrained regions. On the other hand, conservation policy and technology are meant to reduce the amount of energy and water consumed by crops. Some of these technologies have marginally increased yield levels as well. By using crop models, it would be possible to assess these dynamics between energy, water, climate and yield. Such a model would provide important insights on the future climate impacts and the effects of conservation strategies. Such approaches are rare in the literature. A key component of this study is the set of conservation strategies. Some conservation efforts need federal support while there are others that can be implemented locally. The use of seed types for restoration through the National Seed Strategy for Rehabilitation and Restoration, land management through the Healthy land initiative, and Agriculture Management Assistance are all federal level programs that drive conservation efforts. But the selection and the use of conservation technologies like irrigation technologies, and no tillage approaches are decisions that need to be taken domestically, at least at the state level. There has been no research on the potential of such state driven conservation efforts to manage the effects of climate change on the FEW nexus. This dissertation quantifies the climate impacts and conservation impacts on the FEW nexus to assess the dynamic between these opposing forces.

Trade is another aspect that also exemplifies the complexity of the food system. The food trade literature has largely focused on consumption , climate change , food supply, traceability and safety. Studies that use the resource management lens typically revolve around virtual water . The central concept around these studies is crop trade between regions of interest. A region can be a producer, consumer, importer, exporter, a storage location, or any combination of these roles. But production is concentrated in a few regions while demand is consistent across states. When most of the crop produced is exported or when production of a crop becomes infeasible in a region, the only option to meet demand is import via trade. Hence crop trade is a network connecting the producers to the consumers. Depending on the roles that states play, food is transported into and/or out of a state. Given the potential impacts of climate change on agriculture, food trade becomes critical for food security . Hence a clear understanding of the food trade network is necessary to understand the security risk to food supply and demand. To date, the only inter-state trade data that is publicly available is through the Freight Analysis Framework (FAF), which uses the Commodity Flow Survey data (CFS). There are models, such as the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), that simulate agricultural commodity trade. The IMPACT model is a network of linked economic, water, and crop models. It simulates national and international agricultural markets. This model supports longer-term scenario analysis through the integration of these multidisciplinary modules to provide researchers and policymakers with a flexible tool to assess and compare the potential effects of changes in biophysical systems, socioeconomic trends, technologies, and policies. But the IMPACT model tool is not easily accessible. It is expensive, and doesn't inform about energy flows though it does deal with water in agriculture. The CFS data is collected through the survey of products including foods that flow from one region to another. Since the survey covers a large variety of products, they are aggregated into pre-defined groups . While the dataset identifies flows between regions, it does not inform the user of the true origin, true destination of the product or that of storage. Storage of product introduces some complexity in understanding the flow of products from one region to another but is an important aspect of food trade. There are, currently, no models that trace flow food while accounting for storage. Such a model is necessary since it better informs flow of energy and water through food. Trade now transforms to a mechanism through which resources and impacts are shifted across space. Trade related food studies have largely explored virtual water. Typically, these virtual water studies (which are also pseudo FEW nexus research studies) explore the system interdependence from the producer's perspective, since they examine flows from the producer to the consumer. This suggests that the FEW nexus interactions do not exist in a region that does not produce food. In reality, the food system of a region can be an export economy or an import economy. Hence a region's food system can depend on the energy and water system across many regions including itself. To understand these cross-regional interdependencies there is a need for a model that includes food trade into the FEW nexus, by integrating import and export flows between regions while accounting for storage.

1.3 Research Questions

In summary, it is clear from the literature review that there are research gaps with regards to the FEW nexus from the resource management perspective. There is a need for a more robust approaches to assess the FEW nexus across the production, transportation, and storage phases to assess resource use across food's life to better understand the impact it creates. While studies explore the impact of temperature change on agriculture, minimal research has been conducted to explore the spatial variations in productivity and the state's ability to manage productivity losses with conservation technologies. It is also clear that the current food resource use assessment approach is insufficient as it does not consider import of food into a region. Given these research gaps, the following research questions have been framed for this dissertation.

RQ1: What are the direct and indirect energy and water requirements for agriculture in Arizona? How does disproportionate consumption of energy and water occur across crops? What is the impact of conservation strategies and climate change on Arizona's FEW Nexus?

RQ2: Given spatially explicit climatologic forecasts, how might agriculture productivity in Arizona be affected across space and how? What is the impact of conservation strategies and what scale do these assessments need to be made?

RQ3: How does trade influence the FEW nexus to manifest across space? What are the effects of such a manifestation from a resource management perspective?

1.4 Conceptual Framework

There are two components to understanding the movement of energy and water through food – estimation of embedded resources and establishing inter-regional flows of food. Figure 1.2 shows the conceptual framework used in this dissertation that will establish food, energy and water flows. The first is a mechanism where the energy and water embedded in food is estimated. From the FEW nexus literature it is clear that the various phases of food are considered in isolation which does not present a clear picture of the nexus and the broader system interdependencies. There is a methodology that is widely used to determine the environmental impact across various phases of a life cycle –Life Cycle Assessment (LCA). The LCA framework is the best available quantitative framework to estimate energy and water consumption to produce, store and transport crops. Thus, the LCA framework is valuable when assessing the FEW nexus since it critically evaluates the interdependence between the food, energy, and water systems. The FEW nexus estimations need to include both direct and indirect energy and water because the energy-water interconnection is elaborate and is well established. Given that the energy and water embedded in food are estimated in a phase manner, there is a unique opportunity for us to assess the impact of natural phenomenon and the implementation of technologies on the system. The dissertations presents a case for each by looking at the impact of temperature changes on crop productivity as well as the implementation of conservation technologies.

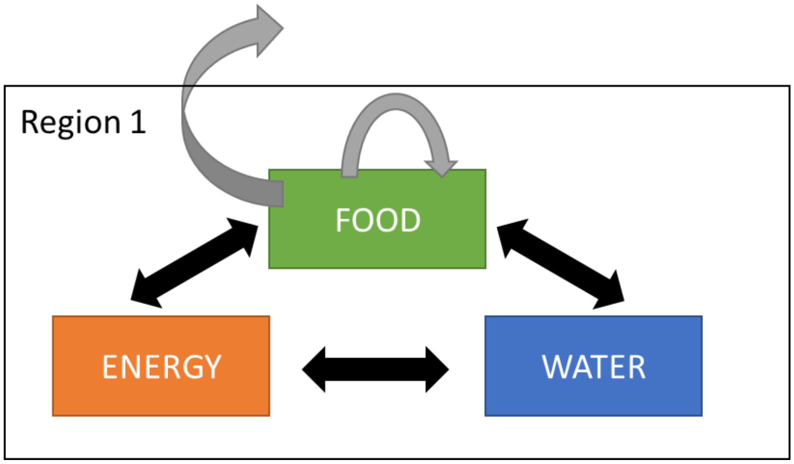


Figure 1.1: FEW Nexus Within Region 1 in System S.

The second component is the trade of food. Within the FEW nexus framework, trade of food is represented purely as export flows. This approach is insufficient because the FEW nexus needs to consider a consumption perspective along with the production perspective so that energy and water flows through food can be understood. The food system in any region involves activities such as production, import, export, consumption and storage.

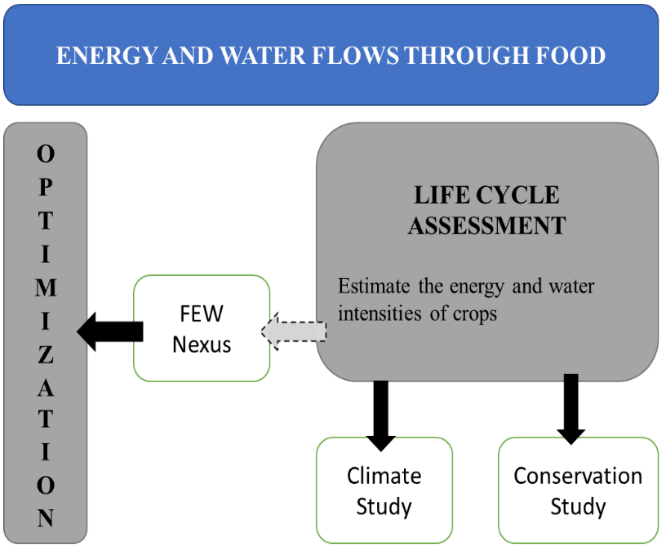


Figure 1.2: Conceptual Framing of the Dissertation.

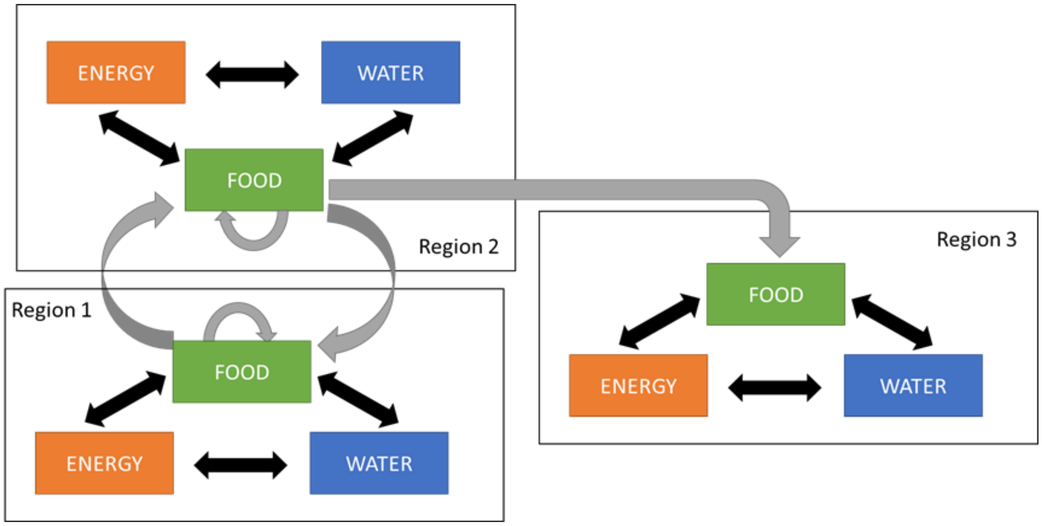


Figure 1.3: The Three Systems Representing the Three Regions Trade Food With Each Other. Each Region Has a FEW Nexus Within Itself.

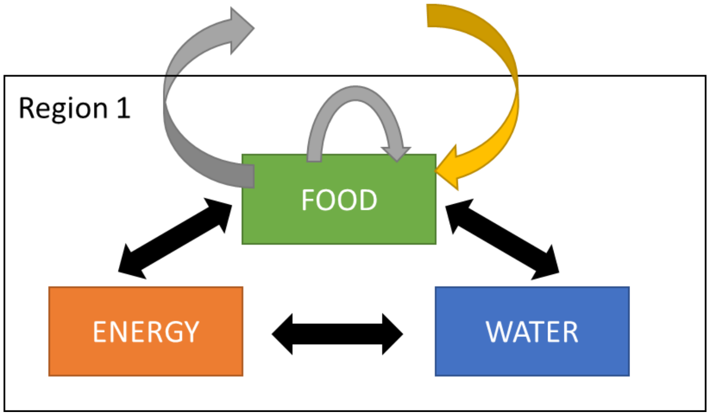


Figure 1.4: Region 1 Isolated From the 3-Region System Shown in Figure 1.3.

The insufficiency of the FEW nexus from the trade perspective can be explained conceptually. Consider the system S with Region 1 shown in Figure 1.1. For simplicity let us assume only the food, energy and water sub-systems exist within S. The intention is to produce food to meet the demand. Thus, there are interactions between these three subsystems to meet this goal; this defines the FEW nexus. Water and energy are needed for food production. Energy crops are used to produce biomass that contributes to energy production. Vegetation influences micro-climates. And as always, energy is needed to move water. The key concept here is that the food demand can be local (within the region) or remote (outside the region) or both. Now let us consider a system S with three systems Region 1, Region 2, and Region 3 with each region being defined as a system shown in Figure 1.1. Only in this case the three regions also interact with each other through food trade as shown in Figure 1.3. Let Region 1 and 2 be the producers and all three regions are the consumers. Figure 3 shows that food is traded from Region 1 to Region 2, Region 2 to Region 1, and Region 2 to Region 3. Region 1 and Region 2 also supply themselves.

Traditionally, the FEW nexus of a specific region is studied by isolating one region. But if Region 1 undergoes all the interactions shown in Figure 1.3, it is clear that the FEW nexus assessment from Figure 1.1 is incomplete in its scope. This insufficiency is highlighted in Figure 1.4.

Isolating a region leads to the exclusion of flows from the region. It is essential to consider the flows into the region as well. The flows into the region determine the footprint of a region with regards to its food consumption. Thus, this approach addresses the concept of virtual water and virtual energy, and the concept of the energy and water footprint of food. This enables us to ask questions regarding net flows of energy and water through food and presents the possibility of managing a network of energy and water flows across the US.

In the traditional nexus approach, since the nexus is defined by the food produced in a region, only virtual energy and virtual water have been studied. Once the food trade is established, it would be possible to assess the extent of energy and water that flows through food trade so that the impacts local resources can be understood. This dissertation hopes to present an approach where virtual energy and virtual water that flows from the region can be determined as well as the spatial extent of food’s energy and water footprint.

CHAPTER 2 CONSERVATION NEXUS: THE LIFE CYCLE EFFECTS OF CONSERVATION STRATEGIES

2.1 Introduction

As global demand for food rises, many regions encounter obstacles to produce an adequate supply. In the US, the desert Southwest faces some severe challenges despite its history of agriculturally based development. There is a pressing need to understand how the industry can be sustained despite rapid population growth, reduced availability of resources, and concerns from climate change. Challenges arise not just from the use of water, but from the interdependence of food, energy, and water systems (subsequently referred to as the FEW nexus). Agriculture requires significant quantities of water and energy. Water production and delivery requires significant quantities of energy, while energy production requires water. As such, there is now much interest in understanding the requirements of each sector from each other, and the dynamics between them.

There has been a significant effort to understand the relationships between water and energy systems and to date few studies have integrated food systems. The typical approach used to estimate energy embedded in water is to quantify the direct and indirect energy requirements for treatment and conveyance for different sources of water. Water embedded in energy is often assessed on the basis of electricity generation technology – coal, natural gas, hydroelectric, and nuclear, all of which require water for running turbines and cooling. The energy-water nexus is established when a region, entity or process that consumes energy and/or water is considered and connections between energy and water use are revealed. Once direct energy and water consumption is established, the embedded components are estimated based on the interdependence of water and energy.

Studies focusing on California are the most common but there are energy-water nexus studies for states including Arizona and Texas, as well as for cities such as New York and Los Angeles. In states where agriculture is a large consumer of energy and water, and where few local water resources are available, such as Arizona and California, understanding the nexus is of critical importance.

In the US, the desert southwest which is home to major agricultural enterprises, has limited local water sources, burgeoning populations, and relies heavily on thermoelectric power generation. This combination raises serious concerns about the long-term viability of agriculture in the region, and understanding the flows and dynamics in the FEW nexus may provide valuable insight into the current and future challenges facing the industry. The US southwest is traditionally understood to include Arizona, California, New Mexico, Nevada, Colorado and Utah and it is expected that the population in this region will grow to 94 million in 2050. Agriculture was a strong driver of development in the southwest. In 2013, California ranked first in cash receipts for agricultural produce, valued at $46.4 billion. Arizona ranks 5th in the production of vegetables, melons, and potatoes; is among the top 5 producers of durum and spring wheat, broccoli, cabbage, cantaloupe, cauliflower, honeydew, lettuce; and ranks 7th in the production of watermelon, and is a top 10 producer of cotton. The water challenges of the desert Southwest are well documented. There is heavy reliance on the Colorado River for power, agriculture, and other services. The high agricultural productivity of the region as well as the increasing population puts stress on this water source. The flow in the Colorado River basin has also been reducing, thus reducing the ability to meet water demands. Understanding the dynamics of the FEW nexus requires a systems-oriented approach that reveals the interdependencies between sectors.

The life-cycle assessment (LCA) framework provides valuable insight into the interdependencies of energy and water systems and its application to the FEW nexus shows the relationships between processes, and ultimately how the three systems interconnect. Major life-cycle phases for food include production, transport, storage, use and end of life. Agricultural produce can be either consumed directly or converted into other products which are later consumed. Each phase consumes biomatter, energy and water. The biomatter consumed can be expressed in embedded energy and water. The interactions between the food, energy and water systems are complex. But in the case of Arizona, the interaction between the food system and the water system, as well as the food system and the energy system are unidirectional. While energy and water interdependencies are direct, the influence of the food on the water and energy systems are indirect and ambiguous. The primary focus of FEW nexus research seems to be water, but there are some studies that consider energy input and environmental impact of agriculture. These studies typically exclude upstream effects. Also, LCA studies on agriculture tend to focus on one crop or food product. Opportunity exists for using LCA to examine the direct and indirect effects of the FEW nexus more critically.

In a future with possible constraints on water and energy, it is essential to understand the interactions between the food, energy, and water systems particularly in the desert southwest. Using Arizona as a case study, the FEW nexus model is developed to study direct and indirect effects of these systems using the LCA framework. The LCA framework is used to determine the net energy and water requirements of food, but the purpose of this paper is not to estimate impacts in a full LCA. To this end, this study answers the following questions: 1) How do Arizona's food, energy, and water systems interconnect and how much does each system require from the others? and 2) What conservation technologies should be prioritized to reduce energy and water use in the agricultural system?

2.2 Methodology

The LCA framework is used to model and estimate the FEW nexus in Arizona. Water and energy used in the agricultural system are calculated based on the production, transportation, and storage phases. Since this study focuses on fresh produce, the distribution, consumption, and disposal phases are not included in the analysis. Additionally, upstream supply chain processes are considered that capture indirect water and energy use. Figure 2.1 shows the system boundary of the analysis.

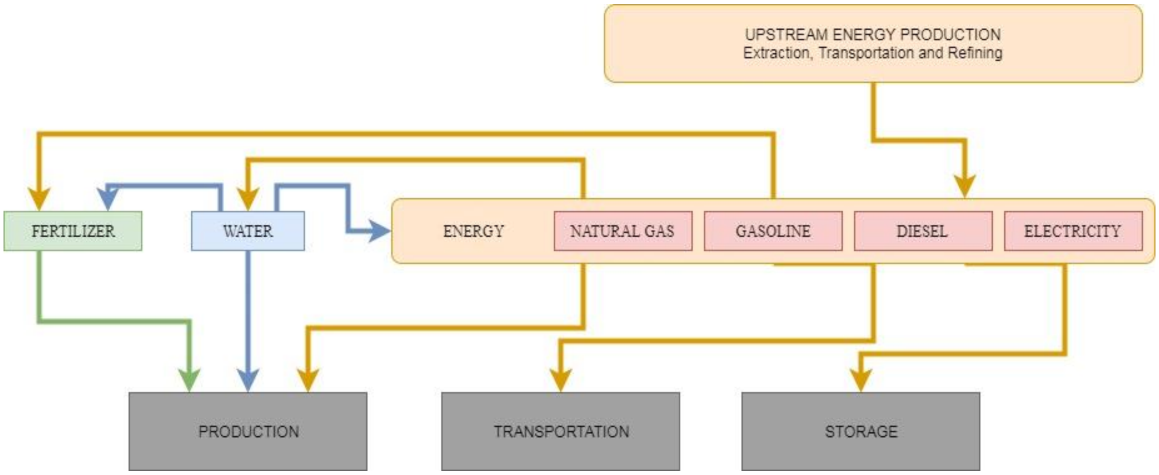


Figure 2.1: FEW Nexus System Boundary. The LCA Framework Is Used to Build the System Boundary for the FEW Nexus. It Consists of the Production, Transport and Storage Phases Which Have One or More Inputs Which in Turn Have Embedded Energy or Embedded Water.

Production

Data from CropScape suggests that the variety of crops that are cultivated has changed from year to year. A base year of 2014 is chosen as this is the most recent time period with available crop cultivation data. CropScape, a USDA tool which represents the extent of agriculture across every state in the US, is used to estimate land area by crop type for the state using satellite imagery. Agriculture in Arizona is concentrated mainly in southern Arizona in the Pinal, Pima, Maricopa, and Yuma counties.

Water Consumption

Water consumption by crop is estimated through the evapotranspiration processes, considering both evaporation and transpiration. Evaporation is the process by which water is transferred from the plant to the atmosphere. Transpiration is the process by which water is carried from the roots to small pores on the underside of leaves, where it changes to vapor and is released into the atmosphere.

The evapotranspiration rate (E_T) of various crops was estimated using Equation 1,

$$E_T = E_{To} \times K_C \tag{1}$$

where E_{To} is the reference evapotranspiration rate (modeled using the Penmann-Montieth method) and K_c is the crop factor. The crop factor is the ratio of the crop's evapotranspiration and a reference evapotranspiration. The evapotranspiration rate depends on the temperature, rainfall, humidity, soil conditions and wind speed. The reference evapotranspiration rate is defined as the rate at which readily available soil water is vaporized from reference surface, typically hypothetical grass reference crop with specific characteristics. The Penmann-Montieth method is a standard approach for calculating the reference evapotranspiration rate (Equation 2), requiring radiation, air temperature, air humidity and wind speed data.

$$ET_0 = \frac{0.408(R_n - G) + \gamma u_2 (e_s - e_a)\frac{900}{T+273}}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where,

ETo: reference evapotranspiration [mm/day],

Rn: net radiation at the crop surface [MJ.m^2/ day],

G: soil heat flux density [MJ/m^2. day],

T: mean daily air temperature at 2 m height [°C],

u2: wind speed at 2 m height [m/s],

es: saturation vapor pressure [kPa],

ea: actual vapor pressure [kPa],

es – ea: saturation vapor pressure deficit [kPa],

D: slope vapor pressure curve [kPa/°C],

g: psychrometric constant [kPa/°C]

Reference evapotranspiration rates are estimated with Eto Calculator, a software tool developed by the FAO using temperature, humidity, sunshine and wind speed. Evapotranspiration values for 2014 are based on average monthly radiation, air temperature, air humidity and wind speed. This information is obtained from the of the Phoenix weather station. Most Arizona agriculture is in the southern part of the state, which has a climate like that of Phoenix. Crop factors are obtained from the FAO. Crop factors vary based on growth stage. An average crop factor value is calculated based on the number of days the crop spends in each stage as determined by the FAO. This weighted average and the reference evapotranspiration are used in equation 1.

Total water by crop was estimated from the evapotranspiration rate and land area used, and includes compensation by rainfall. The evapotranspiration rate is the minimum amount of water (measured in mm/day) that is required to sustain plant growth. When multiplied by the total land acreage that each crop covers, it produces the average volume of water required every day during cultivation. The total number of days of cultivation required for each crop were obtained from the planting calendar from a local urban farm and agricultural studies. The data on cultivation periods were used to determine the compensation of water through precipitation. The Sonoran Desert is known to be the wettest desert in the world; Arizona receives on average 230 mm/year of rainfall. The precipitation volume was removed from the estimated water demand to capture irrigation requirements. Not all the rainwater is captured but for this study it is assumed that all the rainwater is available to the crops.

Energy Consumption

The energy consumption of crops was estimated using data obtained from crop budgets provided by the Arizona Cooperative Extension. Financial crop budgets are developed from surveys of farmers’ expenditures. The data are recorded at county scale and include cereal grain such as wheat, corn, and barley as well as vegetables and fruits such as cabbage, apples, and pecans. Total electricity used or fuel used were available in kWh and gallons but in some cases only financial expenditure were available for fuels.

Financial expenditures were converted to energy quantities using unit prices for fuels ($1.60/gal, $1.50/gal, and $7.90/1,000 ft^3 for gasoline, diesel, and natural gas) for the year 2001.

Transportation

Transportation Energy associated with the transportation of agricultural products is estimated using the 'Cereal grains' and 'Other ag prods' food category flows reported in FAF. Flows from Arizona to every FAF zone provides the total weight transported via truck, rail, and multiple modes. The weight of food produce transported through multiple modes is less than 5% and therefore excluded. A GIS analysis is used to estimate the distance between the centroid of Arizona and every other FAF region centroid. This result is used along with the material flow data from FAF to determine flow of food in ton-miles. Weber & Matthews (2007) estimated the energy per ton-km for various modes of food transport. They report a value of 2.7 MJ/ton-km for trucks and 0.3 MJ/ton-km for rail, which are used to determine the energy associated with the FAF flows. The results are segregated using the crop categories defined by FAF – 'Cereal grain' and 'Other Ag'. Using the energy data set and the FAF tonnage dataset along with this crop categorization the average transport energy per unit weight for the categories is estimated. The transport energy for each crop is assigned using the yield of the various crops and the energy per weight of the crop groups defined in FAF. According to FAF, Arizona exports 78.5 Ktons of Cereal grain and 369.1Ktons of Other Ag to international destinations. On the other hand, Arizona contributes 1332.8 Ktons of Cereal grain and 2966.2 Ktons of Other Ag to the domestic supply. Given that Arizona export is considerably smaller and the lack of precise data on destination cities, the transportation impacts of export has been excluded.

Storage

Storage energy was evaluated from the conditions under which the crop can remain unspoiled. Every crop has an ideal storage temperature and requires specific humidity conditions. Temperature is the primary factor considered to model storage energy use. Fruits and vegetables are more sensitive to storage temperature than grain. Storage temperatures along with Arizona average annual temperatures were used to determine the temperature difference that needs to be maintained and ultimately the associated energy for air conditioning. To estimate the energy required for storage the specific heats of various crops as specified by ASHRAE were used. Using the temperature difference and the specific heats the energy required to keep crops at ideal storage conditions was estimated. Cereal grains can be stored for 10-12 years while soft grains can be stored for 8 years at an ideal temperature of 70°F. Grains are usually stored in large warehouses that may or may not have refrigeration. Refrigeration is critical for vegetables and fruits but not as much for grains. Given the extent of storage and the dependence of crops on temperature, the refrigeration for grains has been excluded. The primary source of energy in storage is assumed to be electrical energy. The US electrical mix in 2014 was used since storage locations can be located anywhere within the US. This refrigeration energy contributes only to 54% of the total energy consumed by a cold storage unit. The total energy for storage is then estimated.

Embedded Energy and Embedded Water

Energy embedded in water and water embedded in energy are traditionally considered embedded components but in this study, there is also energy and water embedded in fuel and fertilizer that needs to be considered. While fertilizer and fuel are directly consumed, energy and water are spent for the production and transport of these resources. Hence the energy and water consumed to produce and transport fuel and fertilizer have been aggregated into embedded energy and embedded water. Fertilizer production is energy intensive and the transport of these fertilizers can also be energy intense. Although fertilizer is directly used on farm, the energy and water in fertilizer are embedded into fertilizer and hence has been aggregated into the embedded components. As such, the embedded energy associated with N-type, P-type, and K-type fertilizers for Arizona agriculture were estimated. A review study LCAs of fertilizers was used to estimate the average energy required to produce the resource. The average energy required to produce N-type fertilizer is 44MJ/kg, P-type is 22 MJ/kg and K-type is 10 MJ/kg.

Transportation energy from the fertilizer production source to the location of use depends on the mode and distance. A study by the Fertilizer Institute reports that there are 52 operational N-type fertilizer production sites, 33 operational P-type sites and 7 operational K-type sites. The US depends on the import of nitrogen and potash supplies. 50% of nitrogen and 85% of potash were imported in 2011. Phosphate on the other hand is mainly produced through domestic production since the US is the second largest producer of phosphate fertilizers and exports 41% of phosphate fertilizer produced. As per the data from the Freight Analysis Framework (FAF), it is estimated that Mexico supplies more than 90% of fertilizer imported to the state of Arizona of which 80% is via trucks and 20% is via rail. Rail and truck transport are the primary modes for domestic supply of fertilizer with the respective modes being used for 71% and 29% of fertilizer imported from US states. The distances between Phoenix and each of those 52 plants were estimated using GIS and the associated transportation energy was calculated on that basis. The fuel economy of medium and heavy-duty trucks is estimated at 22.6 gal/1000 ton-miles while the energy intensity of rail transport is estimated at 296 BTU/ ton-mile50.

The energy used to produce and transport fuels need to be estimated, similar to fertilizer. According to the U.S. Energy Information Administration, 91% of the US energy consumption is satisfied using domestic energy production of which 33% is from natural gas sources and 28% is from petroleum sources. The energy required to produce 1MJ of diesel, gasoline and natural gas is 1.211 MJ, 1.645 MJ, and 1.072 MJ respectively. These specific data are obtained from the GREET 2016 model. Off road diesel, which are not low on sulfur, is predominantly the type of diesel fuel used on farms and hence the conventional diesel option was chosen on GREET. Similarly, the E85 gasoline values as well as natural gas from conventional recovery were selected from the GREET model for embedded energy estimation. Arizona has no refineries and have minimal crude oil production. Most fuels are imported, either from other states, mainly California and Texas, or internationally. According to FAF 96% of foreign gasoline imports into Arizona are from the ‘Rest of Americas’ via Texas and the remaining 4% is diesel from other parts of the world. But according to FAF the total imported fuel by Arizona when compared to domestic (intra-U.S.) supply is less than 0.025% and hence international import of fuel has not been included in this analysis. Texas is also the largest producer of natural gas, accounting for 26% of the nation’s production and hence it is also assumed that all the natural gas for Arizona is bought from Texas via the El Paso Natural Gas/ Mojave pipeline. As for gasoline and diesel, the FAF data set is used to determine the average distance that the fuel travels based on the amount of fuel that is obtained from other US states.

Past nexus studies have quantified the dependence of energy systems on water systems and vice versa, and these are used to estimate embedded effects associated with Arizona agriculture. Previous studies have considered thermoelectric power generation, water pumping, and energy associated with water treatment to estimate the embedded effects of water and energy in Arizona. For water, the embedded energy was estimated by calculating the energy required to bring water from the Colorado river through the CAP canal, groundwater pumping, and treatment. Also, some farms use ground water only while others use both ground and canal water. Data from the USGS show that about 73% of agricultural water is from ground water withdrawals while only 27% is from surface water sources51. Using this split the total energy required to supply water was estimated.

2.3 FEW Results

The energy invested in Arizona's agriculture is more distributed across the production, transport, and storage phase than the water is. The only contributions to water consumption from the transport and storage phases are via the water embedded in energy. First, we explore the FEW nexus for all crops and then focus only on food crops. All three phases require fuel in some form to operate machinery and equipment that helps produce, transport, and store these crops. Embedded energy primarily consists of producing and transporting fertilizer and fuel to Arizona, with smaller contributions from water.

There is a disparity in energy allocated between the crop categories – cereal grain and non-grain – for each phase. The production energy for both the cereal grain and non-grain crops are at about 12% and 14% of total energy respectively, while the embedded energy was split at 86% and 62%. In the case of the storage and the transport phases, the energy invested in non-grain crops was an order of magnitude higher than that of cereal grain. The discrepancy in storage energy arises from the sensitivity of non-grain crops to temperature and that in transport energy is primarily due to longer net transport distances of non-grain crops from Arizona. This is due to Arizona being one of the largest producer of many non-grain crops which are then exported to other states. This underscores the nature and purpose of agricultural production in Arizona. Another interesting result is that the embedded energy outweighs the sum of direct energy by production, transportation and storage phases. The amount of non-grain crops produced is greater than that of cereal grain, thus leading to a greater water consumption in the production phase.

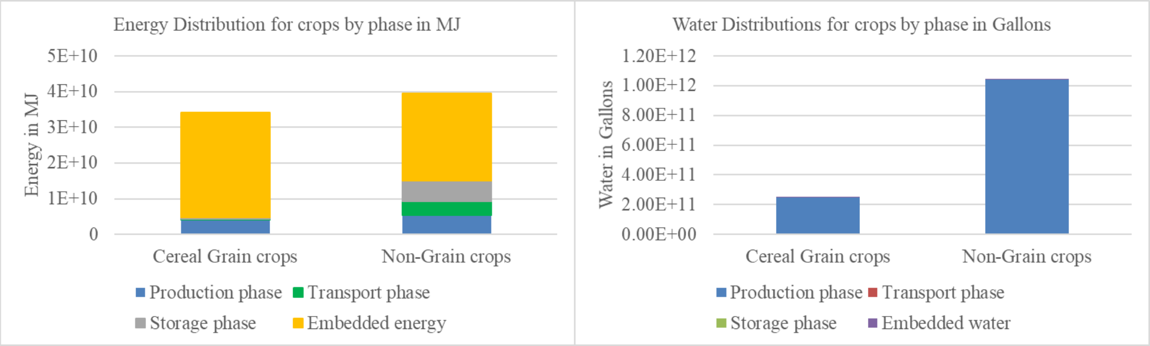


Figure 2.2: Energy and Water Consumption of All Crops. Energy Flow Is Represented in MJ While Water Flows Are Represented in Gallons.

Water consumption is concentrated in the production phase; while crop factors align to augment the water use of crops covering large area the general trend is that crops that cover a larger area tend to consume more water. Energy consumption, on the other hand depends on all three phases and hence the influence of land area on energy consumption is not as direct as in the case of water. This is highlighted in Figure 2.2. Corn is one example where it covers 14% of the land but contributes 36% to net energy consumption and 14% to net water consumption. On the other hand, Cotton covers 38% of the land area and consumes 45% of total water but contributes only 15% to energy consumption. This suggests that land area is not the only driver of energy consumption but is a major driver with regards to water consumption.

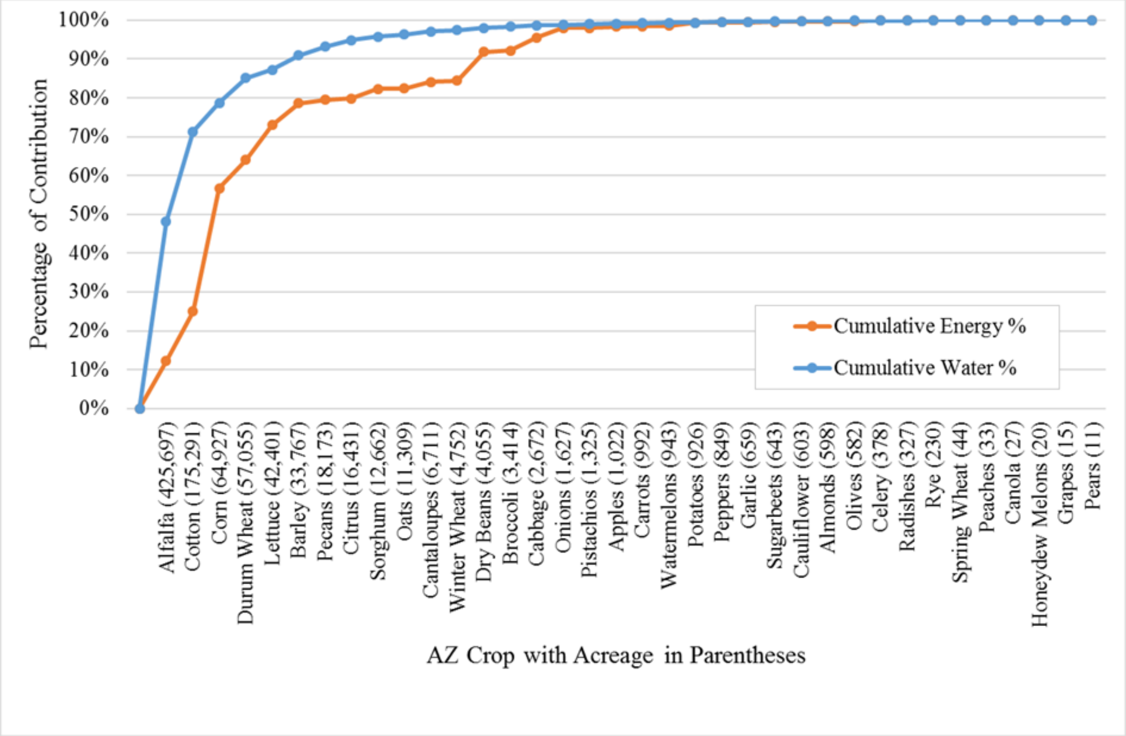


Figure 2.3: Contribution to Water and Energy Consumption by Crop. The Percentage Contribution to the Net Energy and Water Consumption of Various Crops Grown in Arizona in the Year 2014.

It is necessary to look at the efficiency of the crops to convert energy and water to bio matter as well as the efficiency of the processes involved with crop production, transport, and storage. It is important to remember that, while alfalfa is included in characterizing the nexus and the crop wise analysis there is data available to characterize its transport and storage phases.

As shown in Figure 2.3, some crops have relatively greater energy consumption compared to water consumption per acre cultivated. The top six crops by land area cultivated – alfalfa, cotton, corn, durum wheat, lettuce, and barley – occupy 90% of the agricultural land area and contribute to 79% of the energy consumption as well as about 90% of the total water consumption. A small number of crops account for most of Arizona's net water and energy consumption, raising questions about the efficacy of cultivating certain products and directing conservation strategies. Cotton accounts for 20% of the total agricultural land and is the second highest net consumer of water and second highest net consumer of energy while Corn occupies 14% of the total agricultural land and is the highest net consumer of energy and the third highest net consumer of water. These dominating shares show where conservation strategies can be directed, as discussed later.

The focus is on the FEW nexus, alfalfa and cotton has been excluded and the inter-system dependencies have been analyzed, as shown in Figure 2.4. Once Alfalfa and Cotton is removed from consideration, the energy and water use of non-grain crops drop significantly. The extent of resource use of alfalfa and cotton when we compare Figure 2.2 and2.3 is clear. Total energy use decreases by 0.5PJ while water use reduces by 230 billion gallon over one growing cycle.

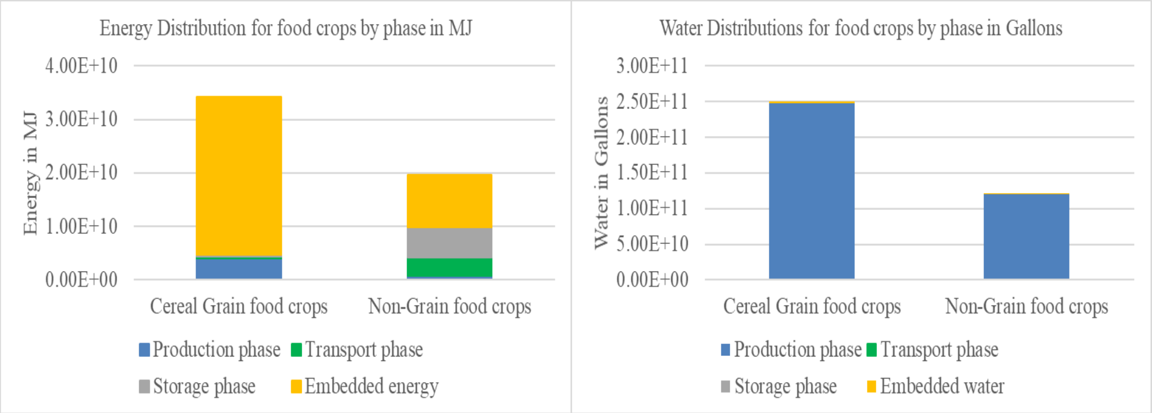


Figure 2.4: Energy and Water Consumption of Food Crops. Energy Flow Is Represented in MJ While Water Flows Are Represented in Gallons.

Food crop water and energy efficiency are calculated on a per kg basis, while some crops can be less efficient they have significant economic value. Normalizing by kg of crop highlights the energy efficiency and water efficiency of crop production, transport, and storage. Dry beans, at 1478 MJ/kg, clearly is the most energy intense in Arizona while the carrot is the least water efficient at 10593 Gal/kg. While these crops are resource intense, they also cover lesser area. Corn, lettuce, wheat, and barley are food crops that cover the most area, but have lower energy and water intensities compared to other crops. These food crops have an energy efficiency between 20 and 50 MJ/kg. The water efficiencies of these food crops fall between 190 and 1100 Gal/kg. These efficiencies can be improved by using conservation techniques and technologies to achieve energy and water savings. It makes sense to have low water consuming crops in the desert, but Arizona’s agriculture has an important role to play. Many industries depend on Arizona agriculture, and using data from 2011 it is estimated that Arizona’s economic agribusiness system contributes $7.3 billion in 2014 dollars to Arizona’s GDP. Agriculture is essential to the farmers and ranchers in Arizona who manage $18.1 billion in capital assets. Lettuce alone accounts for nearly 12% of Arizona’s agricultural value.

Given these economic benefits it is essential to maintain the productivity of agriculture but to manage water and energy – conservation strategies are necessary. Implementation of conservation technologies saves energy and water, and maintains Arizona's agricultural productivity at its current level.

2.4 Conservation Strategies

With an understanding of the dependencies of agriculture on the water and energy sectors, conservation strategies should be examined across the nexus. The strategies selected are those where significant energy and water use were identified in the life-cycle. In the production phase the largest contributors to energy and water consumption are farm equipment use, irrigation, fertilizer use. Similarly, the largest energy consumers in the transportation and storage phases are truck transport and refrigeration. As such, strategies were identified and assessed for each of these life-cycle processes:

- No tillage strategy as part of conservation tillage to reduce on farm equipment use;
- Improving water application efficiency through irrigation technologies such as Low Elevation Precision Application, Low Energy Spray Application, Sub-surface drip irrigation;
- Replacing fertilizer with manure to meet nutrient requirements;
- Improving fuel economy of trucks to reduce fuel consumption in transportation; and,

- Improving the efficiency of storage facilities by shifting to lower energy use refrigeration.

Conservation Tillage - No Tillage

The No Tillage strategy avoids land preparation activities, thus saving fuel. The soil is left undisturbed from harvest to planting except for planting strips. Machinery used to plow and level the land are avoided, thus fuel requirements are reduced. To estimate the fuel that is saved, the crop budgets dataset is used. It is assumed that all the machinery is similar with respect to the fuel consumed per unit time and hence total diesel fuel consumed is temporally distributed to all the processes involved with cultivation. The fuel allocated to the land preparation activities is then reduced to zero. There have been multiple studies that have looked at the conservation potential of this strategy for various cereal grain crops and there is very little work done for vegetable crops. Hence the strategy is implemented only for cereal grains. Some studies also say that there is water conservation potential for this strategy but that has not been implemented here. There has also been evidence of increased herbicide use for some crops since the husks from the previous harvest tend to act as weeds. This herbicide use has not been accounted for either since there are no data available on the rate of increase.

Irrigation Efficiency Strategies

Water delivery requires pumping energy, but recent energy efficient technologies have been developed. According to the USGS the most common type of irrigation is flood irrigation though other technologies are being adopted. Irrigation is a method by which water is delivered to crops at regular intervals in areas where water access is an issue, to assist their growth. We consider Subsurface Drip Irrigation (SDI), Low Energy Precision

Application (LEPA) and Low Energy Spray Application (LESA). These are considered efficient irrigation technologies. Efficient irrigation technologies reduce the evaporation of water supplied to crops. SDI is a system where water is applied directly to the crop's root zone. Both LEPA and LESA applies water at reduced pressure in a precise manner. These systems also have some water savings due to higher application efficiency and energy savings since they operate at lower pressure.

The net water savings are estimated using the irrigation efficiency of SDI, LEPA and LESA. Irrigation efficiency is expressed as the product of conveyance efficiency and the application efficiency. The entire CAP canal is lined with concrete and hence the conveyance efficiency is about 95% and the application efficiency of SDI, LEPA and LESA are 90%, 95% and 93% respectively. The net irrigation efficiency for SDI, LEPA and LESA are 85.5%, 90.25% and 88.35% respectively. A similar methodology is used for flood irrigation estimating its efficiency at 69.35%. In Arizona, between 72% and 89% of the irrigated land uses flood irrigation techniques along with other sprinkler technologies. It is estimated that the energy consumed to provide water through these technologies amount to 0.056 kwh/m^3. Arizona agriculture uses 4.4 acre-feet of water per acre of crop. If all the lands are converted to LEPA, LESA and SDI this would reduce to 3.38, 3.45 and 3.57 acre-feet of water per acre of crop respectively. These irrigation systems also consume less energy that the typical water distribution system in Arizona. Based on existing studies[2] it is estimated that LEPA, LESA and SDI systems consume 0.05, 0.05 and 0.17 kwh/ m^3 of energy.

Replace Fertilizer with Manure

Manure is readily available as a byproduct of the beef and dairy industry in Arizona. Fertilizer is replaced with manure based on the nutrient content. Manure from both beef and dairy cows has different amounts of Nitrogen, Phosphorous oxide, and Potassium oxide. An average nutrient value is calculated using an equal mix of dairy and beef cow manure. This results in the mixed manure containing about 2.55lb/ton of N, 2.1 lb/ton of P and 5.85 lb/ton of K. The total amount of N, P and K type fertilizers is obtained from the crop budgets and a mix is picked where at least half of the nitrogen and phosphorous nutrient requirement is satisfied by manure. This approach also meets the entire need of the K type fertilizer in Arizona. Thus, the energy through the N and P type fertilizers are halved and the energy through the K type fertilizer is eliminated.

Improving fuel efficiency of Trucks

Proposed fuel economy standards can reduce transportation energy use in the FEW nexus. A study conducted by the Union of Concerned Scientist estimated that the fuel efficiency of long haul trucks could increase from 5.8 mpg to 10.7 mpg with an advanced engine and transmission, new axle design, and improved aerodynamics. This 46% improvement is used to estimate energy savings.

Improving Storage Facility efficiency

The storage phase accounts for nearly 24% of the energy used but less than 0.1% of the total water used. Non-grain crops are the primary contributors to storage energy use since they are more sensitive to temperature and moisture conditions. The current method of storage is assumed to be industrial refrigeration. There are opportunities to improve refrigeration plants using retrofit technologies as well as refrigeration technologies.

Hence improvements in both are modeled. A 17.6% energy saving can be achieved by installing variable pressure controls, temperature and fan controls, among others when compared to the standard refrigeration plant currently designed. The major areas of improvements that were considered under the study were pressure control, compressor staging, plant design, control logic for plant operation and defrost management. This percentage improvement is applied to the baseline model.

2.5 Impact of Conservation Strategies

Regardless of whether the conservation strategy is targeting water or energy, savings are produced across both water and energy due to the nexus. Each strategy impacts the nexus differently. LEPA has the most water savings and energy savings at 29%. Conservation tillage can be applied to only field crops such as wheat, sorghum, and corn. Hence, they have reduced fuel use leading to only a 3.1% reduction in energy consumed compared to the base case. It is essential to consider the combination of crops that are cultivated during the year for this strategy to influence the nexus. One of the key findings with regards to the irrigation strategies is that energy is not always conserved along with water. While the SDI, LEPA and LESA systems do reduce water consumption through evaporation reduction, they consume more energy than the flood irrigation system. Flood irrigation systems are gravity fed and hence consumes almost no on field energy. However, in the case of LEPA and LESA the water savings incurred is so high that there is net energy savings due to embedded energy in water. The energy required to pump water is so high in SDI systems that the energy consumed is almost the same as the baseline case. Hence LEPA and LESA technologies would have the greatest impact, from a resource conservation perspective.

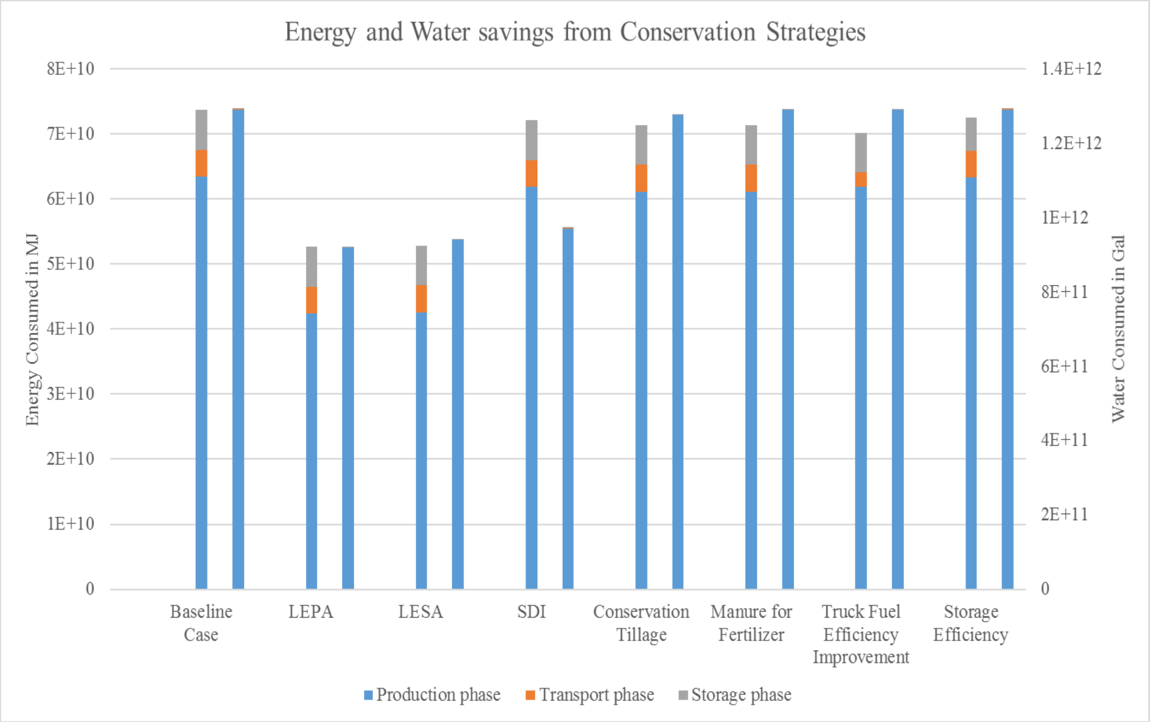


Figure 2.5: Energy and Water Consumption by Phase. The First Bar Highlights the Energy Consumed and the Second Bar Highlights the Water Consumed. The Bars Represented in This Graph Is an Aggregate of Production, Transport and Storage Energy and Water for All Crops Cultivated in Arizona in 2014. The Production Phase Contributes the Most to Energy Consumption Across the Various Strategies. Though Storage and Transportation Are Relatively Smaller They Still Have Considerable Contribution and Need to Be Targeted for Energy Conservation. Water Consumption Is Concentrated in the Production Phase and the Water to Transport and Storage Water Is Only Through Water Embedded in Energy and Hence Are Small.

Comparing the results from Figure 2.5, energy conservation strategies from the transport and storage phases have a greater impact on the entire system when compared to water conservation strategies. The reason for this goes back to the highly-distributed nature of energy as shown in Figure 2.2. The high concentration of water in the production phase makes it easier to achieve direct water conservation through irrigation technologies but to achieve similar conservation results with direct energy, multiple energy conservation strategies may need to be applied simultaneously. Another outcome is the large variation between strategies is primarily due to the production phase, which further highlights the need for effective strategies to address this phase. This comparative result between different strategies addressing different components of an agricultural system highlights the trade-offs that exist and would help select a conservation strategy as well as understand its implications.

There are economic, temporal, aesthetic problems with the implementation of the technologies discussed above. The conservation strategy section exclusively discusses the extent of impact of the adoption of various technologies, but it is essential to explore the likelihood of adoption of these technologies. Reduction in use of resources are cost saving measures but it also requires considerable change in the existing setup. The biggest barrier to implementation of these technologies are upfront costs. Implementation of the LEPA, LESA and SDI systems are a very good example. While traditional flood irrigation mechanism does not involve any irrigation equipment cost, there are installation and operational costs associated with the suggested technologies. The fixed and variable costs of the LESA, LEPA and SDI systems add up to \$13.60, \$13.76 and \$17.04 per acre-inch of water respectively. The storage efficiency strategy suffers from similar cost challenges since technology, though efficient is also expensive. There are also temporal barriers to the adoption of a strategies due to the limits of technology. The best example among the strategies is the EPA Truck standards. It is estimated that about 10.6 million trucks were operated in the US in 2013 and the average age of the trucks was about 11.5 years. Heavy duty trucks can last between 25 to 30 years on the road before they are scrapped. It is expected to take about 20 years to replace the entire fleet of trucks and this time period presents political challenges since policies are bound to change with changing administrations. Conservation tillage suffers from the view point of resource use. The technique has been tested only for grain and not for other agricultural produce. Since the stalk from the previous cycle are left over there is also an increase in pesticide use as these stalk act as weeds. The extent of pesticide use is erratic, and hence could potentially add to the cost of production. The aesthetic problems arise in the manure strategy, while it is a natural fertilizer there are odor issues. The odor can travel far and wide and will cause discomfort in the various urban regions, especially near the urban-exurban boundary of cities in Arizona.

2.6 Conclusion

The impacts of the energy and water system on the food system is important since there are economic, security and environmental impacts associated with it. Any changes to the water and energy system will propagate to the food system. This can have economic impact to the farmers in Arizona as this affects the ability to produce crop. While this study focuses on establishing the reliance of the agricultural system on the energy and water system, future studies can analyze the relative changes that the agricultural system would undergo if there are changes to components in the energy and water system. This directly would address the growing food security concerns as productivity of crops would change. Also, climate change has proven to be a deterrent to infrastructure as well as crop productivity. Understanding the FEW nexus would help build policy and even implement technology to counteract some of the risks that arise due to the vulnerabilities in the FEW system.

A change in the various factors within the system boundary will influence the results of any model. If FEW nexus study components such as the electricity and fuel mix change then the amount of energy and water input into the food system will change. Another impact of changing fuel-electricity composition is the effect on the energy and water efficiency metrics that were estimated. This presents opportunities, from an environmental perspective, to make the production, transport and storage of crops less impactful. A major hurdle in estimation of the FEW nexus is in the transportation phase, where the international export of agricultural produce from Arizona was excluded. This was primarily due to the lack of information about the various transportation modes of international trade for food. When data is available an expansion of the system boundary to include this international trade would more accurately depict the energy and water consumption of agriculture. Another aspect in the transportation phase is that of trade between states. There is little to no data on specific trade numbers between states, and the availability of this data would far improve the result of this static model. These are some issues within the system boundary that have the potential to make the model result more accurate provided availability of primary data. These are some of the typical conclusions and analysis that can be done by building a model that represents the FEW nexus. The quantification of the FEW nexus allows us to measure the feasibility of strategies. This approach helps build and implement policies that could have positive impacts on the environment and livelihoods.

There is an ideal solution to improve efficiency to the maximum but there are certain strategies that will not work alongside each other. The ideals setup would be where the LEPA/LESA irrigation system is implemented and manure is used as fertilizer thus leading to water and energy savings in the production phase; the truck standards have been adopted completely and hence leads to energy savings in the transport phase; the storage efficiency technologies are implemented to improve energy savings in the storage phase. If they above mentioned strategies are implemented, then there would be a 16% cumulative decrease in energy use and 27% cumulative decrease in water use. But considering the costs of these transitions would make it too expensive for agriculture. But this would require a coordinated effort between policy makers and industry leaders with the agricultural supply chain in mind. This level of coordination has never been achieved and is highly unlikely. Hence starting with localized mechanisms to install LEPA/LESA at specific farms would be ideal for effective resources management as well as cost management. Climate introduces another large uncertainty into the food productivity of the region. There are a few cases where productivity drops by 50%, in which case complete transformation of the food system is necessary in Arizona. County level decision making is essential since there are considerable variability in productivity. It is also essential in terms of conservation strategies since these technologies are expensive.

CHAPTER 3 CONSERVATION NEXUS: CLIMATE VARIANCE AND THE FEW NEXUS

3.1 Introduction

Climate plays an important role in food production as well as food preservation. Crops are very sensitive to temperature changes and it directly impacts crop growth. Climate change literature has covered the impact that changing temperatures has on crop productivity (Challinor, et al., 2014; Luo, 2011). Literature suggests that increasing temperatures decrease the yield of a crop after a threshold value . There exist global studies that examine crop productivity changes on a spatial manner , accounting for the variability in temperature changes. But an important aspect of temperature variance is that the change in temperature is not constant across a region. Thus, crop productivity does not always decrease. This trend creates uncertainties with regard to resource management. Decrease in productivity triggers more intense management practices since climate effects crop water demand, but an increase in productivity may allow less water use. Thus, water intensity of crops, as estimated in Chapter 1, are not constant and can vary due to many factors including climate change (specifically temperature rise and/or precipitation changes) and conservation practices. Fear of droughts has sparked the need for irrigation strategies leading to the use of sprinklers and drip systems in Arizona and would create a market for more expensive but more efficient systems . An important aspect of adoption of these high efficiency systems such as low energy precision application (LEPA) and low elevation spray application (LESA) is the scale of adoption. Given the cost of these technologies, it is essential to recognize the scale at which decisions on technology adoption need to be made. Thus, there is a two-part question that needs to be addressed for Arizona.

What is the extent of crop productivity change in Arizona due to spatial variability in temperature? What is the extent of water use and at what scale is best for effective water management strategies given these productivity changes?

The hypothesis going into the chapter is that there is considerable variation in productivity which creates the need for decision making at a scale smaller than the state level. The energy and water use of crops under these varying conditions of climate can be accurately estimated. In order to assess crop productivity changes, Cropsyst is used. Cropsyst is a software which uses established equations to model crop growth. Wheat, barley, corn, and sorghum are the crops that are assessed. These crops were chosen because, Chapter 1 results indicate that these food crops consume more than 60% of the state's irrigation water.

3.2 Cropsyst: An Overview

Cropsyst is an analytical tool that simulates crop system productivity. It is a model that can operate over multiple years and multiple crops at a daily scale . The model simulates crop growth over a plot with uniform soil, weather, crop rotation and management. There are multiple modules that accept specific inputs like weather and management practices that account for different aspects of crop growth like water, nitrogen, temperature, biomass accumulation, leaf area development, root growth, and yield . A review of the various models in Cropsyst is provided based on the model description in Stockle, Donatelli, & Nelson (2003).

Water & Nitrogen Model

There are multiple components included in the Cropsyst water budget model including precipitation, evapotranspiration, deep percolation, water redistribution in soil, and runoff. Crop evapotranspiration (Et) is a key component as this is the amount of water required by the plant. The evapotranspiration of a crop is determined as the product reference evapotranspiration rate (Et_0) and the crop factor. Et_0 is weather specific and is estimated in Cropsyst through using either the Penman-Monteith model or the Priestley-Taylor model . As shown in equation 2, the Penman-Monteith method estimates Et_0 using maximum and minimum temperature, solar radiation, maximum and minimum relative humidity, and wind speed. On the other hand, the Priestly-Taylor method estimates Et_0 using only temperature, radiation and the appropriate Priestly-Taylor Constant value.

Nitrogen is a key nutrient for crops and needs to be available in the form that can be absorbed by crops . Hence nitrogen undergoes transformations such as net mineralization, nitrification, and denitrification. Ammonia also gets attached to the soil through a phenomenon called ammonia sorption, while nitrogen is made available for crops through a mutualistic relationship called symbiotic N fixation where bacteria in the soil provide the nitrogen in exchange for carbon. These interactions have been modeled in pre-existing works and have been adopted into the Cropsyst nitrogen model. Crop N uptake is modeled in Cropsyst as the minimum between crop nitrogen demand and potential nitrogen uptake. This combination of the water and the nitrogen model simulate the nitrogen transport through the soil.

Crop Phenology and Biomass accumulation

Crop development is the process of accumulation of biomass as the crop progresses from the germination phase to the maturity phase. This is simulated based on thermal time. Thermal time is the daily accumulation of average air temperature, but it is essential that this air temperature is between a base temperature and a cutoff temperature. The base temperature and the cutoff temperature are specific, as well as critical, to each growth phase. As the crop grows, biomass accumulates, and the core of this crop growth simulation is crop transpiration and crop intercepted photosynthetically active radiation (PAR). The growth, and hence biomass, is then corrected based on water and nitrogen limitations, if any. The crop potential transpiration dependent biomass production (B_{PT} in kg.m^{-2}.day^{-1}) is calculated as,

$$B_{PT} = \frac{K_{BT}T_P}{VPD} \qquad (1)$$

where T_P is crop potential transpiration (kg.m^{-2}.day^{-1}) and VPD is the daytime mean atmospheric vapor pressure (kPa) and K_{BT} is a biomass-transpiration coefficient (kPa). Equation 3 becomes unstable when VPD is low, in which case the intercepted PAR-dependent biomass production (B_{IPAR} in kg.m^{-2}.day^{-1}) is estimated as ,

$$B_{IPAR} = e.IPAR \qquad (2)$$

where e is radiation-use efficiency (kg.Mj^{-1}) whose value can be found in the biomass literature, and IPAR is the crop intercepted photosynthetically active radiation (Mj.m^{-2}.day^{-1}). An issue with (4) is that temperature limitations during early growth is not included. This issue is corrected in Cropsyst by the inclusion of a temperature limitation factor, which is assumed to increase linearly from 0 to 1 as air temperature fluctuates from base temperature for development to optimum temperature for early growth. As shown in Figure 3.1, the potential biomass (B_P) for each simulation day is determined as the minimum of B_{PT} and B_{IPAR} which is then used to determine actual biomass which is estimated after nitrogen and water limitations are applied.

The water limitation is determined by estimating the effect of nitrogen deficiency on crop transpiration. Increasing canopy resistance (r_{cNS}) accounts for this effect and is calculated as,

$$r_{cNS} = \frac{r_c}{1-\frac{N_{crit}-N_c}{N_{crit}-N_{min}}} \tag{3}$$

where r_c is canopy resistance, N_c is the current plant N concentration, N_{max} is maximum attainable plant N concentration, N_{crit} is the critical plant N concentration below which biomass growth is reduced, and N_{min} is minimum plant N concentration. r_c remains constant when unstressed bu9t increases when N concentration is between N_{crit} and N_{min}.

N-limited crop transpiration (T_N) is estimated as a response to changes in r_c.

$$T_N = \frac{T_P+\gamma(1+\frac{r_c}{r_a})}{\Delta+\gamma(1+\frac{r_{cNS}}{r_a})}$$

(4)

where Δ is the slope of the saturation vapor pressure function of temperature (kPa C^{-1}), γ is the psychrometric constant (kPa C^{-1}), and r_a is aerodynamic resistance to vapor transfer (day m^{-1}). Transpiration limited biomass (B_T in kg.m^{-2}.day^{-1}) is then estimated using the potential biomass (B_P), actual crop transpiration (T_A), and nitrogen limited transpiration.

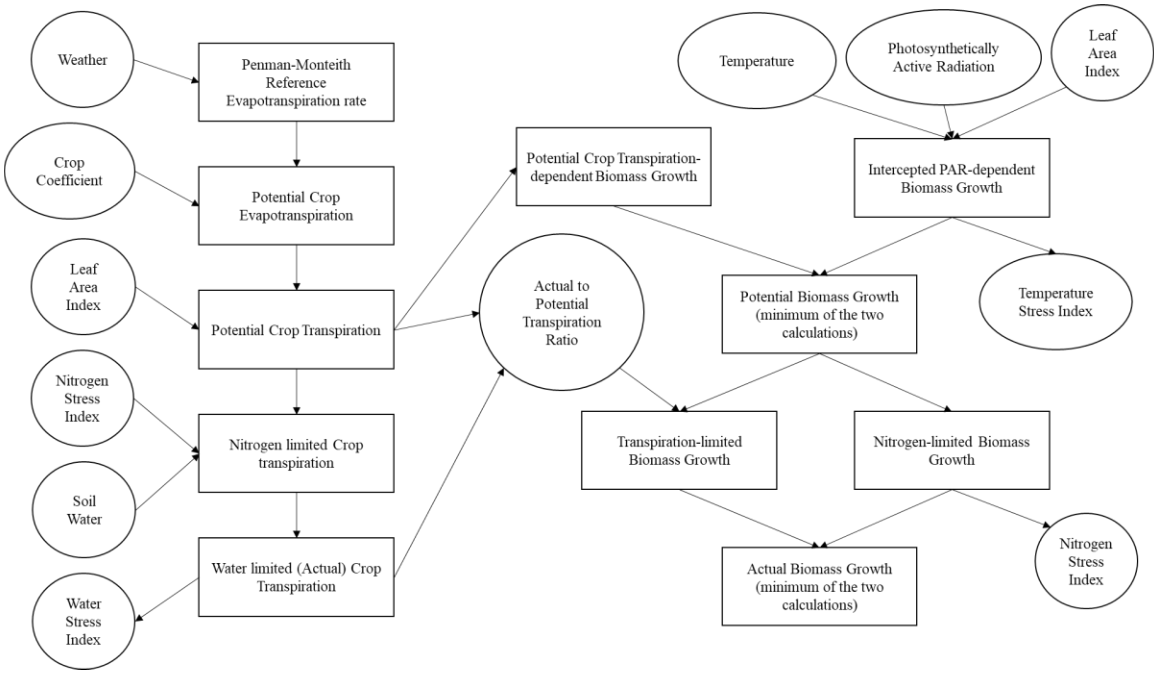


Figure 3.1: Biomass Accumulation Simulation. The Flow Chart of Biomass Growth Calculations in Cropsyst As Presented in Stockle, Donatelli & Nelson (2003).

$$B_T = B_P \frac{T_A}{T_P} \tag{5}$$

T_A is the total water uptake(U_T) .

$$U_T = \sum_{i=1}^{n} K_t \frac{C_{ri}}{1.5} (\Psi_{si} - \overline{\Psi}_l) \tag{6}$$

where K_t is a unit conversion coefficient (s.day^{-1}),C_{ri} is the root conductance for the soil layer I (kg s m^{-4}), Ψ_{si} is the soil layer water potential (Jkg^{-1} equivalent to m^2 s^{-2}), and $\overline{\Psi_l}$ is the canopy average leaf water potential(Jkg^{-1}). Stockle and Jara (1988) go into more detail in the calculations of the water potentials and the root conductance. Similarly, nitrogen limited biomass (B_N in kg.m^{-2}.day^{-1}) is estimated as

$$B_N = B_T \frac{r_c}{r_{cNS}} \tag{7}$$

The actual biomass growth is then determined as the minimum between B_T and B_N.

Leaf Area Index, Root development, and Yield

Leaf area index (LAI) is the leaf area per unit soil area and is calculated as a function of biomass.

$$LAI = \frac{SLA.B}{1+pB} \tag{8}$$

where B is the above ground biomass, SLA is the specific leaf area, and p is the partition coefficient that controls the portion of biomass appropriated to leaves. Root growth is described through root depth and root density. Root depth value and LCAI are synchronous until it root density starts at 0 near the end of the root and increases as we go up to the soil surface. Yield is another factor that is estimated from accumulated biomass using a factor called the harvest index (HI).

$$Y = B.HI \tag{9}$$

The harvest index for the given conditions is estimated using the unstressed harvest index modified according to water and nitrogen stress intensities.

3.3 Methodology

The methodology primarily revolves around data preparation for Cropsyst. The goal of the climate study is to estimate the change in productivity and the identify if a state strategy is possible to conserve water. Cropsyst is a software with climate, soil, crop, and management input requirements. These inputs need to be prepared in a format specific to Cropsyst for the simulation of each scenario.

Crop Locations

Crop locations, spatially explicit weather and crop specific management practices are the three major inputs that are prepared for Cropsyst. Barley, corn, sorghum, and wheat are the crops chosen for this analysis due to their large energy and water footprint, as well as data unavailability of other crops. CropScape is used to determine the spatial extent of the crops. CropScape uses remote sensing to determine locations of various crops. This image data is then converted to a shapefile for easier processing. The creates slivers in the shapefile, that are not farmlands. In order to remove these slivers and other spatial inaccuracies, an area restriction is applied to the CropScape shapefile. Only polygons that cover an area greater than 2.5 acres have been selected leading to a selection of 90% of the cultivated land across the four crops. The density of crop locations after the spatial data was cleaned is shown in Figure 3.2. This map accounts for 87% of lands growing barley, 95% of lands growing corn, 83% of lands growing sorghum, and 88% of lands growing wheat.

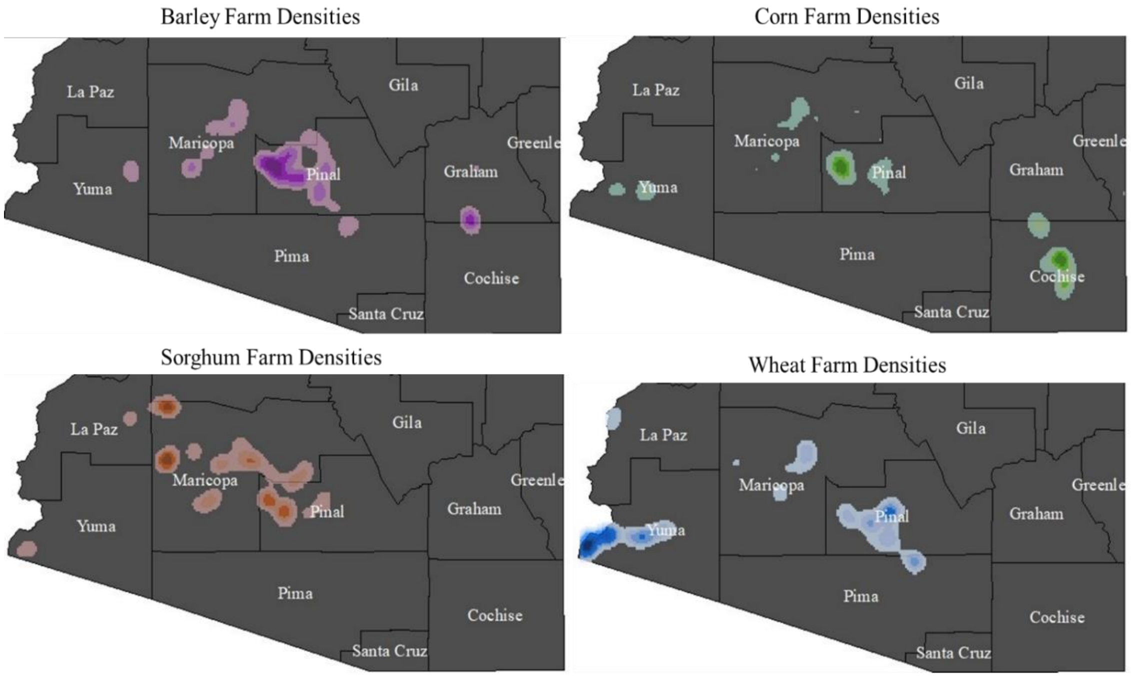


Figure 3.2: Arizona Crop Distribution. Map Developed From USDA's CropScape Data Highlighting the Locations of Barley, Corn, Wheat and Sorghum Cultivation.

Climate Inputs

It is clear from Figure 3.2 that the 4 crops are mostly grown in the southern part of Arizona, as is most of Arizona's agriculture. Barley, corn, sorghum, and wheat cultivation is primarily spread across nine counties – Cochise, Graham, Greenlee, La Paz, Maricopa, Pima, Pinal, Santa Cruz, and Yuma. Hence, the focus is on these counties and the spatial location of these farms to obtain weather data. In order to determine the spatial locations, we identify the centroids of the farm polygons using ArcGIS. Based on the extent of all the centroids, the gridded climate data set is obtained for 2013-14, 2030-31, 2050-51. The weather datasets are obtained from a database at University of Washington, Pullman. One weather dataset describes the observed weather through 2013 and 2014. That data set is obtained from gridMET, a daily weather dataset with a 4 km spatial resolution. This data set is a model prediction of past data and has been proven to have high accuracy rates with regards to climate. The second dataset consists of future weather for the years 2030-31 and 2050-51 that is queried from the REACCH database. The REACCH database is part of the REACCH project which was setup in 2011 and funded through the National Institute of Food and Agriculture's Climate Variability and Change Program. It was developed by an interdisciplinary team of researchers from the USDA, University of Idaho, Oregon State University, and Washington State University (WSU). The team at WSU has written a program that uses the REST service API that matches the climate grids (4km x 4km) that is nearest to the centroids generated for the farm polygons. 226 weather points are identified across the spatial extent of these farms and the data for these are obtained for the baseline years as well as the future years.

Scenario Development

In order to determine the feasibility of a state level irrigation strategy, the simulation would be run across these 226 grid points for each of the 4 crops and for each of the 5 climate scenarios (baseline 2013-14, RCP 4.5 2030-31 across 13 GCMs, RCP 4.5 2050-51 across 13 GCMs, RCP 8.5 2030-30 across 13 GCMs, and RCP 8.5 2050-51 across 13 GCMs). Using these 226 grid points would provide better perspective on variability in crop productivity, but there is 83 day run time associated with this simulation. Hence the county scale is selected for the analysis. The number of climate conditions considered for each county is reduced to the 5 that correspond to the average temperature for each county across the baseline 2013-14, RCP 4.5 2030-31, RCP 8.5 2030-31, RCP 4.5 2050-51, and RCP 8.5 2050-51 conditions. The 226 points are segregated based on the county that they are located in. The average county weather is estimated by accumulating the daily weather conditions across all points in each county. The average daily weather of each county under the RCP 4.5 and 8.5 conditions are shown in Figure 3.3. The average variation in temperature across these counties is close to 10 ^{0}C.

Currently the authors of Cropsyst have not provided a tool to convert custom weather data to Cropsyst readable formats. Hence one location needs to be identified as the representative for that county. The identification process is carried out in R. From all the points within a county, one point with most similar daily maximum and minimum temperature values to that of the average daily maximum and minimum temperature values of the county is identified. As such, the weather pattern of the representative point is used for the crop growth simulation.

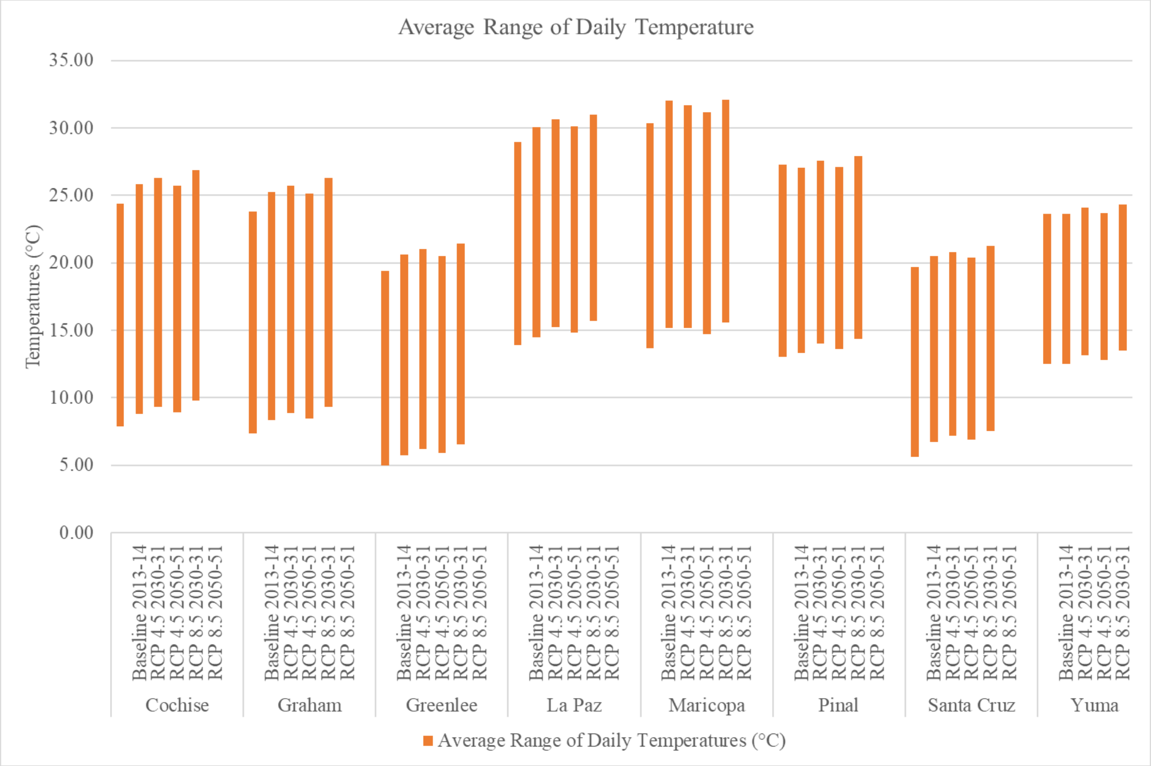


Figure 3.3: Average Daily Temperature Ranges for the Different Counties That Grow Barley, Corn, Cotton, and Sorghum.

Barley, corn, sorghum, and wheat do not grow in every one of the nine counties, and this setup is used to reduce the number of scenarios. ArcGIS is used to conduct a spatial analysis to identify the crops that grow in each county, as shown in the table below.

These crops are grown on different soil types in each county. To simplify the analysis, the most commonly used crop type is identified for each crop in each county. The crop layer is overlaid with the soil layer in ArcGIS. The soil dataset is obtained from Soil Survey Geographic Database. This procedure assigns crops to their respective counties while identifying one soil type commonly used to grow the crop in the corresponding county.

Table 3.1: Crops Across Counties. The Table Highlights the Crops That Are Grown Across All the Counties.

	Barley	Corn	Sorghum	Wheat
Cochise	X	X		X
Graham	X	X		X
Greenlee	X	X		X
La Paz	X	X	X	X
Maricopa	X	X	X	X
Pima	X	X		X
Pinal	X	X	X	X
Santa Cruz	X	X		
Yuma	X	X	X	X

It is critical to notice that the average future temperatures of Pima have not been included. The average baseline temperatures are lower by 10^0C. This is primarily due to the limitations of the data processing. The process of retrieval and conversion to the required format has introduced unusable climate results for Pima even after multiple attempts. Due to this drastic change in temperature, Pima have been excluded from the analysis to avoid skewed results. Moreover, Pima has less than 5% of barley producing lands, less than 2% of corn producing lands, less than 15% of the wheat producing lands. From a resource perspective, the resource impact of crop cultivation from Pima is small. Using these two approaches, the number of scenarios is reduced to 150 and the total run time is reduced to 60 minutes.

Management practices are another major input to Cropsyst since it defines the level of irrigation water provided, the amount of fertilizer used, as well as on-farm practices. The fertilizer requirements and the farmland preparation processes are obtained from the Crop budgets. The crop water demand is estimated using the Pennman-Monteith method used in Chapter 1. The crop water demand clearly depends on the climate. Thus, the baseline evapotranspiration rates as well as the evapotranspiration rate for the future cases are determined using the average county climate, as shown in Table 3.2.

Table 3.2: Evapotranspiration Rates. Each Climate Conditions Generates a Unique Reference Evapotranspiration Rate. The Table Shows the Evapotranspiration Rates for the Average Climate Across Each Case.

County	Crop	Baseline Et(mm)	RCP 4.5 Et (mm)		RCP 8.5 Et (mm)	
		2013-14	2030-31	2050-51	2030-31	2050-51
Cochise	Barley	4.89	5.33	5.35	5.23	5.45

	Corn	5.06	5.51	5.53	5.41	5.63
	Wheat	5.00	5.45	5.47	5.35	5.57
Graham	Barley	4.93	5.19	5.25	5.12	5.34
	Corn	5.10	5.37	5.43	5.30	5.52
	Wheat	5.04	5.31	5.37	5.24	5.46
Greenlee	Barley	4.16	4.30	4.36	4.26	4.38
	Corn	4.30	4.45	4.50	4.40	4.53
	Wheat	4.26	4.40	4.46	4.36	4.48
LaPaz	Barley	5.88	6.09	6.19	6.08	6.20
	Corn	6.08	6.30	6.40	6.29	6.41
	Sorghum	5.68	5.88	5.98	5.87	5.98
	Wheat	6.01	6.23	6.33	6.22	6.34
Maricopa	Barley	5.92	6.12	6.25	6.13	6.27
	Corn	6.12	6.33	6.46	6.34	6.48
	Sorghum	5.72	5.92	6.04	5.92	6.05
	Wheat	6.06	6.26	6.39	6.27	6.41
Pinal	Barley	4.88	5.59	5.69	5.58	5.70
	Corn	5.04	5.78	5.89	5.77	5.90
	Sorghum	4.71	5.40	5.50	5.39	5.51

	Wheat	4.99	5.72	5.82	5.71	5.83
SantaCruz	Barley	4.36	4.52	4.60	4.49	4.64
	Corn	4.50	4.68	4.76	4.64	4.80
Yuma	Barley	4.71	4.74	4.82	4.75	4.82
	Corn	4.87	4.90	4.99	4.91	4.99
	Sorghum	4.55	4.58	4.66	4.59	4.66
	Wheat	4.82	4.85	4.93	4.86	4.93

To assess crop productivity, we use the above ground biomass value that is generated by Cropsyst. Even though Cropsyst generates an internal Harvest Index (HI) for these crops, the HI can vary significantly for the same crop based not just on climatic conditions but also genetic modifications.

Cropsyst is currently incapable of recognizing irrigation technologies as it processes only crop water demand. Hence the irrigation technologies are modeled separately to assess their effectiveness. LEPA/LESA were identified as the most efficient technologies in Chapter 1. The impact of these technologies was estimated by identifying the water supply required. The water supply required is a scaled version of the crop water demand so that the application efficiency of these technologies have been accounted for. The embedded energy associated with the water supply required is also estimated by using the energy required by these technologies to apply water to the crops. Finally, the cost associated with implementation of LEPA/LESA were estimated.

In order to test the hypothesis that a state level strategy to address climate effects is not possible, the dynamics between crop productivity, temperature change, and change in water availability is studied. Cropsyst scenarios are generated under two broad themes – one where the same evapotranspiration rate water is provided to the future climate scenarios as the baseline case and the other where new evapotranspiration rate is estimated for each of the climate scenarios. The difference in biomass accumulation amounts estimated using the baseline climate, the future climates with baseline water levels, and the future climates with corresponding water levels would provide insight on the relationship between crop productivity change, temperature change and change in water availability. Once the scenarios are generated for all the counties, the responses are accumulated by the crop to identify potential state level crop response trends. If the hypothesis is true, this will yield no definable relationships. This would mean that adoption of conservation strategies would need to be considered on a case by case basis at least at the county level.

3.4 Results

Impacts of Temperature and Water Availability on crop productivity

As expected, there is considerable variation in the productivity of crop across Arizona. The biomass output from growth in each RCP for each time period is compared to the baseline time period of 2013-14. The spatial variability of productivity when temperature changes, and when both temperature and water supplied changes is captured in Figure 3.4. As suggested by the quartile limits, a few cases of increasing productivity can be expected among largely decreasing productivity trends. Under most climate change scenarios, the mean variance in crop productivity is expected to be negative suggesting that crop productivity will reduce into the future. The few exceptions are corn and wheat in 2030. These two cases also present the most variability with regards to crop production. The surprising outcome is the lack of response to increasing water supply. Increasing water supply to meet new crop water demand leads to only marginal increases in productivity in some crops and not in others. This clearly highlights the extent at which temperature influences crop productivity.

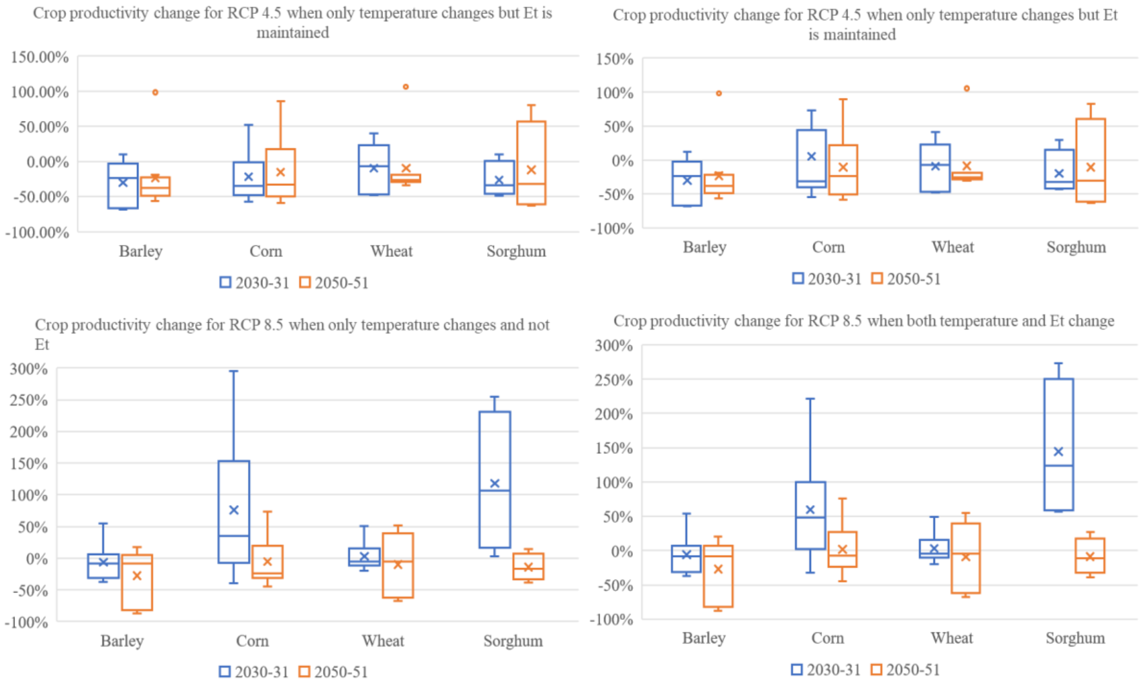


Figure 3.4: Variance in Crop Productivity. The Spatial Variance in Crop Productivity Across the 9 Counties Is Shown for the Different Climate Scenarios. The Two Graphs on the Left Is the Variance in Crop Productivity When Et Is the Same as That of 2013-14, and the Two Graphs on the Right Is the Variance in Crop Productivity When Et Is Estimated Based on the New Climate Conditions.

In order to manage water use around the loss in productivity, policy action and adoption of high efficiency technologies are necessary. State level trends in change in productivity are necessary to justify a state level response. The relationship between the change in productivity when both temperature and irrigation water availability changes simultaneously was plotted in an attempt to establish a multivariable function of the form

$$\Delta Productivity \ \propto F(\Delta temperature, \Delta irrigation\ water\ available)$$

Using the Curve fitting tool in MATLAB, a sixth-degree relationship was generated where the model had 26 coefficients and a R-squared value of > 75% (best case scenarios) for all the crops. But this model fails to have significance, especially in the case of barley, corn, and sorghum, as many of the coefficients fell outside the 95% confidence levels. The model also had very high (>2500) Sum of Squared Errors (SSE) as well as high (>25) Root Mean Squared Errors (RMSE) for these crops thus invalidating the relationship. The model performed best in the case of wheat with a R-squared value of 99% but with an SSE of 147 and a RMSE of 5. The multi-variable model's limitation confirms the suspicion that crop growth is a complex process that depends on not just temperature and water but other factors such as soil and nutrients. It is clear that the crop response to temperature variations are not consistent. Assuming generic future crop productivity response to temperature change at the state level is redundant. This makes planning state-level resource management strategies into the future difficult. Temperature and water availability do have considerable influences on productivity, but local decision-making capacity based on case specific analysis is necessary for effective resource management and crop production.

Enabling decision making on resource management through conservation strategies at the county level

Crops at every location respond differently to additional water available and the lack of trends in these responses necessitates the needs for county level decision making with regards to water management. It is important to remember that the additional water is made available to meet the evapotranspiration rates of the crops under the new climate conditions. Any additional water above the evapotranspiration rate will not be absorbed by the crops and will be wasted either as run-off or as soil water loss. Hence, the change in productivity across each county and each crop when water availability is increased from the baseline water levels to the climate specific water levels is simulated. This allows us to identify the counties and crops that respond positively to the additional water. Then the effects of conservation technologies to conserve water is analyzed. Water conservation techniques are part of the water application process. Hence the water demand for the crop remains the same, but the water that is supplied so that the crop water demand is met after accounting for losses varies. In essence the water supplied amount will be a scaled, based on water application efficiencies, to determine the total water that needs to be supplied. We have already identified LEPA and LESA as the best performing conservation strategies in the production phase of food. Thus, we will be able to estimate the amount of water savings as well as the installations costs.

Cochise

Water demand for barley, corn and wheat depends on the temperature but the amount supplied is controlled by the farmer. Table 3.3 provides insight on the total water demand based on climate and land area covered for the crops grown in Cochise.

Table 3.3: Cochise Crop Water Demand.

Crop	Crop Area (Acres)	Baseline Water Demand (AF)	RCP 4.5 2030 Water Demand (AF)	RCP 4.5 2050 Water Demand (AF)	RCP 8.5 2030 Water Demand (AF)	RCP 8.5 2050 Water Demand (AF)
Barley	1717.89	7572.32	8253.29	8280.53	8092.58	8430.34
Corn	19667.18	89646.83	97708.60	98031.07	95806.02	99804.66
Wheat	1035.99	4140.00	4512.30	4527.19	4424.44	4609.10

The productivity changes when the baseline climate's water amounts are made available to these farms under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions are shown in Table 3.4.

Table 3.4: Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in Cochise.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-23.21%	-26.98%	-8.92%	-4.45%
Corn	-57.44%	-58.75%	-11.74%	-27.90%

Wheat	-8.35%	-29.66%	-11.29%	1.13%

But the different temperatures that change the demand for water by these crops. Under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions, the water needs of barley, corn, and wheat are different than that of the baseline demand, as shown in table. The change in biomass production when the new water demand is met is shown in Table 3.5.

Table 3.5: Change in Productivity When Only Temperature Changes and Irrigation Water Is Increased to Meet the Scenario’s Demand in Cochise.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-23.21%	-26.53%	-8.75%	-4.45%
Corn	-54.02%	-58.64%	6.03%	-7.03%
Wheat	-8.35%	-28.00%	-10.32%	2.73%

Water savings can be achieved by selecting the crop whose future water demands can be met, as well as improving the efficiency of water delivery to crops. There is very little to no improvement in barley and wheat production with increasing the water supply to these crops. Corn production increases by a maximum of 20 percentage points if the new water demands are met. Meeting the crop water demand for all crops would increase the need for water supply from 101359 acre-feet (AF) to a maximum of 112844 AF of water. On the other hand, by meeting the future demands of only corn, total water demand would increase to 111516 AF saving 1300 AF of water. The current water delivery mechanism is largely through flood irrigation and its system efficiency is just 70%. Thus 159309 AF of water needs to be supplied to meet the demand of 111516 AF of water. LEPA and LESA system, with their 90% system efficiency, would reduce the supply side water to 123907 AF, thus saving us 35402 AF of water. But this assumes the use of LEPA/LESA on all barley, corn and wheat farmlands. The fixed and the variable costs of the LEPA/LESA technology amounts to $156 per AF of water or $19.3 million in total. In order to reduce costs, if LEPA/LESA were implemented only on 50% of farmlands growing corn, then the water supply amount would be 143468 AF and would cost about $8.6 million.

Graham

Water demand for barley, corn and wheat depends on the temperature but the amount supplied is controlled by the farmer. Table 3.6 provides insight on the total water demand based on climate and land area covered for the crops grown in Graham.

Table 3.6: Graham Crop Water Demand.

Crop	Crop Area (Acres)	Baseline Water Demand (AF)	RCP 4.5 2030 Water Demand (AF)	RCP 4.5 2050 Water Demand (AF)	RCP 8.5 2030 Water Demand (AF)	RCP 8.5 2050 Water Demand (AF)

Barley	1119.90	4971.93	5238.29	5300.43	5167.26	5389.22
Corn	567.86	2607.03	2746.70	2779.28	2709.45	2825.84
Wheat	773.35	3112.70	3279.45	3318.36	3234.98	3373.94

The productivity changes when the baseline climate's water amounts are made available to these farms under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions are shown in Table 3.7.

Table 3.7: Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in Graham.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-5.58%	-19.24%	-3.59%	14.25%
Corn	-49.57%	-32.49%	-39.28%	-27.64%
Wheat	10.30%	-27.42%	-2.01%	25.38%

But the future scenarios have different temperatures that change the demand for water by these crops. Under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions, the water needs of barley, corn, and wheat are different than that of the baseline demand, as shown in table. The change in biomass production when the new water demand is met is shown in Table 3.8.

Table 3.8: Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in Graham.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-5.58%	-18.84%	-3.05%	14.36%
Corn	-40.37%	-23.19%	-32.05%	-20.53%
Wheat	10.44%	-24.24%	-0.30%	26.79%

Water savings can be achieved by selecting the crop whose future water demands can be met, as well as improving the efficiency of water delivery to crops. There is very little to no improvement in barley and wheat production with increasing the water supply to these crops. Corn production increases by a maximum of 9 percentage points if the new water demands are met. Meeting the crop water demand for all crops would increase the need for water supply from 10691 acre-feet (AF) to a maximum of 11589 AF of water. On the other hand, by meeting the future demands of only corn, total water demand would increase to 10910 AF saving 679 AF of water. By applying the current system's irrigation efficiency of 70%, 15586 AF of water needs to be supplied to meet the demand of 10910 AF of water. LEPA and LESA system, with their 90% system efficiency, would reduce the supply side water to 12122 AF, thus saving us 3464 AF of water. But this assumes the use of LEPA/LESA on all barley, corn and wheat farmlands. The fixed and the variable costs of the LEPA/LESA technology amounts to $156 per AF of water or $1.9 million in total. In order to reduce costs, if LEPA/LESA were implemented only on 50% of farmlands growing corn, then the water supply amount would be 15138 AF and would cost about $0.2 million.

Greenlee

Water demand for barley, corn and wheat depends on the temperature but the amount supplied is controlled by the farmer. Table 3.9 provides insight on the total water demand based on climate and land area covered for the crops grown in Greenlee.

Table 3.9: Greenlee Crop Water Demand.

Crop	Crop Area (Acres)	Baseline Water Demand (AF)	RCP 4.5 2030 Water Demand (AF)	RCP 4.5 2050 Water Demand (AF)	RCP 8.5 2030 Water Demand (AF)	RCP 8.5 2050 Water Demand (AF)
Barley	101.08	379.05	391.87	396.68	387.86	399.08
Corn	322.54	1250.72	1293.03	1308.90	1279.81	1316.83
Wheat	3.78	12.85	13.28	13.45	13.15	13.53

The productivity changes when the baseline climate’s water amounts are made available to these farms under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions are shown in Table 3.10.

Table 3.10: Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in Greenlee.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	0.28%	-48.34%	-11.12%	-3.50%
Corn	-19.19%	-3.85%	-2.68%	9.71%
Wheat	39.75%	-33.42%	4.06%	51.56%

But the future scenarios have different temperatures that change the demand for water by these crops. Under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions, the water needs of barley, corn, and wheat are different than that of the baseline demand, as shown in table. The change in biomass production when the new water demand is met is shown in Table 3.11.

Table 3.11: Change in Productivity When Only Temperature Changes and Irrigation Water Levels Is Increased to Meet the Scenario’s Demand in Greenlee.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51

Barley	0.99%	-47.02%	-10.24%	0.19%
Corn	-17.79%	-3.55%	-1.54%	10.01%
Wheat	41.44%	-30.62%	5.74%	54.59%

Water savings can be achieved by selecting the crop whose future water demands can be met, as well as improving the efficiency of water delivery to crops. There is very little (<5%) to no improvement in barley, corn and wheat production with increasing the water supply to these crops. Hence not meeting the new water demands would be best in Greenlee, but let's explore the effect of LEPA/LESA. By applying the current system's irrigation efficiency of 70%, 610 AF of water needs to be supplied to meet the demand of 427 AF of water. LEPA and LESA system, with their 90% system efficiency, would reduce the supply side water to 475 AF, thus saving us 135 AF of water. But this assumes the use of LEPA/LESA on all barley, corn and wheat farmlands. The fixed and the variable costs of the LEPA/LESA technology amounts to $156 per AF of water or $74,100 in total.

La Paz

Water demand for barley, corn, sorghum and wheat depends on the temperature but the amount supplied is controlled by the farmer. Table 3.12 provides insight on the total water demand based on climate and land area covered for the crops grown in La Paz.

Table 3.12: La Paz Crop Water Demand.

Crop	Crop Area (Acres)	Baseline Water Demand (AF)	RCP 4.5 2030 Water Demand (AF)	RCP 4.5 2050 Water Demand (AF)	RCP 8.5 2030 Water Demand (AF)	RCP 8.5 2050 Water Demand (AF)
Barley	7.79	41.28	42.76	43.44	42.70	43.50
Corn	144.91	793.57	822.08	835.15	820.89	836.33
Sorghum	71.17	366.74	379.92	385.96	379.37	386.50
Wheat	4422.83	21234.80	21997.73	22347.40	21965.94	22379.19

The productivity changes when the baseline climate's water amounts are made available to these farms under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions are shown in Table 3.13.

Table 3.13: Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in La Paz.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-67.88%	-49.98%	-28.57%	-87.35%

Corn	-37.53%	-51.30%	101.62%	-23.53%
Sorghum	-28.08%	-63.31%	158.56%	-18.17%
Wheat	-44.14%	-25.81%	-10.54%	-67.59%

But the future scenarios have different temperatures that change the demand for water by these crops. Under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions, the water needs of barley, corn, sorghum, and wheat are different than that of the baseline demand, as shown in table. The change in biomass production when the new water demand is met is shown in Table 3.14.

Table 3.14: Change in Productivity When Only Temperature Changes and Irrigation Water Levels Are Increased to Meet the Scenario's Demand in La Paz.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-67.88%	-49.98%	-28.57%	-87.35%
Corn	-30.98%	-51.30%	112.26%	-16.21%
Sorghum	-25.78%	-63.31%	182.75%	-13.44%
Wheat	-44.14%	-25.81%	-10.54%	-67.59%

Water savings can be achieved by selecting the crop whose future water demands can be met, as well as improving the efficiency of water delivery to crops. There is very little to

no improvement in barley and wheat production with increasing the water supply to these crops. Corn and sorghum production increases by a maximum of 12 percentage points and 24 percentage points respectively, if the new water demands are met. Meeting the crop water demand for all crops would increase the need for water supply from 22436 acre-feet (AF) to a maximum of 23645 AF of water. Wheat is a major crop in La Paz, accounting for 95% of the land use and water demand among these four crops. By meeting the future demands of corn and sorghum, total water demand would increase to 22498 AF saving 1147 AF of water. By applying the current system's irrigation efficiency of 70%, 32140 AF of water needs to be supplied to meet the demand of 22498 AF of water. LEPA and LESA system, with their 90% system efficiency, would reduce the supply side water to 24998 AF, thus saving us 7142 AF of water. But this assumes the use of LEPA/LESA on all barley, corn, sorghum and wheat farmlands. The fixed and the variable costs of the LEPA/LESA technology amounts to $156 per AF of water or $ 3.9 million in total. Since wheat is the dominant crop in the county, water savings and a lower cost of implementation can be easily achieved by implementing LEPA/LESA on wheat farms. If LEPA/LESA were implemented only on 50% of farmlands growing wheat, then the water supply amount would be 28681 AF and would cost about $1.8 million.

Maricopa

Water demand for barley, corn, sorghum and wheat depends on the temperature but the amount supplied is controlled by the farmer. Table 3.15 provides insight on the total water demand based on climate and land area covered for the crops grown in Maricopa.

Table 3.15: Maricopa Crop Water Demand.

Crop	Crop Area (Acres)	Baseline Water Demand (AF)	RCP 4.5 2030 Water Demand (AF)	RCP 4.5 2050 Water Demand (AF)	RCP 8.5 2030 Water Demand (AF)	RCP 8.5 2050 Water Demand (AF)
Barley	6390.49	34096.41	35261.66	35982.46	35312.33	36072.28
Corn	8297.75	45781.83	47346.44	48291.34	47414.47	48434.86
Sorghum	3497.39	18156.21	18776.70	19170.26	18803.68	19208.35
Wheat	6538.26	31626.33	32707.17	33365.07	32754.16	33459.06

The productivity changes when the baseline climate's water amounts are made available to these farms under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions are shown in Table 3.16.

Table 3.16: Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in Maricopa.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-68.35%	-43.49%	-34.95%	-82.21%

Corn	-13.19%	-24.13%	204.75%	29.65%
Sorghum	10.23%	-11.25%	255.28%	14.13%
Wheat	-47.38%	-18.60%	-8.75%	-63.45%

But the future scenarios have different temperatures that change the demand for water by these crops. Under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions, the water needs of barley, corn, sorghum, and wheat are different than that of the baseline demand, as shown in table. The change in biomass production when the new water demand is met is shown in Table 3.17.

Table 3.17: Change in Productivity When Only Temperature Changes and Irrigation Water Level Is Increased to Meet the Scenario's Demand in Maricopa.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-68.35%	-43.49%	-34.95%	-82.21%
Corn	72.63%	4.82%	221.61%	44.27%
Sorghum	29.18%	-7.94%	273.21%	27.10%
Wheat	-47.38%	-18.60%	-8.75%	-63.45%

Water savings can be achieved by selecting the crop whose future water demands can be met, as well as improving the efficiency of water delivery to crops. There is very little to

no improvement in barley and wheat production with increasing the water supply to these crops. In fact, there is more than a 50% decrease in barley and wheat production in two of the four scenarios. It is critical to reconsider cultivating barley and wheat in Maricopa. Corn and sorghum production, on the other hand, increases by a maximum of 85 percentage points and 19 percentage points respectively, if the new water demands are met. Meeting the crop water demand for all crops would increase the need for water supply from 129661 acre-feet (AF) to a maximum of 137175 AF of water. By meeting the future demands of corn and sorghum, total water demand would increase to 133366 AF saving 3809 AF of water. By applying the current system's irrigation efficiency of 70%, 190522 AF of water needs to be supplied to meet the demand of 133366 AF of water. LEPA and LESA system, with their 90% system efficiency, would reduce the supply side water to 148184 AF, thus saving us 42338 AF of water. But this assumes the use of LEPA/LESA on all barley, corn, sorghum and wheat farmlands. The fixed and the variable costs of the LEPA/LESA technology amounts to $156 per AF of water or $ 23.1 million in total. If LEPA/LESA were implemented only on 50% of farmlands growing corn and sorghum, then the water supply amount would be 179785 AF and would cost about $5.9 million.

Pinal

Water demand for barley, corn, sorghum and wheat depends on the temperature but the amount supplied is controlled by the farmer. Table 3.18 provides insight on the total water demand based on climate and land area covered for the crops grown in Pinal.

Table 3.18: Pinal Crop Water Demand.

Crop	Crop Area (Acres)	Baseline Water Demand (AF)	RCP 4.5 2030 Water Demand (AF)	RCP 4.5 2050 Water Demand (AF)	RCP 8.5 2030 Water Demand (AF)	RCP 8.5 2050 Water Demand (AF)
Barley	14912.71	65497.64	75074.00	76492.73	74955.78	76610.95
Corn	22447.99	101954.24	116860.91	119069.30	116676.87	119253.33
Sorghum	2373.73	10143.93	11627.07	11846.79	11608.75	11865.10
Wheat	13285.69	52901.24	60635.90	61781.77	60540.41	61877.26

The productivity changes when the baseline climate's water amounts are made available to these farms under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions are shown in Table 3.19.

Table 3.19: Pinal Crop Water demand. Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in Pinal.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-65.82%	-38.04%	-37.26%	-82.34%

Corn	-46.53%	-49.03%	16.47%	-35.60%
Sorghum	-40.01%	-53.56%	3.38%	-38.72%
Wheat	-47.52%	-28.15%	-19.53%	-59.33%

But the future scenarios have different temperatures that change the demand for water by these crops. Under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions, the water needs of barley, corn, sorghum, and wheat are different than that of the baseline demand, as shown in table. The change in biomass production when the new water demand is met is shown in Table 3.20.

Table 3.20: Change in Productivity When Only Temperature Changes and Irrigation Water Levels Are Increased to Meet the Scenario's Demand in Pinal.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-65.69%	-38.04%	-37.26%	-82.34%
Corn	-40.04%	-49.03%	59.38%	-25.95%
Sorghum	-38.68%	-53.56%	65.46%	-38.72%
Wheat	-47.52%	-28.15%	-19.53%	-59.33%

Water savings can be achieved by selecting the crop whose future water demands can be met, as well as improving the efficiency of water delivery to crops. There is very little to

no improvement (<5%) in barley, sorghum, and wheat production with increasing the water supply to these crops. In fact, there decrease in barley and wheat production by 50% or more in two of the four scenarios. It is critical to reconsider cultivating barley and wheat in Pinal. Corn and Sorghum production, on the other hand, increases by a maximum of 43 and 62 percentage points respectively, if the new water demands are met. Meeting the crop water demand for all crops would increase the need for water supply from 230479 acre-feet (AF) to a maximum of 269607 AF of water. By meeting the future demands of corn alone, total water demand would increase to 247796 AF saving 21811 AF of water. By applying the current system's irrigation efficiency of 70%, 353994 AF of water needs to be supplied to meet the demand of 247796 AF of water. LEPA and LESA system, with their 90% system efficiency, would reduce the supply side water to 275329 AF, thus saving us 78665 AF of water. But this assumes the use of LEPA/LESA on all barley, corn, sorghum and wheat farmlands. The fixed and the variable costs of the LEPA/LESA technology amounts to $156 per AF of water or $ 43 million in total. If LEPA/LESA were implemented only on 50% of farmlands growing corn, then the water supply amount would be 335066 AF and would cost about $10.3 million.

Santa Cruz

Water demand for barley and corn depends on the temperature but the amount supplied is controlled by the farmer. Table 3.21 provides insight on the total water demand based on climate and land area covered for the crops grown in Pinal.

Table 3.21: Santa Cruz Crop Water Demand.

Crop	Crop Area (Acres)	Baseline Water Demand (AF)	RCP 4.5 2030 Water Demand (AF)	RCP 4.5 2050 Water Demand (AF)	RCP 8.5 2030 Water Demand (AF)	RCP 8.5 2050 Water Demand (AF)
Barley	10.26%	-27.17%	-1.37%	17.23%	10.26%	-27.17%
Corn	10.55%	39.32%	82.20%	73.47%	10.55%	39.32%

The productivity changes when the baseline climate's water amounts are made available to these farms under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions are shown in Table 3.22.

Table 3.22: Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in Santa Cruz.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	10.26%	-27.17%	-1.37%	17.23%
Corn	10.55%	39.32%	82.20%	73.47%

But the future scenarios have different temperatures that change the demand for water by these crops. Under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5

2050-51 conditions, the water needs of barley, corn, and wheat are different than that of the baseline demand, as shown in table. The change in biomass production when the new water demand is met is shown in Table 3.23.

Table 3.23: Change in Productivity When Only Temperature Changes and Irrigation Water Levels Are Increased to Meet the Scenario's Demand in Santa Cruz.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	12.51%	-24.79%	-0.04%	20.48%
Corn	15.14%	39.67%	87.11%	76.36%

Water savings can be achieved by selecting the crop whose future water demands can be met, as well as improving the efficiency of water delivery to crops. There is very little (<5%) to no improvement in barley and corn production with increasing the water supply to these crops, but this is the only county where the change crop production has been positive, indicating that crop production increases into the future. Hence not meeting the new water demands would be the best course of action in Santa Cruz, but let's explore the effect of LEPA/LESA. By applying the current system's irrigation efficiency of 70%, 78.6 AF of water needs to be supplied to meet the demand of 55.1 AF of water. LEPA and LESA system, with their 90% system efficiency, would reduce the supply side water to 61.2 AF, thus saving 17.4 AF of water. But this assumes the use of LEPA/LESA on all barley, corn and wheat farmlands. The fixed and the variable costs of the LEPA/LESA technology amounts to $156 per AF of water or $2174 in total.

Yuma

Water demand for barley, corn, sorghum and wheat depends on the temperature but the amount supplied is controlled by the farmer. Table 3.24 provides insight on the total water demand based on climate and land area covered for the crops grown in Yuma.

Table 3.24: Yuma Crop Water Demand.

Crop	Crop Area (Acres)	Baseline Water Demand (AF)	RCP 4.5 2030 Water Demand (AF)	RCP 4.5 2050 Water Demand (AF)	RCP 8.5 2030 Water Demand (AF)	RCP 8.5 2050 Water Demand (AF)
Barley	1026.26	4352.83	4385.37	4458.60	4393.51	4458.60
Corn	1548.58	6792.12	6842.90	6957.16	6855.60	6957.16
Sorghum	557.07	2298.96	2316.15	2354.82	2320.45	2354.82
Wheat	7939.36	30528.89	30757.15	31270.72	30814.21	31270.72

The productivity changes when the baseline climate’s water amounts are made available to these farms under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions are shown in Table 3.25.

Table 3.25: Change in Productivity When Only Temperature Changes but Baseline Irrigation Water Levels Are Maintained in Yuma.

Crop	Change in crop production from Baseline to RCP 4.5 2030-31 (%)	Change in crop production from Baseline to RCP 4.5 2050-51 (%)	Change in crop production from Baseline to RCP 8.5 2030-31	Change in crop production from Baseline to RCP 8.5 2050-51
Barley	-23.66%	-56.60%	13.48%	-12.31%
Corn	-35.09%	85.99%	35.50%	-3.65%
Sorghum	-48.57%	80.13%	54.18%	-14.46%
Wheat	-5.46%	-19.53%	18.77%	-11.95%

But the future scenarios have different temperatures that change the demand for water by these crops. Under RCP 4.5 2030-31, RCP 4.5 2050-51, RCP 8.5 2030-31, and RCP 8.5 2050-51 conditions, the water needs of barley, corn, sorghum, and wheat are different than that of the baseline demand, as shown in table. The change in biomass production when the new water demand is met is shown in Table 3.26.

Table 3.26: Change in productivity when only temperature changes and irrigation water levels are increased to meet the scenario's demand in Yuma.

Crop	Change in crop production from	Change in crop production from	Change in crop production from	Change in crop production from

	Baseline to RCP 4.5 2030-31 (%)	Baseline to RCP 4.5 2050-51 (%)	Baseline to RCP 8.5 2030-31	Baseline to RCP 8.5 2050-51
Barley	-23.66%	-56.60%	13.48%	-12.31%
Corn	-33.84%	89.57%	36.45%	0.42%
Sorghum	-43.25%	82.71%	56.89%	-9.74%
Wheat	-5.46%	-19.53%	18.77%	-11.95%

Water savings can be achieved by selecting the crop whose future water demands can be met, as well as improving the efficiency of water delivery to crops. There is very little to no improvement (<5%) in barley and wheat production with increasing the water supply to these crops. Corn production and barley production, on the other hand, increases by a maximum of 4 percentage points and 6 percentage points respectively, if the new water demands are met. Meeting the crop water demand for all crops would increase the need for water supply from 43973 acre-feet (AF) to a maximum of 45041 AF of water. By meeting the future demands of corn alone, total water demand would increase to 44135AF saving 906 AF of water. By applying the current system's irrigation efficiency of 70%, 63050 AF of water needs to be supplied to meet the demand of 44135 AF of water. LEPA and LESA system, with their 90% system efficiency, would reduce the supply side water to 49039 AF, thus saving us 14011 AF of water. But this assumes the use of LEPA/LESA on all barley, corn, sorghum and wheat farmlands. The fixed and the variable costs of the LEPA/LESA technology amounts to $156 per AF of water or $ 7.7 million in total. If LEPA/LESA were implemented only on 50% of farmlands growing corn, then the water supply amount would be 61950 AF and would cost about $0.6 million.

3.5 Discussion

While results differ significantly by count, targeting the critical counties that contribute at least 80% of barley, corn, sorghum, and wheat farmlands would minimize the extent of water resource management while reducing implementation costs. The criticality of Maricopa, Pinal, and Yuma from a production perspective can be seen in Figure 3.2, as they host 83% of the barley production area, and 94% of the sorghum production area. Additionally, Maricopa, Pinal, Yuma, and La Paz have 80% of the wheat production area while Maricopa, Pinal, Yuma, and Cochise have 95% of the corn production area. By applying LEPA/LESA to all the crops the total water demand drops from 0.8 million AF to 0.62 million AF. The energy required for water conveyance and pumping is estimated to drop from 2.3 Terajoules (TJ) to 1.9 TJ. Though there is additional pumping energy, there is energy savings by avoiding additional water conveyance. But this will lead to an additional $97 million in fixed and variable costs. Targeting the crops with better performance in each county to implement LEPA/LESA technologies would only reduce water use from 0.8 million AF to 0.75 million AF, but in this case the total energy needed increases to 2.35 TJ due to the additional pumping energy requirements. But there is a positive on the cost side as the fixed and variable costs associated with LEPA/LESA implementation drops down to $27 million.

3.6 Conclusion

Since crop productivity is dependent on multiple factors, such as soil, fertilizer, climate, and water, it is difficult to predict state level crop productivity changes. County level changes in productivity are severely dependent on the temperature conditions which are again variable given the various RCP’s and the GCM’s. But it can be concluded that crop production will decrease in the future. Corn and sorghum productivity reduce with increasing temperatures but respond positively to increasing irrigation water. Barley and wheat productivity will again decrease in response to increasing temperatures but increasing irrigation water has no impact on their productivity. Implementing LEPA/LESA on corn fields at specific counties would be the best solution to address the water constraint concerns. While the implementation of the technology would increase water savings, there are no guarantees on energy savings as this depends on the extent of implementation. More than 50% of the corn fields need to be converted to a LEPA/LESA system to achieve any energy savings, but the cost of implementation is prohibitive. The hope is that this work helps informs the policy makers of these dynamics in order to enable effective agricultural policy making in the face of climate change and food security risk.

CHAPTER 4 FEW – EXCHANGE NEXUS: EFFECTS OF FOOD TRADE

4.1 Introduction

Despite volatility, scarcity and trade issues around water and energy resources, planning and policymaking largely occurs within geopolitical boundaries. Water and energy are indispensable to the social and economic development of a region and with growing populations and concerns over climate change stable access to the resources becomes ever more critical. Studies have established the problem of shifting energy impacts by moving production to another location and overconsumption of a common pool resource like water. Both these problem stem from the inequitable distribution of impacts and resource use respectively. These issues are only compounded by the exchange of embedded water and embedded energy through products, that often are moved long distances. For example, scarce water in Arizona is often used to grow water-intense crops and is then exported to states where water scarcity is less.

The flow of embedded water and embedded energy through products is the focus of this study. To assess this phenomenon, the Food Energy Water Nexus approach is used, since energy and water (both direct and embedded) are key inputs to agriculture . When we trade food, we essentially trade the energy and water input to produce the food which is never accounted for by energy and water policy. Agricultural trade has an open market and hence has its own rules of operation. Profit maximization is one since businesses operate to generate profit, and another rule is that supply needs to meet demand, as is evident from basic economic theory. Food demand by a state can be characterized as consumption and international export. On the other hand, food can be made available via production and international import. As a net exporter of food, the amount of food available in the US is often far greater than the amount of food consumed. Food production is concentrated in certain parts of the country, but demand for food is highly distributed across the various states. Thus, food is transported across state boundaries to meet demand . This temporal and spatial fluctuation in availability and demand, makes food storage critical for a food secure future. While there are policies that govern the food trade, there are no policies that account for the embedded water and embedded energy of trade. Accounting for the trade of embedded components is essential for long term energy and water management. Let us explore this phenomenon with an example where 1 ton of corn is traded from Arizona to California. Arizona uses Colorado river water allocated to the state and conveyed to the farm, to grow corn, and sends this corn to California. California, hence, imports not just the corn but the Arizona-allocated Colorado river water. The energy portfolio of Arizona is dirtier when compared to California. But California is not held responsible for the carbon emissions of the 1 ton of corn it imports from Arizona. The onus of the emissions falls on Arizona. Policy mechanisms and open markets are clearly not in sync while accounting for energy and water due to the complexity of the system which leads to issues of equity in resource distribution. As food demand grows, and as water and energy needs change, the holistic accounting of resources becomes more critical for effective resource management policy. This problem needs to be first understood by estimating the flow of critical resources through products traded between regions. There is a need for a systemic Life Cycle Assessment (LCA) of food, from production to storage to distribution, to fill the gap on the movement of embedded water and embedded energy associated with food.

Literature Review

Research on the how resources are embedded in food and move across regions is pervasive and has been presented from various perspectives. LCA is the preeminent framework to assess the environmental impacts and embedded resource use of food across its life cycle, that is, from growth of the crop through to finished product including transport and consumption. Typical LCA studies explore only select life phases, the most common one being the production phase. The literature in the production based LCA is vast, varying from beer to beef to beets to barley . These LCA studies focus on environmental impacts of production identify hot-spots and improve the environmental performance of the production process, which in-turn reduces the environmental impact of the product. When sourcing is of concern, LCA studies have focused on transportation. There are other types of LCA's which incorporate multiple life-phases of the product to identify the various impacts of these food products across production, processing, manufacture, transport, and use . While these LCA studies focus on estimating environmental impacts, it is observed that these impacts are stationary. In reality, movement of food involves the movement of embedded resource along with the food product itself.

The concept of virtual water was a major break-through in the food energy water nexus space as the virtual water flows help estimate the water input to crops and water sent out to other regions via trade. Virtual water studies have explored and quantified the flow of embedded water through agriculture on a global level . The net estimate of virtual water surplus or deficit from crop trade on a country has been conducted . Even the issue of food security has been addressed where virtual water studies suggest using virtual water concepts to shift agriculture away from arid and desert regions across the world and discuss the need to consider comparative advantages of the market and the local impacts of the food produced. While it is important to consider international trade, there seem to be a lack of literature on domestic flows. Little work exists that study these domestic flows. The work that has been conducted often uses an input-output model approach and doesn't provide crop specific information as different crops are generally part of different economic sectors. The studies that do look at domestic flows do not account for storage – a key step to make sure there are reserves in the case of emergencies, and to respond to market signals. There is a clear gap in the literature to explore crop-wise trade mechanisms that identify not just water flows within a country but also the energy flow associated with intra-regional crop trade.

This study focuses on specific agricultural produce and systematically shows how embedded water and energy in food are moved across regions. Food trade data will be used to capture the import-export dynamic within the Food-Energy-Water (FEW) nexus. The traditional definition of the nexus compels us to consider only crops produced in a state and the export from the state. In this study we hope to present another approach that closely matches the FEW nexus's spatial perspective. Spatial scale is inherent to the FEW nexus framework, be it a city, state or a nation. The region under investigation has a food system which can produce, import, export, store and/or consume food. This dynamic is often ignored, and we present a FEW nexus assessment that accounts for these dynamics. Our FEW nexus approach would thus estimate the influence on the energy and the water system through food, where the food can be produced locally, imported, and/or exported. This approach recognizes the embeddedness of sub-regions (e.g., Arizona FEW Nexus) in a larger system (US FEW Nexus) and would help better inform policy that is generally constrained by geopolitical boundaries.

4.2 Methodology

To estimate the import and export dynamics of embedded energy and embedded water in food, we need to two sets of data – the trade data between states, and the energy and water in the crop at each state. There are two key components - LCA to quantify the energy and water intensity of crops and an optimization program to estimate trade flows – that will enable us to quantify the import and export of embedded energy and embedded water. Barley, corn, sorghum, wheat are the crops that will be assessed due to data availability across production, import, storage, consumption, and export. The LCA framework is used to assess the embedded energy and embedded water in the production phase of the crop since that is the resource that moves. Embedded energy associated with storage and transportation are created to enable the movement of food, and hence are not traded with food. Food trade data is hence a key component to this assessment. While the US has extensive data on international trade, data on the domestic trade of food is almost non-existent. Domestic trade data is only available from the Freight Analysis Framework (FAF) which is derived from the Commodity Flow Survey (CFS). The CFS data is grouped into categories making crop specific trade data unavailable. There is no clear indication of origin or destination, and the intermediate storage locations are also hard to predict. Grain storage data from the USDA suggests that the crops under consideration, after it is made available either by production or import, is always stored (on-farm or off-farm) before it is sent out to the destination for consumption or export. Hence, we have a framed the system such that the crop is sent to the destination from origin only after storage, as shown in Figure 4.1. Food storage is a critical piece in the flow of food since, it provides some flexibility with regards to how food is traded. It adheres to the typical capitalistic mindset where there are multiple providers and the consumer has the option to buy from the cheapest provider or from any other provider of their choosing. Storage also extends the lifetime of crop by weeks in the case of vegetables and months in the case of grains. Other benefits of storage are the ability of the system to respond accordingly during food shortage related shocks created due to externalities like war and climate impacts,

The problem presented here is a modified transportation problem with an intermediate stop (i.e., storage). Linear programming is a reasonable approach for solving this transportation logistic network to estimate how crops are moved from state to state and stored between. The optimal solution would ensure that supply meets demand within the system constraints. The allocations between origin, storage, and destination represent the flows. The optimization result will be fed into the LCA framework to determine the import export dynamic of the crops, as well as the energy and water embedded in crops.

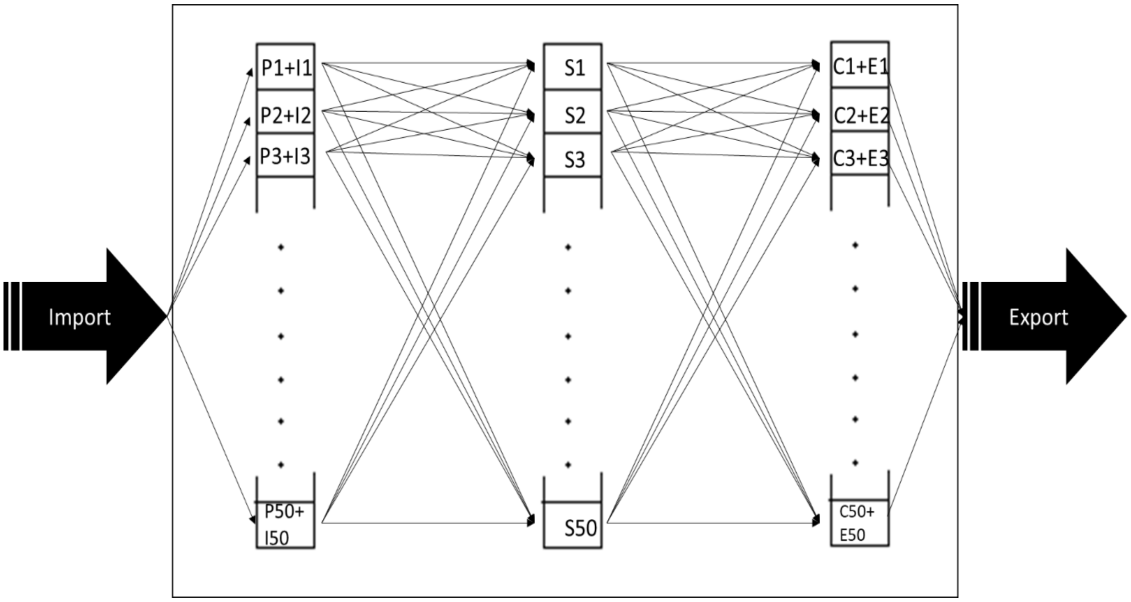


Figure 4.1: Food Flow: P+I Represents the Food Available for Consumption Through Production and Import, S Represent the Storage Across All States, and C+E Represents the Consumption by State As Well As Export From Each State.

<u>Optimization Program</u>

Profit drives trade in a free market, hence, the profit from crop consumed determines the trade network within the US. Thus, the objective of the optimization program would be to maximize profit. There are two components to profit – revenue and costs. Revenue is characterized as the price at which the crop is sold. Cost is a bit more complicated as there are costs associated with production, transportation, and storage. The import and production accounts for the net availability of crop while the export and consumption of crop account for the total crop that leaves the system. Food is made available in each state either by production or by international import, stored in-state or out-of-state, and then disappears either due to consumption in-state or international export from state. The limiting factors for this optimization problem are the amount of crop produced, the amount of crop imported, the amount of crop consumed, the amount of crop exported and the stock fluctuations at storage locations. As such the optimization program is defined as follows.

Maximize

$$Z = \sum_{t=1}^{N} \sum_{i=1}^{50} \sum_{j=1}^{50} \left[(Qc_j * Pr + Qe_j * Pe) - \left[(Qp_i * Cp + Qi_i * Ci) + \sum_{i=1}^{50} T_{ik} * Cd * Dt_{ik} + \sum_{k=1}^{50} Qs_k * Cs + \sum_{j=1}^{50} T_{kj} * Cd * Dt_{kj} \right] \right]$$

Subject to:

$Production\ Constraint$:

$$Qp_i = Prod_i \qquad \forall\ i\ in\ 1\ to\ 50$$

$Import\ Constraint$:

$$Qi_i = Im_i \qquad \forall\ i\ in\ 1\ to\ 50$$

$Consumption\ Constraint$:

$$Qc_j = Cons_j \qquad \forall\ j\ in\ 1\ to\ 50$$

$Export\ Constraint$:

$$Qe_j = Ex_j \qquad \forall\ j\ in\ 1\ to\ 50$$

$Origin\ to\ Storage\ Constraint$:

$$\sum_{k=1}^{50} T_{ik} = Qp_i + Qi_i \qquad \forall\ i\ in\ 1\ to\ 50, t\ in\ 1\ to\ N$$

$Storage\ to\ Destination\ Constraint$:

$$\sum_{k=1}^{50} T_{kj} = Qc_j + Qe_j \qquad \forall\ j\ in\ 1\ to\ 50, t\ in\ 1\ to\ N$$

$Stock\ Constraint$:

$$\sum_{i=1}^{50} T_{ik} - \sum_{j=1}^{50} T_{kj} = Qs_k \qquad \forall\ k\ in\ 1\ to\ 50, t\ in\ 1\ to\ N$$

$Storage\ Constraint$:

$$Qs_k \leq St_k \qquad \forall\ k\ in\ 1\ to\ 50, t\ in\ 1\ to\ N$$

$Positive\ Value\ cContraint$:

$$\mathrm{T_{ik}}, \mathrm{T_{kj}} \geq 0 \qquad \forall\ \mathrm{i, j, k\ in\ 1\ to\ 50}$$

where,

T_{ik} → Amount traded from i to k. These are decision variables. It is the tonnage of crop traded from origin to storage.

T_{kj} → Amount traded from k to j. These are decision variables. It is the tonnage of crop traded between storage to destination.

Qp_i → Decision variable for crop produced in state i.

Qi_i → Decision variable for crop imported by state i.

Qe_j → Decision variable for crop exported by state j.

Qc_j → Decision variable for crop consumed in state j.

Qs_k → Decision variable for crop stored in state k.

t → Seasonality, where N is the number of seasons. N=4 in this study of barley, corn, sorghum and wheat.

j → Destination state where the food is either consumed or is exported internationally.

i → Origin state where the food is either produced of is imported into from other countries.

k → State where there is intermediate storage.

Pr → Price at which the grain is sold.

Pe → Price at which the grain is exported.

Cp → Cost of grain production.

Ci → Cost of grain imported.

Cd → Transport cost that considers rail and truck transport per ton-mile.

Cs → Storage costs.

Dt_{ik} → distance between state i and state k.

Dt_{kj} → distance between state k and state j.

$Prod_i$ → Total amount of grain produced in state i.

Im_i → Total amount of crop imported by state i.

Ex_j → Total amount of crop exported by state j.

$Cons_j$ → Total amount of grain consumed in state j.

St_k → Storage Capacity and storage maintained at state k.

A variety of data sources were used as inputs into the optimization, except storage data, all data is represented on a monthly basis and aggregated to four 3-month time steps. These periods are adopted from the time scale at which the grain stock data is available. The grain stock data represents the amount of grain available in storage during each time step. It is essential that the fluctuations in grain stock is accounted for by the optimization program for two reasons: one, grain production is not uniform across the year, and second, all grain is stored before it is sent out for consumption or export. The USDA Crop Production 2014 Summary dataset is used to determine the amount of crop available in the US through production. Both imports and exports are estimated using the USDA ERS dataset on imports and exports along with the state imports exports by NAICS commodities datasets from the Census Bureau . The consumption amounts are estimated from the Feed Outlook data set from the USDA ERS and US population levels. The Feed Outlook data is available on a per capita basis and hence the state-wise population is used to determine total consumption, including residential and industrial use. Due to lack of data on the prices of import and export by state, an average international import and export price of US barley, corn, sorghum and wheat is estimated from the total trade value and the total trade amount. This international price is available at USDA. The storage cost is estimated as a national average determined using the Ag decision maker from Iowa State University. Distances between states are determined in

Arcmap as the distance between the centroids of every state and the instate travel distance was determined using the ton-mile of goods traded and tons of goods traded in FAF. The transportation cost varies by state (given different centroid to centroid distances) and the mode of transportation used. FAF suggests that more grain is transported by truck but the grain travels longer distances on rail. Hence a national weighted average transportation cost is estimated using the transportation costs from the Department of Transportation and the ton-miles on each transportation mode.

Once the flow of crops between regions is estimated, we estimate the flows of crop produced from origin to destination in order to determine energy and water flows. The production flows are determined at the origin location by applying the ratio of import to production to every origin to storage flow (T_{ik}). The states that supply every storage location are first identified to determine the ratio of crops from each origin location to a supply location. Using the ratio of various origins to every storage location and the ratio of import to production, we determine the extent of production flows in the storage to destination flows(T_{kj}).

Life Cycle Assessment

In order to determine the energy and water flows we need to estimate the energy and water intensities of crop at every origin state. Each crop in each state uses different amounts of water and energy either due to climate, resource application practice, soil conditions, among others. The approaches used to determine water use and energy use are different. The amount of water use for a crop is estimated using an evapotranspiration rate (ET_c). The water used by crop is based on evaporation and transpiration. The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as the crop water requirement. This is estimated using two factors, the reference evapotranspiration rate (ET_o) and crop factor (K_c).

$$ET_{c.} = ET_o \text{ x } K_c$$

ET_o is the evapotranspiration associated with a hypothetical grass surface with specific characteristics as this expresses the evaporation potential of the weather at a specific location. The FAO Penman-Monteith method is recommended as the sole method for determining ET_o. The method has been selected because it closely approximates grass ET_o at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters .

$$.\,ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273}\right) u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where

ET_o: reference evapotranspiration [mm day^{-1}],

R_n: net radiation at the crop surface [MJ m^{-2} day^{-1}],

G: soil heat flux density [MJ m^{-2} day^{-1}],

T: air temperature at 2 m height [°C],

u_2: wind speed at 2 m height [m s^{-1}],

e_s: saturation vapour pressure [kPa],

e_a: actual vapour pressure [kPa],

e_s - e_a: saturation vapour pressure deficit [kPa],

D: slope vapour pressure curve [kPa °C^{-1}],

g: psychrometric constant [kPa °C^{-1}].

Cropwat is a software developed to determine ET_o using local climate variables such as temperature, humidity, windspeed, solar radiation. The average temperature, humidity, windspeed, and solar radiation are determined from the weather data for major cities in every state between 1981 and 2010 from the NOAA National Climatic Data Center of the US was compiled. This was then input into Cropwat 8.0 to generate state specific ET_o values. The crop type and the developmental state of crop establishes the estimation of $ET_{c.}$ These factors are accounted for by the crop factor $K_{c.}$ K_c is a standard value for each crop irrespective of where it is cultivated. The Food and Agriculture Organization has a database with these values.

Energy use for crops is primarily split between fuel and fertilizers. Based on local practices, the fuel and fertilizer use vary. These variations are generally reflected in the dollar amount spent by farmers for fuel and fertilizer. Hence, we collect the cost of fuel and fertilizers across all states from the crop budgets generated by the cooperative extension in each state. When the fuel and fertilizer data are not readily available, the Cost Return data set from the USDA's Agriculture Resource Management Survey is used to determine cost of fuel and fertilizer. In some cases, the fuel data is detailed in the sense that the cooperative extensions provide the data for natural gas, gasoline, diesel and electricity. But, in other cases the fuels costs are just labeled as fuel, in which case it is assumed that all the cost is allocated to diesel since the majority of the farm equipment runs on diesel, including pumps. A similar assumption is made with regards to fertilizer, when data is available the energy content in the N-type, P-type, and K-type are used otherwise it is assumed that N-type fertilizer energy contents are used since nitrogen fertilizer is the most commonly used fertilizer. Thus, the estimated energy and water intensity of crop production is then applied to the production flows to determine the amount of energy and water that is sent from the origin to destination. Energy that is spent on storage across space is estimated as the amount of energy required to refrigerate the crop so that it can be stored for the maximum time possible. The estimation of energy required to transport the crop is dependent on mode of transport and the ton-mile distance. The 2012 Transportation Energy Data Book suggests that the energy per ton-mile for air, truck, water, and rail are 30 BTU/ton-mile, 4 BTU/ton-mile, 0.5 BTU/ton-mile, and 0.4 BTU/ton-mile respectively. From the Freight Analysis Framework, rail, truck, and water cover the most ton-mile distance by accounting for 58.3%, 32.3%, and 9.4% of the total distance. This provides us a weighted average of 0.00166 MJ/ton-mile of grain transported.

In order to better understand the implications of resource flows, a water stress indicator is used. The water stress indicator is the Baseline Water Stress from the World Resources Institute which is estimated as the ratio of amount of water withdrawn to that of water renewed in aqueducts across the US. These water stress values have been developed for every state. The energy-related carbon emission associated with each state is also used as an indicator. Total state carbon emissions include those from direct fuel use across all sectors as well as primary fuels consumed for electricity generation. The physical size of a state, as well as the available fuels, types of businesses, climate, and population size and density, all play a role in determining carbon emissions. The water and carbon indicators help us better understand the flow of water and energy from resource constrained and high impact regions to resource rich and low impact regions.

4.3 Results and Analysis

The optimization program generates a state-to-state trade estimate in a 50 x 50 matrix format for the select crops which is then aggregated into regions for better visualization. The regions are defined by the Bureau of Economic Analysis (BEA) and are shown in Table 4.1.

Table 4.1: Regional Definitions According to the Bureau of Economic Analysis.

Region	States (abbreviated)
New England	CT, MN, MA, NH, RI, VT
Mideast	DE, DC, MD, NJ, NY, PA
Great Lakes	IL, IN, MI, OH, WI
Plains	IA, KS, MN, MO, NE, ND, SD
Southeast	AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, VA, WV
Southwest	AZ, NM, OK, TX
Rocky Mountain	CO, ID, MT, UT, WY
Farwest	AK, CA, HI, NV, OR, WA

The results from the optimization program are split into two flows – flows from origin to storage and flows from storage to destination. The two flows are then combined to determine the flow of barley, corn, sorghum, and wheat from origin to destination, as shown in Figure 4.2. While different regions focus on different crops, the plains have consistently been a major player in the production and storage of grains. These states represent a large fraction of production since they have consistent access to water and fertile soil. It is clear from the import and production data that the Rocky Mountain, Plains and the Southeast states produce or import and store close to 50% of barley, corn, sorghum and wheat. These regions are thus critical for the US to maintain its status as a net exporter of grains. This result makes sense since the states in the Plains, Rocky Mountains and Southeast have been large grain producers and have stored millions of tons of grains over decades. That is why these regions are known as the Corn belt and the Wheat belt in the US.

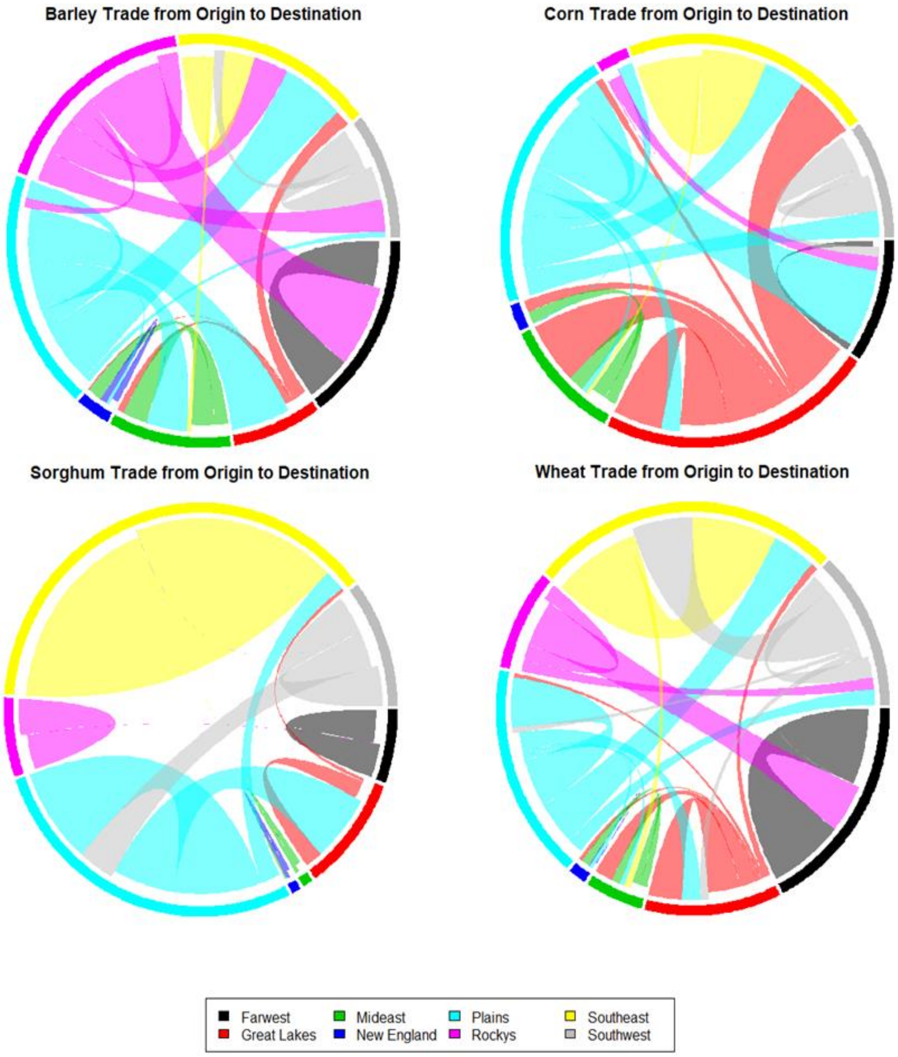
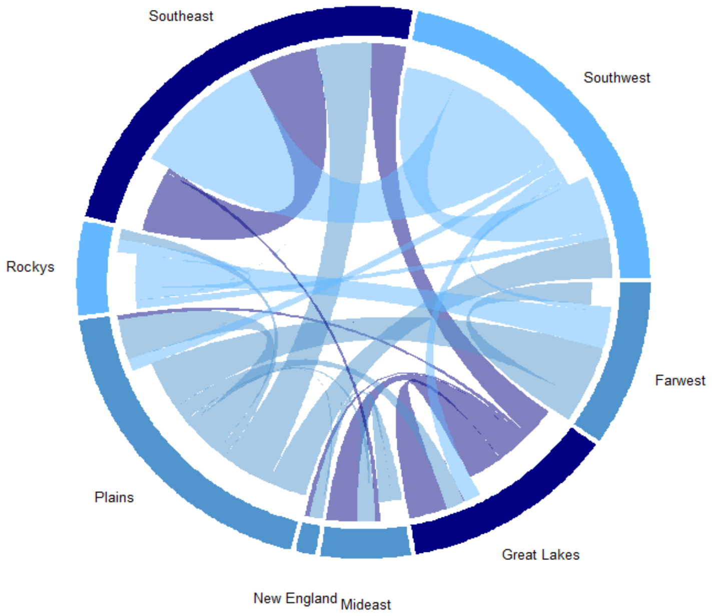


Figure 4.2: Flow of Barley, Corn, Sorghum, Wheat From Origin to Storage After Storage Has Been Accounted for.

Storage is a key component since grain availability at storage determines the flow between origin and storage, and storage and destination. 90% of the crops produced by these regions need to be stored within the region itself, while 20%-50% of the total regional demand is met by inter-regional storage to destination flows. There are significant differences in trade patterns between states and regions. Only 10% to 50% of the crop stored in a state is produced within the state while inter-state storage to demand flows meet 40% to 70% of the demand at a destination state. The inter-regional and intra-regional flows lead to an origin to destination pattern shown in Figure 4.2, but the origin to destination flow pattern between states is far more distributive and crop dependent. This is primarily because at least 60% of the grain that moves within a region actually moves between the states in a region. For example, if we consider the sorghum trade from origin to destination, the Southeast is self-sufficient. This might create an impression that the states in the region are self-sufficient. This is not true, since the state-wise trade flow result shows that 66% of sorghum is between the Southeast states while only 34% of the demand is met with crop produced in-state. Hence it is important to remember that the regional results provide a good overview of only the trade between regions.


Water flow from Origin to Destination

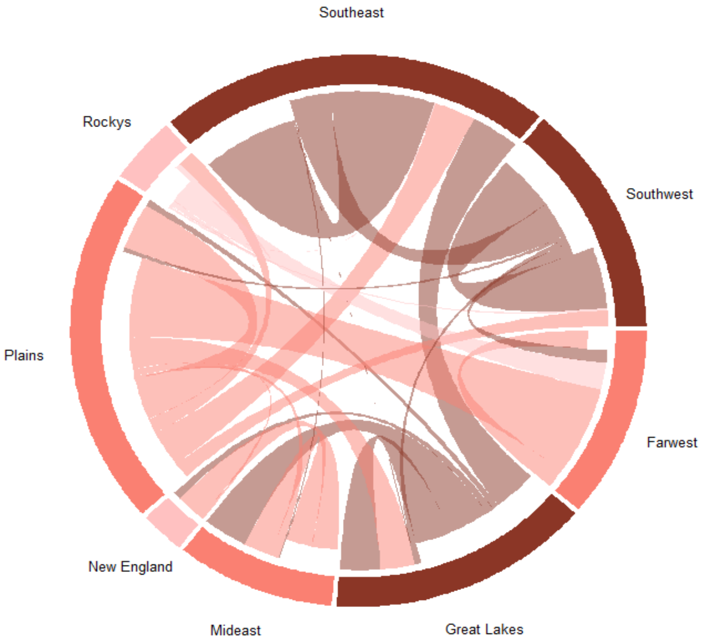

Energy flow from Origin to Destination

Figure 4.3: Total Energy and Water Flows from Origin to Destination. The Darker the Blue, the Lesser the Water Stress in the Region. The Darker the Orange, the Higher the Total Energy Related Carbon Emissions from the Region.

While 50% of production water and energy is retained within the region, the remaining energy typically moves from low carbon emitting regions to high carbon emitting regions, and significant amounts of the remaining water are sent from water constrained regions to water rich regions. These system interactions are complex and there are a multitude of factors that lead to the exchange of water and energy between regions, as shown in Figure 4.3. The outer-band indicates the level of water stress in a region in the water flow diagram and the total energy related carbon emitted by the region in the energy flow diagram. We created a custom classification for water stress under three broad groups: high, medium and low water stress. These categories are based on the water stress levels defined in the Aqueduct Water Risk Atlas . Southeast and Great Lakes fall under the low water stress (LWS) group. Plains, Farwest, Mideast and New England have medium water stress (MWS) while the Rocky's and the Southwest have high water stress (HWS). These bins are derived from the baseline water stress data obtained from WRI and the states are categorized into these bins based on the value A total of 184 million acre-feet (MAF) of water and 4.7 Exajoules (EJ) of production energy moves via barley, corn, sorghum and wheat. About 51 MAF of water moves from HWS regions to LWS and MWS regions, which accounts for 73% of the water used for the crops production in HWS regions. Another 18 MAF is sent from MWS regions to LWS regions. On the other hand, 10.9 MAF and 12.9 MAF of water are sent from LWS to MWS regions and MWS to HWS regions respectively. The most significant result is that no water is sent from a low stress region to a high stress region. The Southeast, Southwest and the Great Lakes have high carbon emissions (HCE); Farwest, Mideast, and New England have medium emission (MCE) levels while the Rocky's and the Plains have low total emissions (LCE). The HCE regions account for 2.35 EJ of the national crop production energy, out of which 50% is sent to LCE and MCE regions. The interesting aspect of energy flows from the trade assessment is that 30% of the total production energy is sent from the LCE regions to the HCE and MCE regions. The water and energy flows seem to exhibit contrasting behavior. The water flows suggest that almost twice the amount of water is sent to regions with higher water constraints to regions with lower water constraints. But the energy flows suggest that three times the energy is sent from lower carbon emitting regions to higher carbon emitting regions. While this is modestly represented in Figure 4.3, it is clearer when we analyze the state-wise energy and water flow results.

Only production energy and production water are transported through crop, but storage energy and transportation energy impacts are created across the US as well. Storage energy is negligible since grain storage is refrigeration free. But in real life there will be storage energy associated with the operation and maintenance of warehouses and grain silos. Transport of imported crops account for anything between 4% and 40% of the total transport energy, as shown in Table 4.2

Table 4.2: Transport Energy of Barley, Corn, Sorghum, and Wheat. The Total Results Include Transport of Production and Import Crops.

Crop	**Crop distance (total)**	**Transport Energy (total)**	**Crop distance (production)**	**Transport Energy (production)**
	ton-mile	MJ	ton-mile	MJ

Barley	5.65E+09	9.37E+06	3.28E+09	5.43E+06
Corn	3.44E+11	5.70E+08	3.01E+11	5.00E+08
Sorghum	4.02E+09	6.66E+06	3.86E+09	6.40E+06
Wheat	4.62E+10	7.67E+07	3.42E+10	5.68E+07

Table 4.3 shows the top 5 states of net energy and water imported and exported. The top export states are largely from the Midwest region while the import states are those with high population densities. It is important to remember that the analysis has been conducted only for barley, corn, sorghum and wheat, which are grains grown extensively in the plains and around the great lakes. Thus, it is no surprise that states in the plains and great lakes region end up as net exporters while states in the Southwest, Southeast and Farwest regions are net importers.

Table 4.3: Top 5 Net Importers and Net Exporters of Energy and Water in the US.

	Net Water Export		**Net Water Import**		**Net Energy Export**		**Net Energy Import**	
	State	Amount MAF	State	Amount MAF	State	Amount EJ	State	Amount EJ
1	OK	42.1	LA	36.4	OK	0.496	CA	0.523
2	SD	12.6	CA	14.2	SD	0.399	LA	0.404

3	KS	12.3	TX	12.4	NE	0.356	FL	0.243
4	IN	5.7	TN	8.6	IN	0.287	NY	0.225
5	ID	5.4	WA	7.5	KY	0.260	WA	0.183

Water prices and access to groundwater are two important factors. While 63% of the irrigation water is from surface water, the rest is from ground water. The use of ground water is prevalent in regions where there is limited surface water in regions like the Southwest. Most ground water sources are privately owned and hence cannot be regulated, and even when regulated, complete enforcement is impractical. Hence using regulation as a pricing tool is the best available option. Water prices, currently, are outdated and water is typically undervalued. Water prices for farmers were determined as part of long-term contracts between agricultural communities and the utility. Crop budgets from the cooperative extensions of all states that a farmer spends anywhere between $10 and $200 per acre for water, but it is observed that the price is not always related to the water constraints of the state. According to the Arizona cooperative extension's crop budget data, a farmer spends about $15 per acre for water, which is on the lower end of the water cost spectrum even though water is a constrained resource. This highlights the lack of effective pricing mechanisms and the need to account for the true value of the resource in the different states. The pricing has encouraged the unregulated use of water for agriculture, leading to the export of limited water resources to other regions. To reduce the export of water, there are several options including regulation of farmers and trade. Water constrained states that export water can increase the price of water through policy by introducing an additional tax that accounts for the scarcity of water. But this would increase the cost of production for the farmer which could encourage the farmer to reduce production or change crops – both of which could have catastrophic impacts on the livelihood of these agricultural communities . The alternative is to charge an additional fee when agricultural produce that is cultivated in a state and leaves the state. This fee can reflect the water scarcity of the state. Such a mechanism would remove the strain from the farmer and would transfer it to the market. Similar policy mechanisms can be implemented to control the amount of water exported from water constrained states.

The inter-regional energy flows show that the market forces stimulate crop trade from regions with lower carbon emissions to regions with higher carbon emissions, but disproportionate levels of emissions are incurred when crop production is shifted without any compensation. This pattern protects the high carbon emitters from further increasing their emissions without any costs to them. Let us consider an example from the flows, 0.19 million metric tons of corn is traded from Arizona to California. Both states use electricity for irrigation to produce the corn, but California's grid emits only 663lb/MWh when compared to Arizona's 1052 lbs/MWh. Thus, California avoids the 663 lbs of carbon but 1052 lbs of carbon emissions are created that fall under Arizona's emission profile. This reduces the effectiveness of policy addressing emission targets set by cities like Phoenix and Flagstaff in Arizona. This mismatch in emission levels offers policy makers from the affected states an opportunity to demand compensation for the excess carbon emissions which are typically excluded from the price of crop. This has the potential to be a new revenue stream for states that are largely dependent on agriculture. If a free market approach is preferred, the exchange of energy provides the opportunity to setup a fair carbon market centered around agricultural produce. One carbon market mechanism that comes to mind is cap and trade. The basis of a cap and trade program is emissions trading between the parties involved. Emissions trading, as set out in Article 17 of the Kyoto Protocol, allows countries that have emission units to spare - emissions allocated to them but not "used" - to sell this excess capacity to countries that are over their targets. The Regional Greenhouse Gas Initiative (RGGI) is an example of a sector specific cap and trade program between nine states in Northeastern US that focuses on power generation. A cap and trade program would provide California an option to purchase carbon credits and emit the necessary carbon to produce the corn it imports, or it can pay Arizona to purchase carbon credits for the excess emissions its generates due to its dirtier grid. These solutions are viable options but consider only the carbon impact due to production alone, and the introduction of carbon emissions due to transportation adds another layer of complexity which needs to be handled efficiently.

Import, Export dynamics and the Arizona FEW Nexus

Given California’s large impact on the limited water in the region, it is important to assess the FEW nexus from the trade perspective for states like Arizona. A significant outcome that this work has achieved is to trace crop flow, both import and export, between states, by state and by crop. Figures 4-7 show the exchange of barley, corn, sorghum, and wheat between the Arizona food system and food systems from other states. By realizing this exchange, we are also able to assess the interaction between the energy and water systems in Arizona and the states Arizona trades with. Now we can identify Arizona’s critical dependencies on other states from the FEW nexus lens. A large portion of Arizona’s barley demand is met by Utah, similarly, New Mexico is the largest source for Arizona's corn demand. Any climate impact or externality on these specific crop systems at these locations will drastically impact the supply of the crop to Arizona. Using the production costs, the transportation costs and the storage costs we can identify an alternative, in case of a failed agricultural season, to supplement the loss of crop to meet demand. The proposed approach can also estimate the energy and water impacts of the next suitable alternative as well as the economic impact on the broader trade network.

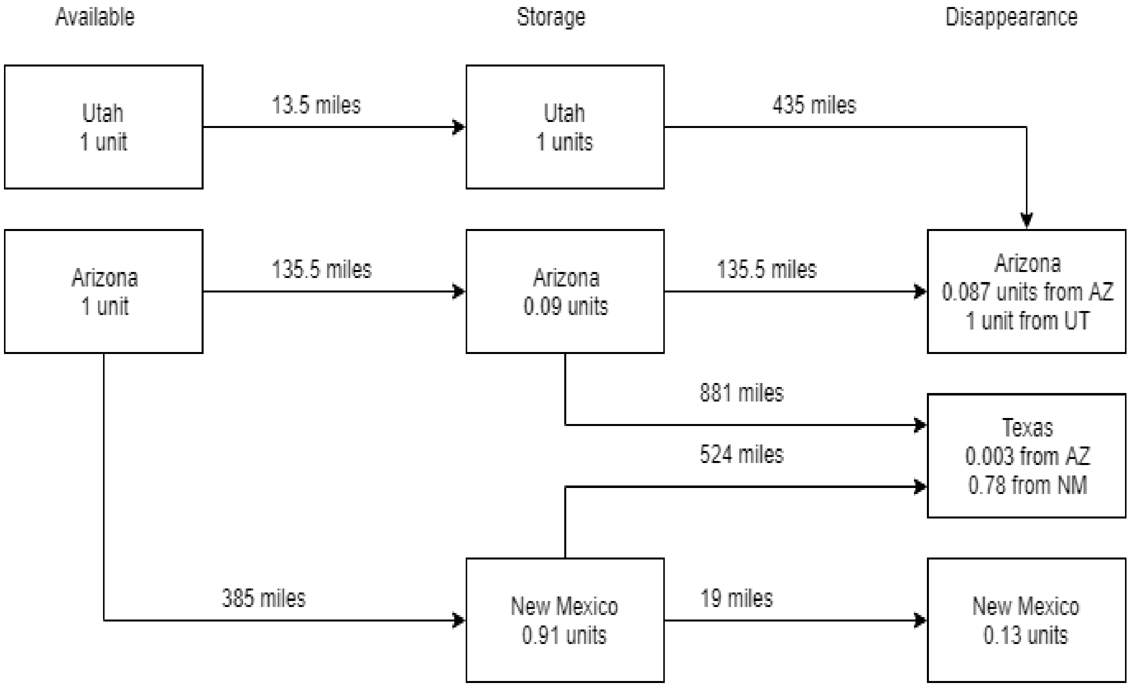


Figure 4.4: Barley Flows Due to Arizona Production and Consumption.

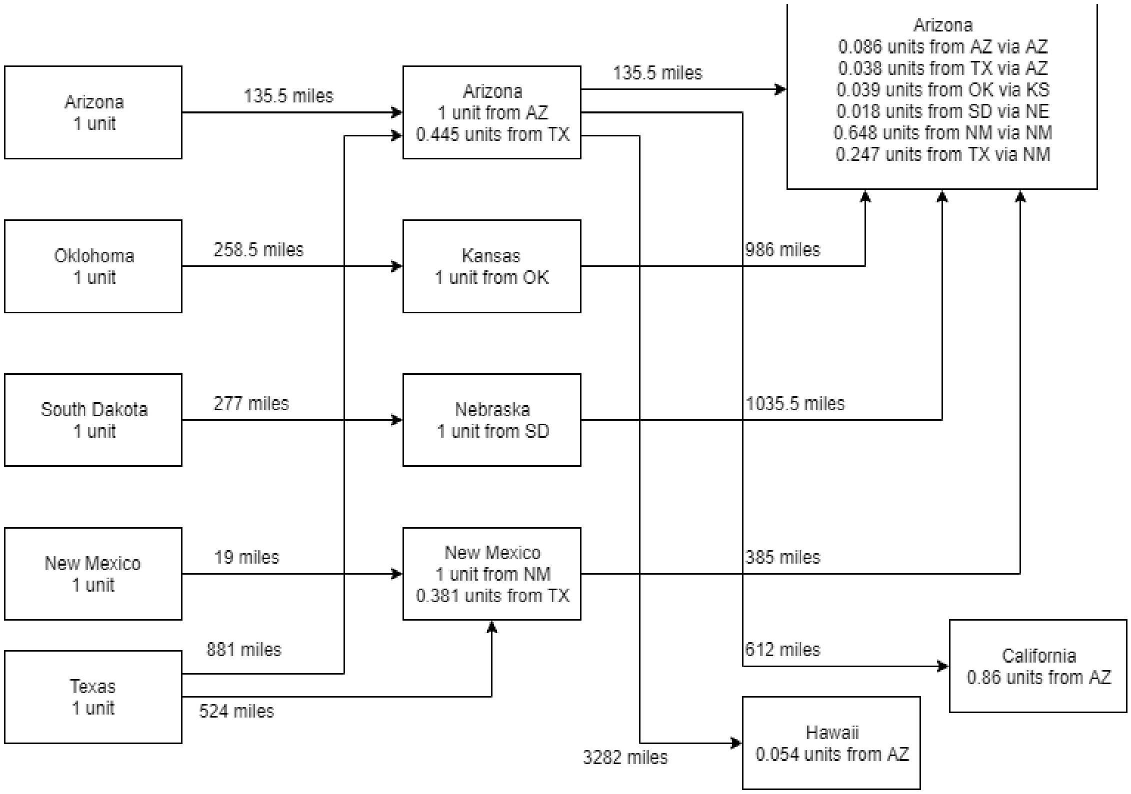


Figure 4.5: Corn Flows Due to Arizona Production and Consumption.

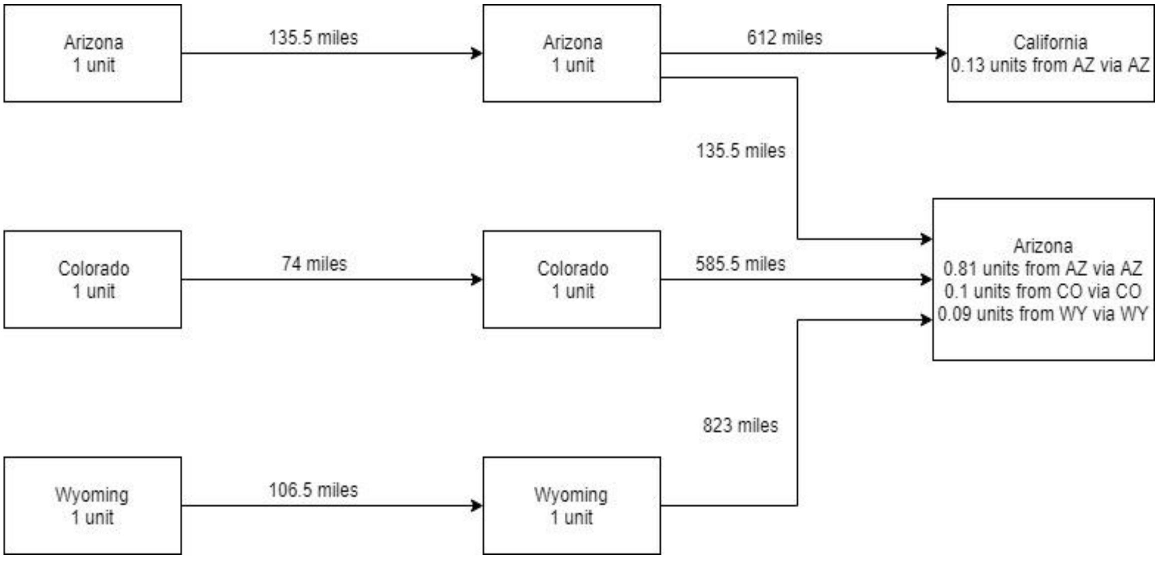


Figure 4.6: Wheat Flows Due to Arizona Production and Consumption.

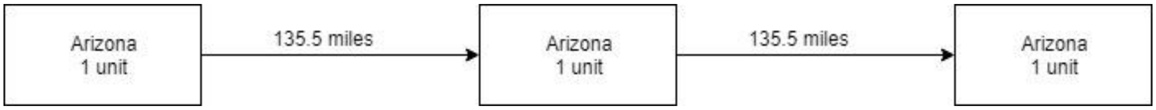


Figure 4.41: Sorghum Flows Due to Production and Consumption.

Apart from production resource use there is also energy use due to food movement. Energy is spent in moving the food and storing food. Figure 4.5 - Figure 4.7 trace the optimal path taken by the Arizona crops from production to storage to consumption. Table 4 gives a brief overview of the amount of production energy and production water that is imported from other states by Arizona, the amount exported from Arizona to other states, the amount of local resource use in Arizona. The key takeaway is that a study of the FEW nexus can no longer be confined to a region, since there are spatial dependencies across the food system, energy system, and the water system. In total, Arizona imports 2.3 million acre-feet of water but export only 0.8 million acre-feet of water through the trade of barley, wheat, corn and wheat. With regards to energy, Arizona imports 88 PJ of energy but exports only 8.7 PJ of energy.

Table 4.4: Water and Energy Impacts of Food Trade.

Crop	**Water in gal/kg of crop produced**			**Energy in MJ/kg of crop produced**		
	Export (crop	Import (crop produced in	In-State	Export (crop	Import (crop produced in	In-State

	produced in AZ)	state mentioned)		produced in AZ)	state mentioned)	
Barley	TX – 182.5 NM – 29.3	UT – 179.2	20.2	TX - 1.68 NM - 0.28	UT - 19.7	0.18
Corn	CA - 110.8 HI – 8.5	TX – 25.1 OK – 4.9 SD - 2 NM – 97.8	11.1	CA - 5.6 HI - 0.39	TX- 4.87 OK - 0.2 SD - 0.71 NM - 11.6	0.56
Sorghum			241.1			11.5
Wheat	CA – 35.8	CO – 35.8 WY – 410.6	211.8	CA - 1.2	CO - 0.475 WY - 10.2	7.9

We have chosen to develop scenarios to inspect the dynamics of trade when Arizona’s supply chain is affected and when Arizona’s ability to supply is affected.

Scenario 1: What happens when there is a change in supply to Arizona?

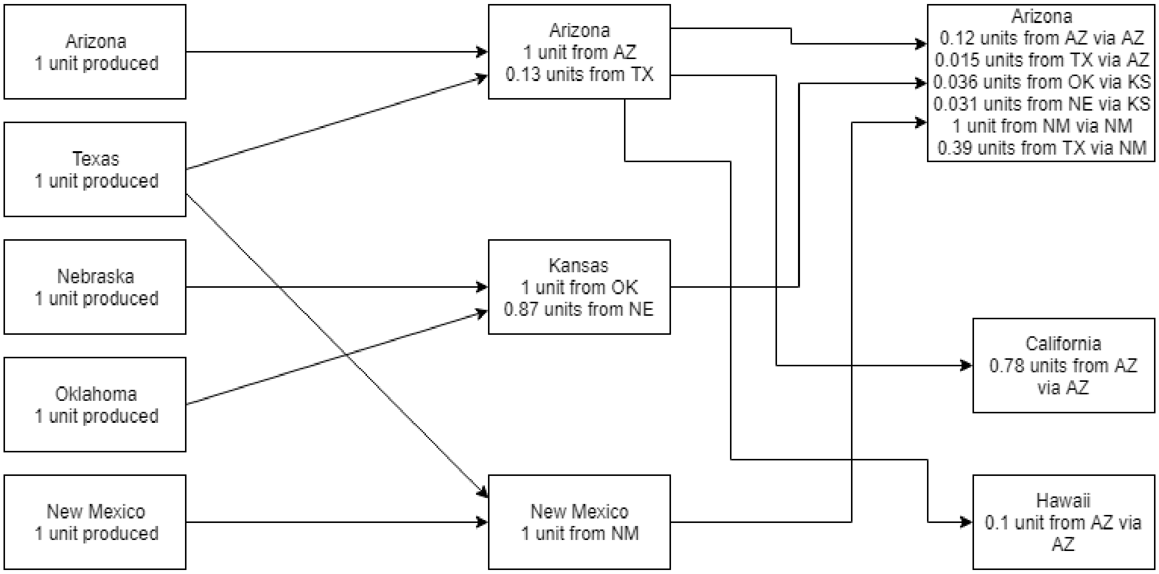


Figure 4.8: New Network When There Is No Corn From South Dakota.

Let us implement and visualize the changes to the trade network through a hypothetical catastrophic event that cuts off a source of food. We can estimate the additional costs that would be required. The total demand from consumption and exports for 2014 is 361.3 million metric tons, while the total production in the US is 383.8 million metric tons, and import accounts for only 0.6 million metric tons. Let us test the model by assuming a hypothetical scenario where a disease hits South Dakota corn reducing production to zero leading to states not storing corn in South Dakota. We chose South Dakota because, a loss of 20 million metric tons can be handled internally within the US and South Dakota is one of the supply locations for Arizona. Arizona's new corn network is shown in Figure 4.8.

Only one new flow from Nebraska is introduced to meet Arizona's demand while the rest of the suppliers remain the same even though there is some redistribution of the amount imported from these states. There is no impact to the export flows from Arizona, but the profitability of the US corn trade system increases by 5%. The increase in profitability is due to reduction in production, transportation and storage costs associated with South Dakota. This reduction far outweighs the revenue generated by corn from South Dakota. Table 4.5 shows the change in water and energy impact of Arizona trade, which leads us to estimate the amount of energy and water imported and exported via corn. A total of 1.36 million acre-feet of water is imported while only 0.05 million acre-feet of water is exported in this scenario. Both the imported and exported water has decreased from 1.45 million acre-feet and 0.08 million acre-feet, the baseline amounts. On the other hand, energy imported increases to 91PJ from 79PJ in the base line scenario, while the energy exported remains the same. The drop in the water amounts can be attributed to the change in the network as Arizona now imports from less water intense sources, but the net export amount decreases slightly leading to a drop in the net water amount exported. The outcome is counter-productive with regards to energy since the sources that are less water intense are energy intense with regards to corn. This leads to the increased energy import via corn.

Table 4.5: Energy and Water Footprint of Corn Trade for Arizona.

Crop	**Water in gal/kg of crop produced**			**Energy in MJ/kg of crop produced**		
	Export (crop produced in AZ)	Import (crop produced in state mentioned)	In-State	Export (crop produced in AZ)	Import (crop produced in state mentioned)	In-State

Corn	CA – 99.6 HI – 12.8	TX – 36 OK – 4.5 NE – 3.4 NM – 15.6	15.3	CA – 5.1 HI – 0.65	TX – 6.9 OK – 0.65 NE – 0.72 NM – 17.9	0.78

Scenario 2: What impact does Arizona's wheat production and storage capacity have on the national wheat trade network?

Arizona's impact on the wheat trade network is primarily assessed using profitability. The true impact of Arizona wheat can be realized when wheat production is dropped to zero and compared to the baseline case. When Arizona's wheat production is zero, the profits increase by about 0.001% - an insignificant amount. This small increase is primarily due to the reduction in storage, transportation, and production costs when compared to the drop in the revenue generated. The major benefit of stopping the production of wheat for Arizona is that it saves Arizona about 125,000 acre-feet of water and avoids the use of 3.5 gigajoules of energy across the system which account for about 0.1% and 0.3% of the water and energy traded across the system. It is clear that Arizona's influence with regards to grains is minimal but given Arizona's water constraint and carbon impacts of Arizona's grid, it is essential to understand the crop flow from Arizona to other regions. There will be significant gains in Arizona's influence on the national agricultural scene, if we model crops such as lettuce and tubers.

Import-Export resource dynamics through crop trade in the Desert Southwest

Transportation costs play a major role in determining the trade between regions and hence seeing California (in Table 3) as a net importer of energy and water piqued our interest in the interactions between states in the desert Southwest as well as the interaction between the Southwest and the rest of the US. The Southwest is often defined to include California, Nevada, Utah, Colorado, Arizona and New Mexico. The energy and water flows from the production of crops in the desert Southwest indicate that 3.2 MAF of water and 0.025 EJ of energy is sent to the rest of US via the domestic export of barley, corn, sorghum, and wheat. This water is a premium resource to these states and is not accounted for in the price of these crops. Colorado is the single largest exporter of energy and water from the Southwest region to the rest of the US, accounting for 45% of the production energy exported and 62.5% of water exported from the region. On the other hand, the Southwest imports 17.5 MAF of water and 0.66 EJ of energy. California is the largest importer from the rest of the US. This result is expected from Table 2. California accounts for 70.5% of water imported and 68% of the production energy imported into the desert Southwest. While California has laudable emissions goals, the emissions related to the energy and water that California imports through agriculture have not been accounted for. California's Water Footprint report say that tracing the footprint per crop is currently difficult due to lack of data. Energy and water are also traded between the desert Southwest states as well. A total of 7.6 MAF of water and 0.14 EJ of production energy is traded between these states, out of which California alone consume 44% of the water and 64% of the energy. California ends up importing 2 MAF of water and 0.075 EJ of energy from rest of the states in the desert Southwest. These individual flows, both intra-regional and inter-regional, are an essential first step for states to examine and maintain accurate accounts of their footprints.

Colorado river water and the effects of crop trade on Arizona

To understand the effects of the crop trade on the Colorado river water policy we must first examine the brief history of the “Law of the River”. The Colorado river compact in 1922 defined the relationship between the upper basin states, where most of the river's water supply originates, and the lower basin states, where most of the water demands were developing. This compact provided the lower basin with 7.5 MAF of water per annum and The Boulder Canyon Project Act of 1928 ratified the 1922 compact and allocated 2.8 MAF to Arizona, 4.4 MAF to California, and 0.3 MAF to Nevada. A 1.5 MAF commitment was later made to Mexico. According to Article III of the Upper Colorado River compact of 1948, water is appropriated to Colorado (51.75%), New Mexico (11.25%), Utah (23%), and Wyoming (14%) as a percentage of their total consumptive use per annum. The water is allocated to the states as per these percentages only after Arizona is provided 0.05 MAF per annum. As these appropriations were made, Arizona planned to build the Central Arizona Project so it could use its full Colorado River apportionment. California objected and argued that Arizona's use of water from the Gila River, a Colorado River tributary, constituted use of its Colorado River apportionment, and that it had developed a historical use of some of Arizona's apportionment. The Supreme court rejected this argument 1964 and in 1968, the Colorado River Basin project act was passed. This Act authorized construction of several water development projects in both the upper and lower basins, including the Central Arizona Project (CAP). It also made the priority of the CAP water supply subordinate to California's apportionment in times of shortage. Along the way multiple decrees were passed that settled water rights to different groups.

While the overall surplus favors Arizona, it is important to look at specific flows between Arizona and another water constrained state, California. Arizona sends California 0.14 million acre-feet of water and 2 PJ of energy and gets nothing back from the trade of barley, corn, sorghum and wheat. The water that is exported includes significant amounts of Colorado river water. 39% of Arizona's water supply is from the Colorado river and agriculture uses 70% of the water available to Arizona . The access to Colorado river water through crops is not accounted for in the limits set by the Colorado River treaty. California is the best example of a beneficiary of crop trade within the desert Southwest, since it gets 2 MAF of water through crop trade from the various desert Southwest states. Even if it is conservatively assumed that only 25% of agricultural water use in all the Southwest states is from the Colorado river, California would end up importing 0.5 MAF of Colorado River water. California would thus be using 0.5 MAF over and above the 4.4 MAF limit set by the various Colorado River treaties. From Arizona's perspective, it is important to account for this water because water is a critical resource and has large economic impact. Arizona spends thousands of dollars to maintain infrastructure so that the water can be supplied to farmers, and to generate energy to pump and treat the water. From the energy perspective not only is energy used to pump water through the CAP canals, there is energy spent in the form of fuel and electricity on farm. While fuel emissions are standard, Arizona has a dirtier grid which generates 1052 lbs of carbon per MWh of electricity, thus adding to more emissions to its carbon portfolio.

4.4 Discussion: Limitations of Modeling Complex Systems

While we have been able to build a logical model that has significant implications in the resource management and resource trade policy space, it is important to understand that this is a model of a complex system. In reality, trade is a complex (not complicated) process involving multiple entities, rules, and forces across space and time. These entities can be any of the following: importer, producer, storage operating company, consumer, the freight operating company, or the exporter. Each of these entities has a unique role and they interact with each other based on market and regulatory forces. Adding to this complexity are middlemen (so to speak) that facilitate interactions between the entities. This leads to intra-trading between the different entities. Moreover, there are contracts and agreements between the producers, transporters, and sometimes even the consumers. Additionally, consumer preferences for say organic foods or locally sourced products also affect demand. Modeling this complexity (if at all possible) is beyond the scope of this work, but is certainly acknowledged. As such, the model and results should be viewed as a representation of certain sub-processes within the overall system, shedding light on how certain dynamics are at play and their implications for energy and water.

The CFS is conducted throughout the survey year with establishments selected into the CFS sample receiving four questionnaires - one during each calendar quarter of the survey year. The establishments are asked to provide shipment information about a sample of their individual outbound shipments during a pre-specified one-week period of the calendar quarter. CFS is thus able to capture the complexity of the trading mechanism since it collects and aggregates primary data from logistics establishments. Though there is no clear indication of production, storage, destination, this dataset is the best available dataset to compare the results from the optimization model. The optimization tries to account to a part of this complexity by accounting for storage, and this is a unique approach that has not been adopted previously while analyzing food flows. Even though this is a step towards building a complex systems model, this approach still linearizes the complex process of trade. Hence a high correlation value between the CFS flow patterns and the flow patterns from the Optimization results is not expected. The correlation factor also highlights the extent of the linearization approach's ability to adequately represent complex systems. MATLAB was used to estimate the correlation between the two matrices using the function 'corrcoef'. The results from MATLAB suggest that there is a 4% correlation between the optimization results and the FAF flows, but the correlation jumps to 15% when considering only flows greater than 500000 metric tons. Though the correlation is weak, the correlation is positive which suggests that profitability is one factor in determining trade flows, but it is not the only one. It is clear that contracts are a major factor that drive trade between states, but this data is not readily available. Apart from that, the optimization model is severely dependent on the quality of data that is used as inputs. While production quantities, price paid to farmers, and storage data are state specific primary data, all other cost and revenue data, and consumption data are national averages which are then adopted to the state level either directly or on a per capita basis. The quality of data has major consequences on the results that are generated by the optimization mechanism. Let us consider them one at a time and start with the consumption data. Consumption can vary significantly across the various states, but state specific information is not available. The data input used is 'per capita' data that has then been scaled to the state level using state population. Similarly fuel costs and costs towards maintenance of infrastructure vary considerably between states thus affecting cost of transportation across all states. The data used is again a national average which doesn't account for state level variations. The price of international import and export of crop used is again a national average since state level finances for international import and export are not readily available at a crop level basis. It is important to recognize that international food prices are volatile and dependent on multiple factors that can be exogenous shocks, conditional causes that include market conditions and political environment, and endogenous shock amplifiers . These exogenous causes are thought to be the root cause of the price volatility. Exogenous shocks can include climate extremes, changes in oil prices, changes in supply and demand, and economic shocks such as trade wars. While changes in oil prices and economic shocks affect the price of the crop, climate extremes and changes in supply-demand dynamics change both the quantity as well as the price of the crop. The changes in quantities within a year are not accounted for in the optimization model either. The import and export quantities are constant for a month and are scaled according to a state's production and storage capacities. But in reality, the quantity of crops imported and exported, at best, vary by the day. These variations affect the internal flows of crop since it drives the availability of crop in a region leading to corresponding crop movement. This speaks to the need for data at smaller timescales which have significant costs associated with its collection and maintenance. All these inputs need to be of the highest quality in order to get a relatively stronger correlation between the FAF results and the Optimization results.

4.5 Conclusion

We have quantified the amount of energy and water that can be shifted using current flows due to market forces thus circumventing energy and water policy barriers. While the current study explores trade from an economic perspective, we have presented an approach that can be expanded on to explore a trade model such that water use/ energy use can be minimized. The case study and the scenarios within the case study for Arizona present the realistic possibility where market forces and effective economic policy will improve management of energy and water resources. In conclusion, it is clear that food trade based purely on profitability would allow limits on resource use to be breached even when there are policies to conserve the resource. It is also clear that the food system is a very complex sphere where profitability is but just one component. It is important to explore and expand research to identify other factors that the food system depends on. Privacy concerns have held back the capabilities of modeling such complex systems, and hence there is a need to explore the characteristics of the actors within the system as well. It is important to consider both up stream resource use as well as the extent of constraint on the resources along with behavioral aspects of the various entities in the food system for effective food sustainability policy.

CHAPTER 5 SYNTHESIS AND FUTURE WORK

5.1 Summary

Managing the input to the agricultural system is critical to managing food security concerns while informing the environmental dimension of food system sustainability. The inputs across the various phases of food, allow food to be produced, stored, and transported to its the eventual destination. The resource inputs as well as the process of making food available generate economic, social, and environmental impacts. This dissertation set out to identify the inputs in terms of energy and water and estimate the impacts that are generated across a crop's lifecycle, which is done using the LCA framework for agriculture in Arizona. Fertilizer, fuel, and electricity inputs were identified and converted to energy across production, storage and transport phases. Similarly, water consumption was modeled for all crops. The Energy-Water nexus is a familiar concept, which is incorporated into the LCA framework to estimate upstream inputs as well. Both direct and indirect system dependencies between the food, energy and water systems have been characterized.

The extent of energy and water use as well as the yield define the energy and water intensities of crop. These intensities can be manipulated naturally through climate change or manually through conservation strategies. Conservation strategies typically improve the efficiency of a process through the implementation of a technology or reduce resource use by using less resource intense alternatives. In that sense, the following conservation strategies were modeled – no tillage, LEPA, LESA, SDI, replacing fertilizer with manure, improving truck fuel efficiencies, and improving storage hardware and design. Since the resource use is heavily skewed in favor of the production phase, strategies revolving around the production of crop conserve the most energy and water. LEPA and LESA are the best performing strategies, reducing energy use and water use by nearly 30%. While this conservation improves the resource intensities of crops, climate factors inevitably increase resource intensities by decreasing yield and increasing energy and water use. Barley, corn, sorghum, and wheat were selected as test subjects to identify climate response. The simulations on crop productivity were carried out in Cropsyst, a crop growth simulation software. There was no standard response to temperature and water availability since crop growth also depends on factors such as nutrient availability, crop characteristics and soil conditions. This led to considerable variance in crop productivity across Arizona, but it was impossible to identify a representative level of variance. Thus, a county specific analysis was carried out and the energy and water savings for counties with the largest share of crop lands was estimated. It was found that a large-scale implementation of LEPA and LESA can save water and energy while a 50% implementation saves water and does not conserve energy.

Crop productivity decreases as temperature increases but the population in Arizona is projected to grow, making trade critical to Arizona’s food supply. This gives rise to the need to integrate trade to the FEW nexus. Barley, corn, sorghum, and wheat are considered here as well due to data constraints. Trading mechanisms allow the flow of food as well as the flow of virtual resources. Thus, the integration of trade to the FEW nexus provides an opportunity to identify critical trading partners as well as the extent of resource flow between regions. Currently there is no data available on trade between states at a crop specific level. Hence, we develop an optimization mechanism that generates the trade routes based on maximizing profitability. Using the output of the optimization mechanism as well as crop water use and energy use, the flow of virtual water and virtual energy between regions was determined. This threw insight on cases where possibility of water flow from water constrained regions, as well as cases where energy flowed from carbon intense regions to regions with less carbon intensity. The trade network made it possible to trace Arizona's supply chain with regards to the crops that are considered. Overall the conceptual framework presented in Chapter 1 was built from bottom up and the resource intensities were characterized and analyzed in order to estimate climate impacts. The flow of food as well as the resource flow through food was also estimated to inform decision making related to water constraints and carbon footprints.

5.2 Significance and Potential for Improvement

The proposed conceptual framework is a closed loop approach that attempts to assess the sustainability of the food system from a resource management perspective. It incorporates aspects of food security and environmental impact of food. The LCA framework offers the opportunity to explore the interactions between the food system and other infrastructures as well as institutions. The energy and water intensities of crop estimated in Chapter 2 provides farmers a benchmark on resource efficiency of current agricultural practices, while acting as a metric for policy makers the impact of cross-sectoral policies that influence agriculture. The climate variability in Chapter 3 allows water managers in Arizona to avoid collective action that may not be an effective solution. The change in crop productivity, change in water and energy use highlight the need for local decision making in the face of climate change. The most significant of all is the inclusion of storage in the trade network. Current works that analyze food trade, and hence resource flow, have been unable to incorporate the storage phase. With the inclusion of the storage phase, the flow of crop can be assessed more accurately.

The three chapters have made contributions to FEW nexus research, but there is always room for improvement with better data. Since a modeling approach was adopted for the dissertation, publicly available data is a primary driver of this research. A major reason the LCA framework excluded the use and waste phases of food was lack of data on fresh produce and processed manufactured food. While it might be difficult to determine all possible manufactured items, it would be useful to have data on the percentage split between the fresh produce and manufactured goods. The crop budgets obtained from the Arizona cooperative extension is from the year 2000. This data is almost two decades ago, and there has not been another effort by the cooperative extension to build new budgets. Now the process of preparing these budgets are expensive, but the data will be immensely useful for researchers in the FEW nexus space. This dataset will definitely update the energy calculations to current day standards in Chapter 2 as well as the energy flow results in Chapter 4. The data format constraints were the most restraining aspect of the crop growth simulations in Chapter 3. While climate data is openly available, Cropsyst is developed to process a specific type of climate format called the UED file format which easily translates the location information as well as climate information into a 2-D format from the 3-D netCDF format. Currently, this conversion is not publicly available and hence custom weather patterns cannot be easily converted to the required UED format. The management files defined in Cropsyst are again defined using the data from the crop budgets, further highlighting the need to update this data. While Cropsyst was intuitive while running simulations manually, it would be useful for the user if there were a manual on batch processing mechanism involving Cropsyst. This automation process would expand the exploration of scenarios that can be simulated at a faster time.

Another model that was severely data constrained was the optimization model in Chapter 4. The major areas of improvement that can be achieved with regards to data quality are the consumption data, import data and export data. The consumption data is scaled off of the monthly food, seed, and industrial use data. Per state consumption data would of better quality and yield more accurate results. The import export datasets are again secondary data, estimated from the Feed grains database's monthly imports/exports and the State Imports by NAICS Commodities dataset. While national level import and export datasets are available, it would be beneficial for FEW nexus research to have this data at the state level. Trade is a complex mechanism and hence establishing food exchanges through food is a messy affair. Storage is an important aspect of food security, but the extent of interaction between storage entities is relatively unknown. It is known that food is stored and that there is maximum storage time. There isn't any information on average storage time of various crops. There is also lack of information on the extent of product exchange between the storage entities. This missing data limits the optimization model to its current conservative form.

5.3 Future Work

There are many opportunities for future work that improve and expand the scope of the dissertation models as well as those that integrate the conceptual framework into research on food system sustainability and food system resilience. Inclusion of food waste would be a good next step while exploring the FEW nexus. Food waste has become a major issue with cities across the US assessing the possibility of capturing the possibility of fuel from food waste. Food waste expands the system boundary presented in Chapter 1 and adds additional interactions between the food, energy and water systems. Only this time, the interaction between energy and water would be bidirectional. The same LCA mechanism can be used to identify the fuel to collect and transport food waste to the digester, the amount of water required to activate the digester, and the amount of biogas generate. The upstream impacts would include the energy and water needed to produce the fuel used for collection and transport, the embedded energy in water, as well as the energy required to process the biogas and pump it to its destination. Another component of the food system is livestock. This dissertation intentionally chose to study agricultural produce, but meat can be thought to have the same life phases of agricultural produce. Thus, the LCA framework can be adopted to livestock to characterize the FEW nexus interactions. Only in this case, there will be livestock feed instead of fertilizer, while water and energy inputs would vary according to the needs of the livestock.

While this dissertation chapter models the bio-physical interactions between the food, energy and water systems, there is an opportunity to build other layers of interactions that characterize institutional interactions and socio-economic interactions. These intangible interactions would address the equity and justice issues associated with the food system. At the institutional level, decision making drives the costs as well as amount of resource available to agriculture. It is possible to use the multiple-criteria decision analysis framework from operations research to model these decisions. This approach explicitly evaluates conflicting criteria to provide a decision recommendation that adhere to the decision maker and stakeholder biases towards the conflicting criteria. Another framework that can model decision making would be the multi-attribute value theory.

This theory builds a value tree, based on the preferences of the decision makers and stakeholders, to determine impact categories and account for all interventions. It would be ideal to use these decision frameworks since they have been known to integrate with the LCA framework. Accounting for the decision-making process would allow FEW nexus researchers to determine the influence of decision making in one system on the biophysical interactions as well as the costs associated with it. This decision-making process would also have to include socio-economic criteria such as wellbeing of stakeholders.

A key aspect that is typically missing in the most FEW nexus work is the influence the quality of soil has on the FEW nexus. Maintenance of soil quality is an important aspect of farming as this determines the amount of fertilizer required which is a major contributor to the energy and water impacts of agriculture. Soil quality also drive farming practices such as duo cropping to allow appropriate levels of nitrogen to be fixed in the soil. Agriculture is a key part of the nitrogen biogeochemical cycle and soil quality plays an important role in this cycle. Other common indicators of soil quality are organic matter, pH, phosphorous and water storage. Changes in levels of these indicators can drastically affect crop productivity in the region. Hence direct climate impacts are not the only threat to agricultural productivity. Changes in soil quality due to climate change is a threat as well. The USDA National Resource Conservation Service along with the Blackland Research Center at the Texas Agricultural Experiment Service has developed a database that indicates areas in the country with the highest potential for soil quality loss. The changes in crop productivity under these new soil conditions need to be modeled and simulated under increasing temperature scenarios to establish the worst-case scenario.

Cropsyst would be a useful simulation software, once the software developers provide extensive instructions on the development of custom weather and soil input files. The results from such a simulation would help policy makers prepare for drastic changes in the FEW nexus and hopefully force action-oriented food security measures.

While there are opportunities to expand scope of the individual models and approaches, there a much larger opportunity to use the conceptual framework. The scope of the conceptual framework itself was limited to Arizona and the US, but the framework provides an opportunity to study the FEW nexus interactions between regions at two different geographic scale, (i.e.) between countries, a country and a state, a country and a county, etc. This dissertation has built a conceptual framework with the bottom up approach at its core. Using the LCA framework, it is possible to assess crop specific FEW interactions for a region at any geographic scale. The optimization mechanism enables the region to identify its trading partners and evaluate its environmental footprint as well as the impacts the region faces due to these exchanges. This nexus of nexuses approach helps inform regions that intend to understand its complex food supply chain in an effort to take positive action. By understanding their supply chains, regions can carefully evaluate trade links that are critical to food supply, as well as identify inefficient exchanges – both economic and environmental. Given the extent of opportunities available, the hope is that this dissertation provides usable methods and information to carry out research to inform food system sustainability.

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