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DEVELOPING AN INTEGRATED MODEL FOR THE CORN, ETHANOL, AND BEEF SYSTEMS USING A LOOSELY COUPLED WEB FRAMEWORK

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DEVELOPING AN INTEGRATED MODEL FOR THE CORN, ETHANOL, AND BEEF SYSTEMS USING A LOOSELY COUPLED WEB FRAMEWORK

by

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With the global population approaching 9 billion people by the year 2050, the world's food, energy, and water (FEW) resources must be used more intelligently to provide for everyone. While we understand how individual FEW systems behave using modeling, we cannot understand the full environmental and production impacts of decisions in each system without understanding how they are all linked together. An approach to coupling these systems is starting with identifying a few highly interconnected FEW systems. The corn, ethanol, and beef systems are large economic and agricultural drivers in the Midwest United States and are highly linked. Many individual models exist for each system and are wrapped in software to be used for decision support. This thesis explores the integration of the corn, ethanol, and beef systems by connecting existing models using a loosely coupled web framework. Each model is wrapped in Python code and linked, also in Python, using connections that reflect the real world system. Environmental impact of the full integrated system is done using life cycle assessment that accounts for inputs and outputs for each model. Simulations done with the models predict the resource production of the integrated system given user inputs and the full environmental impacts in water use, energy use, and greenhouse gas emissions. The objectives of this thesis are: (1) to review literature of FEW nexus integration by coupling models, (2) integrating the crop and biofuel systems with service-oriented architecture, and (3) integrating the corn, ethanol, and beef systems with service-oriented architecture. Scenario analyses are done to test the models' responses to different management, climate, and resource demand scenarios.

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Chapter 1
Review of Literature

1.1. Overview

By the year 2050, the global population is projected to reach 9 billion people which will put significant pressure on essential food, energy, and water resources (Godfray et al., 2010). We have developed strong understandings of how individual food, energy, and water systems work on physical, economic, and environmental levels, but these food, energy, and water (FEW) systems are highly interconnected and understanding these interactions is essential to making more sustainable decisions within the nexus (Bazilian et al., 2011; Finley & Seiber, 2014). There needs to be more work understanding how the FEW nexus is coupled to create more holistic impact assessments of decisions to the environment, economy, resource use, and climate change.

Recently, researchers have been becoming more engaged in interdisciplinary thinking to couple these FEW systems in the form of life-cycle assessments and integrated systems modeling. There is high potential in using the FEW nexus approach to determine public policy for utilizing water and energy sources for more efficient use in agricultural systems. This can be used as a guiding principle on the local, regional, or national level for quantifying economic and environmental effects of trading, tax plans, or innovation (Franz et al., 2017; Kurian, 2017; Pahl-Wostl, 2017).

Some of these studies quantify interconnections in the FEW nexus in general units such as the value of energy or mass of each resource. Other studies look at specific FEW systems and integrate them into a model to better understand how the integrated system behaves. An example is in the Midwestern U.S. which has a variety of connected agricultural production systems such as corn farming, ethanol production, and beef production. Some modelers look at these systems that are specifically prevalent in the Midwestern U.S. and integrate them to understand optimal private or public policy decision making. This paper will review work that has been done to integrate systems of the FEW nexus, both in general context and for the Midwestern U.S. region. In addition, this paper will review computational integration methods that can be used for integrating FEW systems.

1.2. General FEW examples

A common initial approach to integrated modeling is to perform preliminary mapping. Ziv et al. (2018) uses a technique called Fuzzy Cognitive Mapping to connect FEW systems to holistically understand the impact of Brexit on the UK. This study parametrized factors such as trade, taxes, and other legislation, and quantified its effect on the nation’s food, energy, and water resources. Zimmerman et al (2018) focused on creating a general framework for urban FEW systems and mapped the relationship between energy and water to provide safe, quality, and fresh food for urban systems. This mapping helped quantify waste and resident health by using static and dynamic analyses of these systems. These models do not calculate tangible values, but instead output dimensionless index values to compare different scenarios.

Examples of models developed by researchers to integrated FEW systems vary in the types of inputs and scenarios that are fed, the method of linking systems, the types of output objectives, and what case studies are run. Table 1.1 shows examples of integrated models developed and breaks down characteristics of each.

One approach to calculating system outputs is to quantify all resources in terms of exergy. One model aimed to optimize a FEW nexus system by determining the exergy values of food, energy, and water values of a local production system and solving the system (Hang et al., 2016). This same approach was used as an educational tool to help students better understand the connections of the FEW nexus (Kılkış & Kılkış, 2017). A case study on a dairy facility was performed to show how the model behaved under different scenarios.

Land use is an essential input to the FEW nexus and many researchers want to use models to find the optimal allocation of land for agricultural production and resource use. The objective of Chen et al. (2018) was to understand the agricultural land and water use of countries and to optimize global use of trade resources. They developed a multi-regional input/output (MRIO) model that tracks the monetary flow of global trades for economic evaluation of a country's resource use. Chitawo and Chimphango (2017) integrated the rice and biofuel systems for northern Malawi to analyze the environmental and economic impacts of land and irrigation practices on rice farms. They calculate food provided and energy used from using crop residues as biofuel input to irrigate the fields.

Some models analyze countries and the impact of different import/export scenarios. Daher and Mohtar (2015) use import/export heavily when determining how certain food systems affect the nation's ability to use resources and feed the nation economically. Berardy et al. (2017) looks specifically at the state of Arizona and how climate change will affect the state's irrigation and agriculture. Exports are an important output of their model in determining economic stability. Climate change is used as a feedback loop to agricultural water availability and this tool models water and energy consumption in integrated pathways. Another MRIO model analyzes trade scenarios of the UK to produce full environmental analysis in terms of greenhouse gases (GHG) emitted, water used, and energy used (Owen et al., 2018). Quantitative assessment is shown in terms of nexus impacts such as food services, health services, and construction.

Alternatively to calculating outputs as real values, some models calculate dimensionless values as sustainability indices as a way to compare different scenarios or optimize systems. A study by El Gafy et al (2017) assigns index values to various crops in Egypt based on international and national water and energy footprints. Scenarios are run based on population, consumption, trade, yield, and climate change while outputs are the dimensionless index values. Another model optimizes the system based on the sustainability index generated by scenarios (Karan et al., 2018). Inputs for these scenarios are stochastically generated for weather and energy flow. The objective function optimizes energy and water consumption where a sustainability index is assigned to each FEW component.

While many of the previously mentioned models are built from scratch or based on historical data, others are built off of previously developed system models. In Kan et al. (2018), a global optimization method is used on the IHACRES hydrological models to solve for optimal FEW scenarios. IHACRES is an environmental modeling framework with a complex workflow to predict streamflow. The International Food Policy Research Institute (IFPRI) is developing the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to determine the world’s capacity to handle climate change and food security (Robinson et al., 2015). It is a global integration of FEW systems that links various cropping, climate, economic, and other models to solve these problems.

Table 1.1 – Descriptions of integrated model examples

Paper	Inputs	Model Integration	Output	Case Study
Ziv et al., (2018)	Legislation-based scenarios	Fuzzy Cognitive Mapping	FEW nexus concepts	UK – Brexit scenario
Zimmerman et al., (2018)	Descriptions of water and energy usage in system	Network modelling	Impact on water and energy usages	New York City – Hunts Point Food Center
Hang et al., (2016)	Exergy values of FEW resources	Exergy balancing	Food production, energy supply, and water supply	UK towns – Whitehill and Bordon
Kılkış & Kılkış, (2017)	Energy resources	Exergy matching	Energy and waste production	Dairy facility
Chen et al., (2018)	Land use, water use, population, and GDP of countries	MRIO	Net import and export of countries, agricultural land and water trade flows	Global system
Chitawo & Chimphango (2017)	Energy, water and land use of rice farms	Integration of rice and biofuel pathways	Energy and water requirement, profitability	Malawi
Daher & Mohtar (2015)	Environmental and trade characteristics of food products	Calculates indices from connecting system flows	Dimensionless index	Qatar
Berardy et al., (2017)	Population, climate, energy sources, water use, agricultural land use	Dynamic modeling of crop production from water and energy availability	Import/export, crop yield, water requirement	Arizona – climate change
Owen et al., (2018)	Food production, energy and water	MRIO	UK nexus impacts	High producing countries (i.e. UK, China,

	consumption, employment, and gross-value added			US)
El Gafy et al., (2017)	Population, crop production, water footprint and energy footprint inputs, FEW consumption	System dynamic model	Dimensionless index	Egypt
Karan et al., (2018)	Closed system, energy and water use, food demand	Integrated quantitative calculations	Index defined by energy and water consumption	Single greenhouse
Kan et al., (2017)	Soil and hydrological inputs	Accelerated global optimization of IHACRES models	Soil moisture and linear reservoir flow	Dongwan catchment in China
Robinson et al., (2015)	Global climate, crop, and water demand inputs	Integration of climate models, crop models, water demand, and economic trends	Yields, prices, harvested area, trade, production, consumption	Global system

1.3. Midwest US

The Midwest US region is known for having large agricultural output due to its land and weather conditions. The FEW nexus is highly interconnected here with the massive amount of food that is produced and the amount of water and energy that is required in production. In 2017, 160,507 acres of land was allocated to growing and harvesting principal crops such as corn, soybean, and wheat (National Agricultural Statistics Survey, 2018). It particularly grows more corn than any other region and contributes about 28% of the total global corn production (USDA FAS, 2018). Corn is not only used for food consumption but is also deeply connected to other agricultural systems in the Midwest. Corn ethanol plants have been built in large numbers throughout this region. Both corn and cellulosic ethanol plants require corn production for its inputs in order to provide energy for consumers (Renewable Fuels Association, 2018). A large amount of livestock production is also dependent on using corn as feed. Beef cattle that are raised on feedlots have a high concentration of corn grain and distillers grains (corn ethanol byproduct). This is particularly relevant as states in the Midwest have a higher cattle inventory than any other US region (USDA National Agricultural Statistics Survey, 2018a).

All of these systems are high users of energy and water which makes it necessary to understand how they are connected to better utilize these resources. Researchers have spent decades modeling these individual systems but have only recently started to model them together. This section will review models that represent each individual system and integrated models developed to simulate the full corn, ethanol, and beef system.

1.3.1. Models

1.3.1.1. Corn

Crop modelling is a highly researched area and corn itself has many models dedicated to it. CERES-Maize is one of the earliest corn models developed and is continuously improved upon to this day (Jones et al., 1986). Other crop models include CROPGRO, WOFOST, Hybrid-Maize, and APSIM-Maize (Boote et al., 1998; Keating et al., 2003; van Diepen et al., 1989; Yang, 2016).

Furthermore, many programs have been developed as a way to package these models and attach them to a larger modular framework. DSSAT uses the CERES-Maize model in its software and also includes other crop pathways that a user can simulate. It has a large user base in over 100 countries and is well supported by the research community. APSIM works similarly except that it uses its own APSIM-Maize model for corn. AquaCrop-OS is an open source model developed by the Food and Agriculture Organization to give users the ability to analyze crop response from water (Foster et al., 2017). CropSyst is a tool that gives users the ability to integrate the wrapped crop models with environmental, climate, and hydrological models that can be used on different spatial scales (Stöckle et al., 2014). EPIC is another model that includes many environmental and climate components which originally focused on soil erosion and runoff. All of these models and tools are available for researchers and decision-makers to predict yield given certain environmental and management conditions. Developers have made significant effort to make these tools friendly to both end-users and other developers.

1.3.1.2. Ethanol

Modeling the amount of ethanol produced from corn is not as difficult since most facility processes have very little variation to them. The importance of ethanol in this system though comes from its environmental impact. Many life cycle assessments (LCA) have been developed to assess the environmental impact of different products, including biofuels. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) is an LCA that specializes in transportation fuels (Elgowainy et al., 2012). It can analyze environmental outputs from petroleum fuels or biofuels from raw materials to final consumption. It is developed by Argonne National Laboratory and sponsored by the US Department of Energy. It is a free software and includes hundreds of fuel pathways. SimaPro is a paid software that not only has many different product pathways, but also has a variety of different environmental assessments from which users can choose (Pre Sustainability, 2017). The Global Emissions Model for Integrated

Systems (GEMIS) performs LCA for various material flows, energy sources, transports, and wastes (Fritsche, 2000).

1.3.1.3. Beef

Modeling beef growth is dependent on understanding the nutritional requirements of the animal. The National Academies developed a well-accepted beef cattle nutrition model that can predict gain, dry matter intake, and other outputs based on feed ration formulation and animal characteristics (Galyean et al., 2016). This model contains extensive formulas and that can be implemented in different programs. The committee itself has developed the Beef Cattle Nutrient Requirements Model (BCNRM) which is a spreadsheet model where users can create a feed ration and describe the animal in detail to determine average daily gain, methane emissions, nitrogen excretion, and more (Tedeschi et al., 2016). The University of California-Davis developed Taurus, a program that can similarly predict growth from feed inputs. It makes similar calculations to the model developed by the National Academies and has a friendly user interface for beef growers (UC Davis, 2014).

1.3.2. Integrated corn, ethanol, and beef models

Since all of the above systems are capable of being modeled, there is a way to develop a full integrated model linking all of them. The Integrated Farm System Model (IFSM) does this on an individual farm scale (Rotz et al., 2012). A farmer that has their own beef and crop system can describe their farm on the program from management techniques to weather. IFSM calculates environmental, production, and economic outputs of the entire system such as GHG emitted, nitrogen cycled, food produced, profit, soil erosion, etc. It also optimizes the user’s feed ration based on desired beef growth and profitability. IFSM uses equations from BCNRM to model its beef system and equations from CERES-Maize to model the corn system. The equations are written directly into the program as opposed to utilizing the existing software as some of the equations are slightly altered. The Biofuel Energy Systems Simulator (BESS) integrates the entire corn, ethanol, and beef nexus to show final environmental and production outputs (Liska et al., 2009). It uses ethanol production as the functional unit to determine corn and beef production capacity. The crop equations are similar to those used in the Hybrid-Maize crop model and the beef model is similarly taken from BCNRM. Its environmental output is determined by running an LCA built into the model.

1.4. Integration Techniques

There are a number of different computational methodologies that can be used to integrate models. Argent et al., (2004) addresses many of the ways that researchers can develop programs to connect these systems models as well as the challenges, pros, and cons of each type. Object-oriented and component-based modeling are classic approaches and have been used in many examples. A more recent trend of integrating models, particularly environmental models, is using loosely-coupled web-service. Example methodologies used for FEW applications are addressed in this section.

1.4.1. Object-oriented and Component-Based

Argent et al., (2004) describes object-oriented (OO) modeling as a framework of connecting models as inherited objects. Inheritance is the key method of communication as it allows models to easily transfer similar data types and allows flexible reconfiguration of the integrated model framework. Component-based (CB) modeling defines models as separate modules that communicate with each other via subroutines of data exchange. Model connections must be defined in a programming environment in component-based modeling. Both methods are commonly used when researchers integrate models to develop local software.

It is common to integrate existing models using a CB approach as the models are already packaged in their own software and are not inherited in each other. Ma et al., (2006) integrates the CERES-Maize cropping model and the Root Zone Water Quality Model (RZWQM) to create holistic assessment of certain crop production scenarios with water quality. These two models exist separately so they are integrated using a CB design of data exchange. The MARKAL model was developed to simulate the market for biofuels by integrating crop and biofuel systems (Elobeid et al., 2013). Relevant inputs and outputs of existing crop and biofuel models were linked to show the economic effects after integration. Kim & Dale integrated several models and datasets to assess crop-biofuel systems as well. Soil dynamics of this system were modeled with DAYCENT, crop production and management data were provided by the National Agricultural Statistics Survey (NASS), GREET formulas for ethanol production, and the EPA-TRACI assessment method for environmental impact.

The OO approach can be useful for researchers who write individual formulas into their programs can define the inheritance. It is used in the APSIM model which connects several cropping objects using OO modeling (Keating et al., 2003).

1.4.2. Service-oriented architecture

Service-oriented architecture (SOA) is a framework for connecting components as web services. In this case, the components can be different models of the FEW nexus and are exposed to the user via a server. It can take many of the philosophies of OO- and CB-based modeling, but makes all components, including the framework, available as web services. The models are run in the server and are connected by linkages that can be described either by the user or subroutines built into the program. When a user makes a request to the server with certain parameters, the model on the server side will run and send the output back to the user. The benefits of this are (1) the models are available to the user without installation and (2) the integration framework is more accessible to the user and can be changed. The user can have control over how models are connected and can run their own FEW nexus scenarios. Further, they will not have to worry about connecting software that are written in different languages or have data compatibility issues as those problems should already be fixed in the back end when developing the SOA. Vitolo et al., (2015) reviews many other web technologies that environmental modelers use to work with model frameworks and big data.

The Open Geospatial Consortium uses SOA to make environmental datasets and models available online (Castronova et al., 2013). They developed a protocol that allows users to use an open source interface and interact with the models on the server through user-described workflows. The user can communicate with the Representation State Transfer (REST) server by sending requests that activate the subroutines in the back end. A hydrologic model, TOPMODEL, is exposed as a service that the user can interact with. Once the user connects to this exposed resource, they can add it to a workflow of other models such as calculating evapotranspiration.

A similar project to make geospatial services available online was described in Granell et al., (2010). The workflow of geospatial modeling is interdisciplinary by nature, and this project aimed to make the models and data formats available as web services to ease the workflow development. Various hydrological models, datasets, and maps are exposed using SOA with a workflow that can integrate all components.

Belete et al., (2017) describes a Distributed Model Integration Framework (DMIF) to develop SOA for environmental models. It describes 3 layers: (1) a user interface, (2) an integration layer that contains subroutines to run the models, and (3) and a resources layer to run the models on the server with available data repositories. Similarly, Peckham (2014) creates a smart modeling web framework with a Basic Model Interface (BMI) simplify the workflow for users. Jiang et al. (2017) builds onto this work by enabling models with BMI and exposing them with this smart modeling web framework. The example they use is the hydrological TopoFlow model which has various components and can be integrated into a larger workflow. Granell et al., (2013) proposes a similar web framework that is resource-oriented and does not have a data repository but is still connected to the user using REST services.

While most of the described models are strictly environmental and water models, it shows enormous potential for expanding to the other branches of the FEW nexus and can be used to link systems from various disciplines.

1.5. Conclusion

In recent years, researchers have recognized the need to connect interdisciplinary systems to gain a more holistic understanding of how they work. Integrated modeling is a growing field to address this issue using many different techniques for a variety of different applications. This paper reviewed integrated models that address general FEW systems that can be applied to a variety of applications. It also particularly addressed the FEW nexus in the Midwest and the individual system models that can be integrated.

These modelers use many different computational techniques to integrate these models into holistic, user-friendly programs and continue to explore the best ways to do so.

The field of FEW nexus modeling is rapidly growing to tackle complex environmental and sustainability issues of the world. These models all take various approaches, work on different scales, and output different impact assessments, but all are working closer to helping us understand how our valuable food, energy, and water resources are interconnected.

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Chapter 2
An integrated framework for crop and biofuel systems using the DSSAT and GREET models

2.1. Introduction

With the global population nearing 9 billion people by the year 2050, there is a need to better utilize the food, energy, and water (FEW) resources that are essential to living in the 21st century (Godfray et al., 2010). The population growth puts pressure on the existing resources which must be used more intelligently to support the projected population. The food and energy systems of the world are highly interconnected and understanding these interlinkages is vital in sustainably solving the resource demand problem that will perpetuate in the future (Bazilian et al., 2011). Energy is essential for producing crops, but with the progress of biofuels, food is also used as a means to produce energy which can displace the currently used fossil fuels. Crop modelers have been successful in modeling crop systems such as corn which can be processed into corn ethanol. Biofuel experts have also developed models for the biofuel system, but there is a gap in integrating these two systems using the existing tools. This is true for coupling any interconnected system in the FEW nexus.

Daher and Mohtar (2015) explore FEW modeling using a macroscopic approach. Their model, the WEF Nexus Tool, focuses on the environmental impacts of producing a certain food source of a whole region or country by estimating water, land, energy, and carbon requirements. The WEF Nexus tool calculates not only environmental impact, but also financial cost of either producing or importing the food source. Hang et al (2016) on the other hand aims to integrate the FEW nexus on a local-scale rather than regional. It is also very general and can be applied to different food sources for a single production system. It uses an exergy balance approach to make calculations which gives the total environmental impact of the system using food, water, and energy.

Researchers have recently been attempting to couple systems to identify interlinkages in the FEW nexus. Some studies provide a general framework for systems of given scales and others aim specifically to connect certain agricultural systems. The International Food Policy Research Institute (IFPRI) developed the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) as a tool to understand the effect that certain policies and decisions have on sustainability and food security. IMPACT integrates economic, climate, and crop models to simulate the national and international agricultural markets. More meaningful assessments of the impacts on the environment, food production, and economy will result in including all system interconnections. (Robinson et al., 2015).

The Integrated Farm System Model (IFSM) is an example of an integrated model for specific agricultural systems as opposed to using general equations that can be applied broadly. IFSM integrates the crop and livestock systems to measure the total environmental impact of the decisions made in these sectors. The model requires inputs for eight different modules and modifies existing models to create a sustainability assessment (Rotz et al., 2012). The Biofuel Energy Systems Simulator (BESS) ties together the crop, beef, and ethanol systems. BESS calculates the production of each system and also provides a sustainability assessment over an annual production cycle (Liska et al., 2009). The CERES-Maize cropping model was integrated with the Root Zone Water Quality Model (RZWQM) to couple water quality with agricultural crop production. This was done to have a more comprehensive understanding of the interactions between these two systems as a decision support tool (Ma et al., 2006).

The MARKAL energy model and Center for Agricultural and Rural Development (CARD) market model were integrated to properly tie together the crop and biofuel systems. It is mainly an economic integration of two models that simulate the market for the biofuels. Their methodology involved linking relevant inputs and outputs of both models and analyzing the effect that certain events have on the market for fuels and related commodities (Elobeid et al., 2013). An environmental assessment of biofuel production in Greece was performed by using the GEMIS software as an LCA of biofuels from crop production to fuel and byproduct production. Four biofuel products were analyzed and compared based on environmental assessment results (Fontaras et al., 2012). Kim and Dale (2005) integrated several models and datasets to assess crop-biofuel system: DAYCENT for soil dynamics, NASS data for crop production and management, GREET for ethanol production, and the EPA-TRACI assessment method for environmental impact.

Validation is a concern for systems models because it is difficult to find non-controlled data to evaluate and improve the performance of the models using data measured in real-world environments. Tanure et al (2015) developed a bioeconomic model focusing on the crop-livestock system by integrating validated equations and creating four sub-modules: herd structure and animal characteristics, animal nutrient requirements, weather-soil-pasture-animal integration, and economics. The individual equations used were pre-validated and then the whole model will be validated in a dynamic way by comparing scenarios to case studies of Brazilian systems of pasturebased beef cattle production. The IFSM has been slowly validating its simulations using data found in the Midwestern U.S., making it more accurate for temperate climates but less accurate for tropical climates (Tanure et al., 2015). Spatially integrated cropping models can be validated to the USDA NASS dataset. This is done by Zhang et al (2010) as their Spatially Explicit Integrated Modeling Framework (SEIMF) data can be compared to geographic crop production data.

Previous attempts at integrated models were developed in the form of stand-alone software or programs. The individual systems are usually connected by writing the connecting formulas into a single program or running the models manually to develop assessments of the integrated system. This is seen in both the IFSM and BESS models as it integrates several systems using existing models by rewriting the equations as part of a new program. Since many individual models already exist in their own software, it would be much more practical to integrate them using service-oriented architecture (SOA).

SOA is a way to integrate software components as applications using communication subroutines. These models can be integrated as a web service and made available to users and developers as applications. This technique has been used for many disciplines to combine several systems together. The Open Geospatial Consortium (OGC) developed a Web Processing Service (WPS) to expose hydrological models as web services (Castronova et al., 2013). Users can use an Open Modeling Interface to predict runoff in certain areas by sending inputs to a hydrological model (TOPMODEL) which is available in a model workflow. Evapotranspiration calculation is another model that is required in the workflow and an example of integrated models working together on a web service. Many researchers have used web services and SOA to couple climatic and hydrological models to understand the integration of these two systems or for specific end user application such as flood emergency response (Goodall et al., 2011; Goodall et al., 2013; Tan et al., 2016).

In the field of bioinformatics, the European Bioinformatics Institute (EMBI) developed a loosely coupled web service that allows users to access large databases, search tools, and analysis tools (McWilliam et al., 2013). Analysis tools such as genetic sequence similarity and biological sequence alignment are integrated via advanced workflows with the available data in the data repository. Users can integrate additional functionality to web sites and programs on the web. For social sciences, several web services exist to analyze the sentiment and opinions of the public for various online services such as Youtube, Twitter, and Facebook (Serrano-Guerrero et al., 2015). These analysis tools are models that are exposed as a web service application and can analyze data for companies to incorporate into their software. The models are integrated into a workflow and can be used by developers to build analytical tools.

Agricultural models have not capitalized on SOA to improve decision making and couple systems, including the crop and biofuel systems. With a loose coupling framework, these models can be available for anyone to use independently with their original functionality, but can also be used together to run crucial impact assessments. More specifically, the tool developed through this study will help growers and biofuel producers intuitively utilize these models together to understand how different decisions they make can affect the environment on a larger system boundary. This will make computation of the environmental impact more practical. The SOA can be created as a web-service that any user is free to use either to write their own software or to call the functions directly.

The objectives of this study were to:

1) Develop a framework for integrating two well-accepted, validated models in the cropping and biofuel systems using a service-oriented architecture

2) Evaluate scenarios to demonstrate the utility of the framework as a decision support tool

3) Conduct a sensitivity analysis to determine effects of varying key model parameters on system response.

2.2. Material and Methods

2.2.1. Model Description

2.2.1.1. Model Identification

Desirable attributes for models are wide acceptance, high validity, and high functionality. The cropping models need to take weather, soil, and management inputs and generate potential yield for that season. The biofuel model must take crop yield and key resources in production (i.e. fertilizer, irrigation) to generate not only fuel production but also environmental impacts of resource use and emissions. There exist several models that simulate the crop and ethanol systems individually. Because the crop system is inherent to biofuel production, they must be coupled in order to understand the interactions between the systems.

Lopes and Neto (2011) break down many of the cropping models that are widely used and validated in their respective fields. Some of these models include CERES, CROPGRO, Environmental Policy Integrated Climate Model (EPIC), Hybrid-Maize and APSIM. Additionally, the Decision Support System for Agrotechnology Transfer (DSSAT) is a program that acts as a wrapper function for many different cropping models, including the popular CERES and CROPGRO (Hoogenboom et al., 2015). All tools successfully model the cropping system of interest and are meant to be used as decision support systems for either private decision makers or policy makers. The spatial and temporal scales and equations may differ from model to model, but the functionalities are similar.

DSSAT is used in more than 100 countries and has been under constant development for more than 20 years. DSSAT also has a high volume of data backing up calibrating its models so it can be used to predict crop yield in a variety of locations with high validity. There are over 60 inputs that can be plugged into the DSSAT model which shows how functional it can be for researchers and if the model can be properly wrapped, DSSAT can offer high functionality into the integration of the crop and biofuel systems.

DSSAT has also been integrated with other models in the past. The IMPACT model, for example, integrates DSSAT for their crop production module when determining the potential for food supply. IFSM uses equations found in DSSAT to calculate their crop yields. DSSAT is not only high in functionality, but researchers have experience in integrating it with other systems as well, making this the best tool to use for our application.

Since biofuel production is closely associated with environmental impact, most of these models are life cycle assessments (LCA) in order to determine the environmental effect/benefit of producing a certain type of fuel from raw materials to consumption. Some well-known fuels LCAs include the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model, SimaPro, the Global Emission Model for Integrated Systems (GEMIS), and the MARKet ALlocation model (MARKAL). The GREET model is widely used, largely because it is sponsored by the US Department of Energy (Elgowainy et al., 2012) and Argonne National Laboratory consistently updates the data that drives the model. The latest major update to the corn ethanol pathway was in 2014 and the current GREET version used is GREET 2015 (Wang et al., 2014). When performing LCA with GREET, it includes the crop farming pathways, which give some functionality to the user in defining cropping inputs. For example, the corn ethanol pathway includes the corn farming process, which allows the user to specify irrigation, fertilizer, and chemicals per unit weight of corn produced. The MARKAL model behaves in a similar way to calculate environmental impact of biofuel production with a large database. It also includes a linear programming algorithm that helps the user in determining the least-cost solution on the energy resources to use (Kannan et al., 2007). The purpose for this model however is not to find an optimal solution for the user but to calculate the system impact from decisions defined by the user. MARKAL also does not have near the user base or support that GREET has. Given its numerous benefits, GREET is the targeted biofuels model.

DSSAT and GREET are also capable of simulating a wide range of different crops and biofuels. This study will focus on integrating the corn and ethanol systems, but the same principles can be applied to a variety of biofuel systems such as biodiesel from soybean or ethanol from corn residue.

2.2.1.2. Computational structure

The SOA will follow the framework described in Figure 2.1. The middle layer shows the model pipeline and at the very bottom are classes that create inputs from user actions. These feed into the Control and Batch methods that create the crop experiment file and batch file for the DSSAT model under the DSSATFile class. DSSATFile is inherited by the DSSATModel class which runs the file created from the user inputs. DSSATModel returns yield and all other outputs associated with DSSAT. This is inherited by the DS_GREET class which runs the GREET model biofuel pathway based on the crop outputs simulated by DSSAT. Every module of this structure can be called by a client on a Representation State Transfer (REST) server. Any user that has access to the server can make requests to the server to utilize the integrated model in the middle layer. The integrated model interacts with a data repository to store and access data that are used in the subroutines.

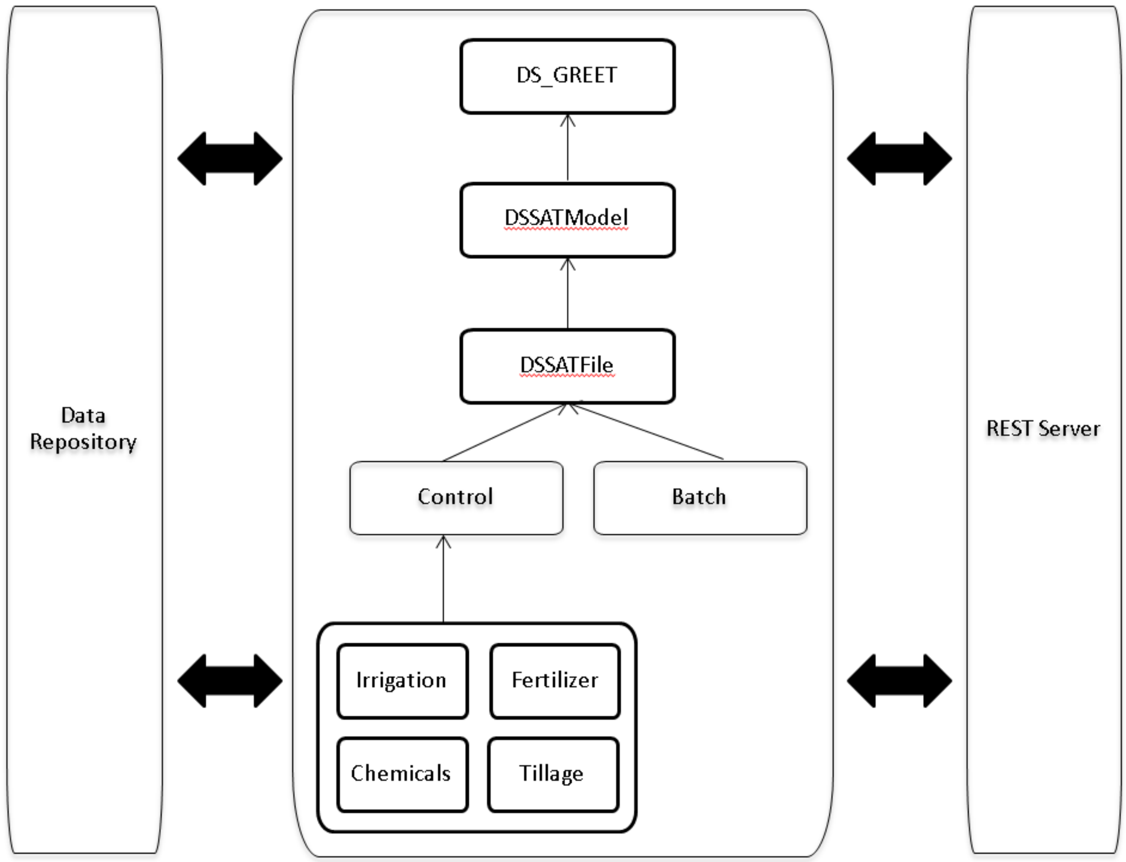


Figure 2.1: Computational model pipeline

2.2.1.3. DSSAT wrapper

The cropping model in this integrated model should be able to simulate crop yield based on several environmental factors and management practices that the user controls. Creating a wrapper for the DSSAT model allows the program to run and be connected to other programs, which makes it viable for integration. pyDSSAT is a Python wrapper that runs the DSSAT model in its original FORTRAN code (He et al., 2015). The program makes a large number of input assumptions and also wraps the model by compiling the original FORTRAN source code. The program is open source so it was used as a reference to write the Python code used in our wrapper.

The method for writing the DSSAT wrapper follows a similar flow to pyDSSAT and is shown in Figure 2.1. It must create an experiment file based on farming inputs, run the file through the model, and process the outputs. The experiment file used by DSSAT is a text file that compiles the inputs in a certain format for the simulation that the user wants to run. In our implementation, this is created by making a Python class, DSSATFile. The pyDSSAT code allows the user to input the following variables: crop type, soil type, weather station, start year, end year, planting date, and model mode. The integrated model only simulates one year, so end year is not needed. It is also only being run in batch mode where a single experiment file is being used so the mode is defaulted as “B” for “Batch”. Since DSSAT is robust and has many inputs, it is difficult to fit them all as inputs into one class practically. Other classes were created to enter management data as comma separated files (CSV) files. Irrigation, fertilizer, harvest, tillage, and chemical application all have their own class defined to take in scheduling inputs written to a CSV file.

The DSSAT model can be run in the command line using DSCSM046.exe which is available with installation of the software. pyDSSAT runs the model by compiling Fortran code but running the batch file in the command line is simpler and provides the same results. The pyDSSSAT class, DSSATModel, runs the model by calling the executable in the terminal and taking in data from the experiment file and the management files. The model controller finishes writing the experiment file that did not yet include the management inputs from the irrigation, fertilizer, harvest, tillage, and chemical classes. After the model is run, it creates output files that show results for yield, crop growth, soil-water balance and more.

2.2.1.4. GREET wrapper

The objective of the biofuel model is to not only calculate the total biofuel production from crop production, but also the resource use and emissions of the biofuel in comparison to a reference fuel. To understand the environmental impact of producing the clean burning fuel, the biofuel pathway is compared to the reformulated gasoline pathway. GREET can compare LCAs of different fuels such as ethanol and gasoline on a per MJ basis. The pathways in the GREET model used for this tool are the “E85 Gasoline Blending and Transportation to Refueling Station” pathway and the “Reformulated Gasoline (E10) Blending and Transportation to Refueling Station” pathway.

The ethanol pathway is broken down into several processes and calculates all results associated with this pathway. It begins with the Corn Production for Biofuel Refinery process which includes some inputs and outputs found in DSSAT. This is where the DSSAT inputs are written into when appropriate. The results feed into the ethanol production process which is chosen as “Dry Mill Ethanol Production w/ Corn Oil Extraction” since this is a common method in many ethanol plants in the U.S. While the user can specify the percent of ethanol being produced from each process in the software, for this study, it was assumed that 100% of the ethanol produced is from dry mill with oil extraction. GREET calculates emissions from the beginning of the corn farming process to the end of the transportation process to show final resource results for the pathway.

While many inputs in GREET overlap with DSSAT inputs, others are more difficult to estimate. The rest of the inputs require the user to know how energy and resources as a whole are used for the rest of the operations such as vehicle usage, tillage, and transportation. GREET also has numerous libraries and pathways for resources that can be edited. The defaults for these inputs are US averages so for the purposes of this study, the default energy uses were kept to make the tool more intuitive.

GREET uses terminology called Well-to-Pump (WTP) and Pump-to-Wheel (PTW) to describe where the product is in its life cycle. The WTP pathway describes resource use and emissions associated with the production of a product from its raw materials to transporting it to a fuel pump ready to be consumed. The PTW pathway describes resource use and emissions associated with the consumption of the product. This study will look at the full Well-to-Wheel (WTW) pathway of the corn ethanol lifecycle.

The corn ethanol pathway in GREET uses a displacement method by default, and Distillers Grains and Solubles (DGS) displaces animal feeds which is a mix of corn, soybean meal, urea, and soyoil for different types of livestock. The displacement values per feed and livestock are averaged and used as the allocation amount to credit to DGS byproduct. Because of the displacement of soybean meal and soybean oil, the water consumption associated with them is taken as credit, which may result in a negative WTP water consumption value if irrigation amount is too low. This must be considered when making conclusions from the GREET results. Also, while DSSAT calculates some environmental footprints such as water use for corn, GREET already takes into account the footprint produced from corn farming. Hence, any environmental assessment done in the integrated model is done based on GREET values, not DSSAT.

GREET operates based on calculating environmental results from ethanol amount, but the DSSAT model only provides corn yield. The program must convert kg/ha of corn to total liters (L) of ethanol based on GREET’s current conversion rate of 10.598 L ethanol/bushel corn. Since a liter of E85 does not provide the same amount of energy as a liter of E10, the volume calculated must be converted into energy (MJ). Further, the crop farming inputs in GREET are on a per unit weight of crop produced basis while the user inputs these values on a per hectare of field basis in DSSAT. Irrigation and fertilizer inputs from DSSAT are converted accordingly to be written into the .greet file.

CalculatorBatch is a program that was compiled using an API developed by the makers of GREET. The arguments for this program are the .greet file name, year(s) of simulation, and the ID for the fuel pathways or mixes. The GREET wrapper runs the written .greet file into the CalculatorBatch program using the values specified by the farming system. There are two pathways being used – Corn Ethanol Production and E10 Reformulated Gasoline – so the GREET model is ran for both pathways using the amount of energy produced in ethanol production.

While this API is a useful tool and essential for the development of this wrapper, it is only able to calculate resources for WTP and does not include the results from actual usage of the fuel. Much of the offset in emissions and resource use comes from the burning of the biofuel in comparison to fossil fuel so it is essential to include the PTW pathways as well. Fortunately, only the WTP pathway results are variable due to the cropping inputs of irrigation, fertilizer, and chemicals. The PTW results do not change on a per MJ basis since those are completely separate from production and only dependent on the vehicle that is consuming the fuel. The results for these PTW pathways on a per MJ basis were stored in a separate class wherever there were PTW emissions present. Once the total amount of ethanol energy is calculated from the beginning of the program, it is input into the PTW class to output total resources. The vehicles chosen for both pathways were ones that are commonly found for their respective fuels; Flex Fuel Vehicle (FFV) was used for ethanol while Standard Ignition Internal Combustion Engine Vehicle (SI ICEV) was used for E10 Reformulated Gasoline. Flex Fuel Vehicles have engines that are able to burn fuels that have higher blends of ethanol which is why they are commonly used for E85 (Alternative Fuels Data Center, 2017). E10 gasoline is similar enough to gasoline that a standard internal combustion engine found in most vehicles can run it (Anjikar et al., 2017). After adding results from the API along with results from the PTW class, the program will output total (WTW) results for ethanol and gasoline. The total flow of the program from inputs to outputs is represented in Figure 2.2.

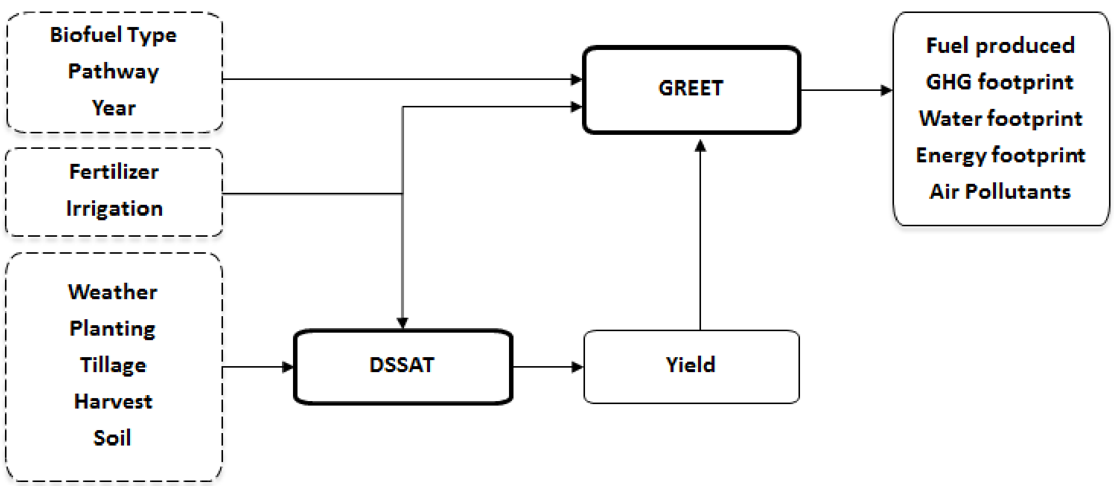


Figure 2.2 – Flow diagram of DSSAT-GREET model connections in Python program

2.2.2. Post-processing

The design for post-processing the resource results is based on Wu et al (2007) who evaluated the benefits of using ethanol relative to gasoline for fueling vehicles. The main outputs that this study analyzes are greenhouse gas (GHG) emissions, energy usage, air pollutants, and water consumption. GHG emissions are calculated as CO_2 equivalent from CO_2, CH_4, N_2O, and biogenic CO_2 based on their global warming potential values (1, 25, 296, and 1 respectively) (IPCC, 2007). The criteria air pollutants identified when comparing the two fuel pathways are Volatile Organic Compounds (VOC), CO, Nitrous Oxide (NOx), Particulate Matter (PM10), and Sulfur Oxide (SOx). These are all significant emissions produced in the corn ethanol pathway that affect human health. The energy savings from nonrenewable fuel use are also important to analyze as total fossil fuel energy and petroleum fuel energy use are compared in this model. Fossil fuel energy consists of total use from coal, natural gas, and petroleum energy in the life cycle. Petroleum fuel use is singled out from the other fossil fuels because most of the benefit from producing ethanol comes from the reduction of petroleum fuel. Water consumption is highly sensitive to irrigation in the crop pathway and can be beneficial or detrimental based on management and weather.

After the yield is calculated in DSSAT in kg/ha, it is converted to ethanol in MJ. To compare the ethanol production to gasoline, an equivalent amount of MJ of gasoline is calculated in the GREET life cycle and the two pathways are compared to each other. In this study, the functional unit of comparison is total MJ of E85 possibly produced by 1 ha of corn production. This effectively defines the system boundary to start with production of cropping inputs and end with the consumption of E85 fuel in a vehicle. The LCA tracks fertilizer and chemical inputs down to energy inputs of raw materials such as ammonia and phosphate. Environmental footprint of raw materials for ethanol production are tracked for enzymes, yeast, and chemicals. Blending gasoline for E85 is also tracked along with its raw inputs. The system boundary ends once the fuel reaches the vehicle that uses it and is consumed. Since DGS displacement of livestock feeds is credited, the boundary also includes consumption of DGS and its environmental benefits.

There are two ways to compare the footprint of E85 fuel to E10 fuel: one is by total footprint and the other is percentage footprint of E10. Simply subtracting the results from the E85 gasoline pathway from the E10 pathway provides the absolute savings. Percentage savings is the percent of the resource saved by using E85 as opposed to E10. This provides a normalized value that can be compared across different categories. Negative values for either method show that producing ethanol is beneficial to gasoline in that category. Wu et al (2007) used percentage savings to compare several different fuel pathways on a per unit of distance basis. It is important to understand both methods when making the assessment since absolute savings encourage larger crop and biofuel production operations while percentage savings encourage more efficient operations on a per unit of energy basis. This gives the user more options on how they can make operations decisions that may be more environmentally sound.

As an additional note, ‘water footprint’ is commonly used referred to as a way to track the use of water in different phases and stages of a process. In this paper, ‘water footprint’ is defined as the difference in total water consumption between E85 and E10 life cycles. A framework for water tracking was not included for this paper in the GREET model.

2.2.3. Scenario Analysis

2.2.3.1. Base Scenario for Comparison

The driving inputs of both models are nitrogen amount from fertilizer application and water use from irrigation. This is because these management inputs have a high effect on yield depending on the growing conditions, and have a high environmental footprint from life cycle production and use. A sensitivity analysis of the effect of fertilizer on the integrated model was conducted to determine the impact on the system from changing one of the parameters.

A base scenario for corn production is developed from regional data and management recommendations of corn farming in the Eastern Nebraska region. This scenario is based only on environmental and user inputs as GREET default values for emissions and energy use are kept the same. The sample field location and year used are Mead, NE, and 2015. Weather data for this season were obtained from the High Plains Regional Council Center (HRPCC) in the form of daily precipitation, minimum temperature, maximum temperature, relative humidity, solar radiation, and location coordinates. The plant population for irrigated corn that is typically used in the Midwestern region is roughly 10 plants/m^2 (Barr et al., 2013). Anhydrous ammonia is a common fertilizer used for nitrogen application so this method was used for the baseline scenario. The corn hybrid chosen for this study, called “GDD2600”, has a 113-day maturity (medium season hybrid) from planting to physiological maturity. The soil type used should accurately reflect the profile found in Eastern Nebraska corn fields so the soil file in DSSAT chosen is for loamy soil. This soil file gives descriptions by layer based on water holding capacity, bulk density, and nutrient characteristics. The water holding capacities were adjusted based on local data to more accurately reflect the Nebraska soil profile (Irmak, 2017; unpublished research data). Values for Field Capacity (FC), Wilting Point (PWP), Organic Carbon Matter (OMC) are represented in Table 1.

Table 2.1 – Soil values by depth

Soil variable	0-30 cm	30-60 cm	60-90 cm	90-120 cm
FC (% vol)	35.4	30.0	29.8	32.0
PWP (% vol)	23.0	18.6	18.8	19.4
Sand (%)	35.1	37.5	34.4	29.6
Silt (%)	48.6	43.2	40.9	42.7
Clay (%)	16.3	19.3	24.6	27.6
OMC (%)	3.5	2.7	2.0	1.6

Planting and harvesting dates are based on common practices based on data from the USDA National Agricultural Statistics Service (NASS). In Eastern Nebraska, recommended times to plant corn are between April 27th and May 18th while the recommended times to harvest corn are between October 4th and November 10th (USDA, 2010). Thus, the dates chosen for planting and harvesting are May 1st and October 15th respectively. Fertilizer amounts used in the simulations were based on the amounts used in long-term field research conducted by Irmak (2015a; 2015b). In Nebraska, it is common to apply fertilizer using side-dressing and especially since it is being applied on the same day as planting, it is used for this scenario. In DSSAT, this application method is named “Banded on surface”. Phosphorous and potassium are normally not included in fertilizer for corn so these were left out of the simulation. DSSAT has an option to automatically irrigate the field if it senses water stress throughout the season. Water stress for yield should not be a constraint for this simulation so irrigation was simulated using automated irrigation option so that water is not a constraint for achieving potential grain yield. The state of Nebraska has a large aquifer and uses groundwater for irrigation. Nebraska commonly uses center pivots to irrigate their fields so the equivalent setting in DSSAT was set to “Sprinkler”. All baseline values are recorded in Table 2.2.

Pesticide use is an option for this integrated model but was left out of this case study since DSSAT does not handle pest hazards well when predicting yield. If pesticide use were to be included, the integrated model would only calculate the negative environmental impacts from GREET and leave out the positive yield effects it has on cropping. In this scenario, it is assumed that there are minimum pressure from pests and weeds so pesticides are not used. Tillage settings are also important to consider in this integrated system and in DSSAT, it is defined as “Drill, no-till”. This is not defined in GREET however due to the difficulty of adding vehicle fuel use in the tool.

Table 2.2 – Values for baseline corn production scenario

Parameter	Baseline Value
Location	Mead, NE
Year	2015
Plant population	10 plants/m^2
Fertilizer material	Anhydrous ammonia
Fertilizer amount	150 kg N/ha
Fertilizer application method	Banded on surface
Soil	Silty Loam
Planting Date	May 1
Harvest Date	October 15
Cultivar (Hybrid)	GDD2600
Irrigation Management	Automatic when needed
Irrigation application method	Sprinkler
Row spacing	75 cm
Plant depth	5 cm
Tillage method	Drill, no-till

2.2.3.2. Nitrogen Fertilizer Sensitivity

The production of corn has several sources of emissions such as soil emissions, fuel use, and chemical applications. The corn production process in GREET has default values of 2.40 g/bu and 2.73 g/bu of NOx and N2O emissions respectively due to soil and fuel use. Fertilizer applications have high added environmental impact and increase the LCA for corn ethanol's emissions. Nitrogen amount was analyzed relative to the baseline value of 150 kg N/ha which is normal for this field. The following values for nitrogen application were run in the model assuming the baseline scenario for all other variables: 0, 50, 100, 150, 200, 250, and 300 kg N/ha. Resource savings from producing E85 over E10 were calculated both as a total difference and as a percent reduction. Total footprint shows the physical results and changes with each scenario while percent footprint shows the sensitivity of output parameters to nitrogen fertilizer application.

The pathway is separated into WTP and PTW which both have different contributions to the overall results. To quantify the difference, the program was altered to calculate emissions from WTP and PTW separately. The two results of GHG emissions and nonrenewable energy use were compared to each other based on these different pathways.

2.2.3.3. Optimal plant population

A range of plant populations was used to gauge the sensitivity of this input on the DSSAT model. There are significant breaks in the relationship between plant population and yield for values under 40k plants/ha and over 120k plants/ha so this sets the bounds for values of plant population (Table 2.3). Therefore, the model was run for plant populations in the range of 5 to 12 plants/m^2 over the span of 15 years from 2001 to 2015. This will show the relationship between varying weather and the optimal plant population as a possible decision point for farmers. With higher plant population, in general, higher nutrient application is required. Each plant population was run with a range of nitrogen fertilizer amounts to determine the optimal value. Nitrogen fertilizer values from 10 to 600 kg N/ha were used to show the full relationship of nitrogen to yield for this plant population and the maximum described by DSSAT. The optimal nitrogen application amount was determined by picking the value where yield exceeds 90% of the max as shown in Figure 2.3. This was done to ensure that a consistent fertilizer value was chosen for each plant population depending on the nutrient requirements.

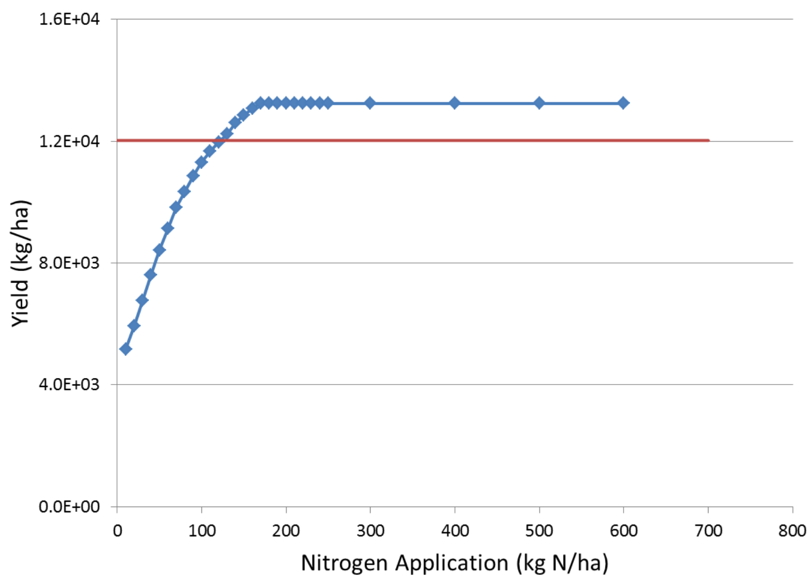


Figure 2.3 – Nitrogen application vs yield of plant population of 100k plants/ha. The horizontal line represents 90% of max yield. The nitrogen amount chosen for 100k plants/ha is 120 kg/ha.

Table 2.3 – Nitrogen values for each plant population scenario

Plant pop (ha^{-2})	**Nitrogen (kg N/ha)**	**Yield (kg/ha)**
50	90	9802
60	110	10679
70	110	11048
80	120	11498
90	120	11849
100	120	11967
110	120	12146
120	130	12556

Once the nitrogen amount is picked for each plant population, they were used as input into the model to calculate resource results for each scenario. Since nitrogen amount increases with plant population, the results should reflect an increase in GHG footprint. However, if the yield offsets the cost of nitrogen then the GHG footprint can actually be reduced.

To show the complete GHG footprint matrix in relation to plant population and nitrogen fertilizer application, combinations of both variables were run. Plant populations were inputted in the range of 5-12 plants/m^2 and nitrogen applications were inputted in the range of 100-250 kg N/ha with increments of 1 plants/m^2 for plant population and 10 kg N/ha for nitrogen applications. The GHG footprints of each scenario are calculated to show the relationships with both of these variables simultaneously.

2.3. Results and Discussion

2.3.1. Model Verification

Before performing analyses, the Python program must be verified with the models in the original software. Verification of the DSSAT wrapper is done by running the model twice using the same scenario both manually through the DSSAT software and with the InputCreator class in the wrapper. Both programs produce a summary file that shows generic outputs of the simulation run including yield, seasonal weather data, soil water balance, and management summary. Three scenarios with three different nitrogen fertilizer amounts (0, 100, and 200 kg/ha) were run in both programs and the summary files exactly matched which verifies the accuracy of the wrapper.

Verification on the GREET model is done in a similar way by running the software manually using a scenario and then running the same scenario with the GREET wrapper written in Python. The WTP pathway is run with the wrapper so that part is validated with the software. The results in the wrapper are based on total emissions from the amount of energy produced in DSSAT since it is inherited so the scenario that is run manually through GREET must be done on the basis of total energy produced. The same baseline scenario is run through the program to get results from the GREET model. Only the WTP results are printed to compare to the results obtained from manual use of the model. PTW calculations are linear and directly taken from the model so these do not need to be verified.

The comparisons are shown in Table 2.5 where results are calculated on the basis of the amount of energy created from the ethanol process. The error between the two results is minimal and is attributed to rounding error from the GREET software.

Table 2.4 – Verification of wrapper program with GREET software for items per hectare

Categories	Wrapper	Software	% Error
Fossil Fuel (Btu/ha)	62443710.7	62000000	0.01
Petroleum Fuel (Btu/ha)	25420719.5	25000000	0.02
VOC (g/ha)	4356.1	4360	0.00
CO (g/ha)	3037.1	3040	0.00
NOx (g/ha)	7065.3	7070	0.00
PM10 (g/ha)	1109.1	1110	0.00
SOx (g/ha)	4302.2	4300	0.00
CH4 (g/ha)	12385.9	12390	0.00
N2O (g/ha)	2446.9	2450	0.00
CO2 (g/ha)	3365647.8	3365090	0.00
CO2_Biogenic (g/ha)	-582.6	-580	0.00

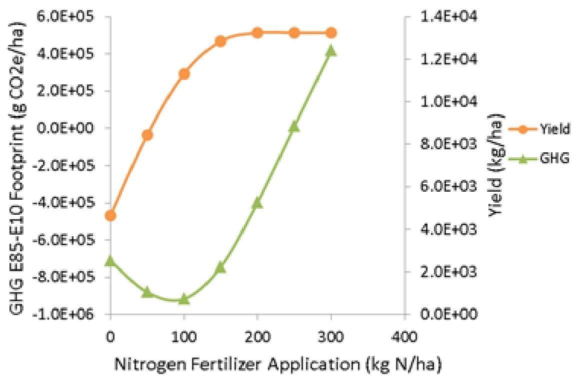
2.3.2. Sensitivity and scenario analysis

2.3.2.1. Sensitivity analysis on nitrogen fertilizer

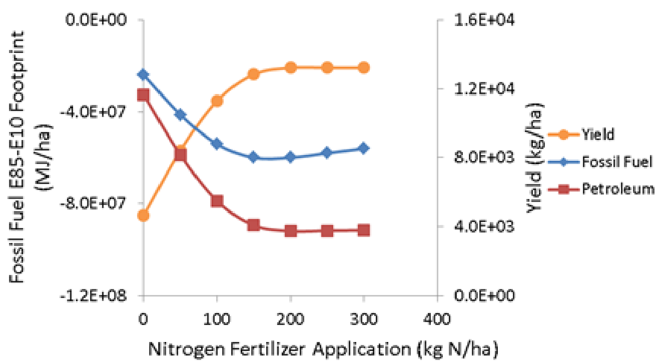
Figures 2.4a and 2.4b show the results for nitrogen application on GHG emissions and nonrenewable energy use overlaid with the corresponding yield. Up to 100 kg N/ha, increasing nitrogen application increases the yield potential and lowers the GHG footprint of the system since more E85 energy can be produced to displace E10. However, yield levels off after this value and can no longer offset the footprint caused by increasing nitrogen rate. Therefore, the GHG footprint of the system will sharply increase beyond 100 kg/ha because these emissions are highly sensitive to nitrogen fertilizer use as displayed in Figure 2.4a.

The total footprint of both nonrenewable energy categories in Figure 2.4b shows a steady increase that evens out past 150 kg N applied per hectare. Fossil fuel and petroleum fuel footprints appear to closely mirror the relationship between yield and nitrogen rate. This means that these footprint categories are more sensitive to the amount of E85 produced than the amount of nitrogen applied. The petroleum fuel footprint is the lowest as E10 requires much more petroleum in production than E85 on a per MJ basis. The total fossil fuel footprint is not as low because E85 is detrimental (higher footprint) in comparison to E10 in its coal and natural gas footprint. Figure 2.4b shows this as the petroleum fuel continues to steadily decrease with nitrogen application while the total fossil fuel footprint starts to increase as yield levels off.

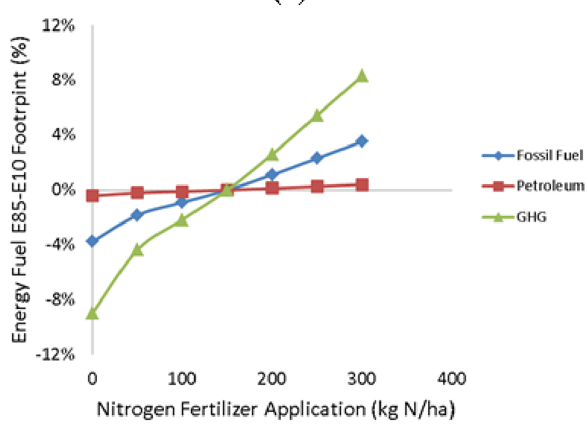
The sensitivity is more clearly shown in Figure 2.4c that normalized footprint for each category in comparison to the optimal fertilizer rate according to GHG footprint. The trends look different in this subfigure because it is comparing all scenarios to a central value of 150 kg N/ha. The percent change in footprint is much higher for GHG across the range of nitrogen rates in comparison to the fossil fuel categories. Petroleum fuel also shows very little sensitivity to nitrogen which confirms the findings from Figure 2.4b. This integrated model can inform decision makers on the optimal fertilizer application not only based on yield but based on environmental impact. In the model, yield would continue to increase with increasing nitrogen but with GHG savings, there is a clear optimum value for this scenario at 100 kg N/ha.



(a)



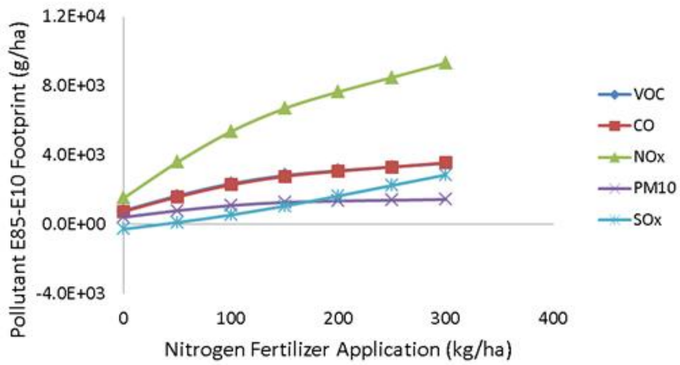
(b)



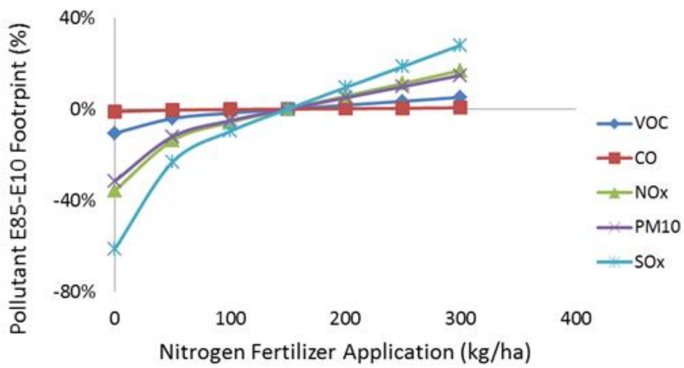
(c)

Figure 2.4 – E85-E10 total footprint of (a) GHG emissions and (b) fossil fuel energy balance and (c) percent footprint of all categories in comparison to middle of 150 kg N/ha

While E85 is beneficial to E10 for all of the categories described above, it is not as beneficial in emission of criteria pollutants as found in Figure 2.5. In every scenario and for each category, E10 gasoline emits fewer pollutants than E85. With increasing nitrogen application, the emissions footprints become more positive. This shows one of the tradeoffs of producing ethanol when using it to displace reformulated gasoline as a fuel. Each pollutant shows a similar increasing trend in Figure 2.5b where emissions compared to the middle nitrogen scenario of 150 kg N/ha. NOx emissions are impacted the greatest with increasing nitrogen which is reflected in GREET's Nitrogen and Corn Production pathway. In the Nitrogen mix pathway, producing 1kg of nitrogen emits 7.46g NOx and in the Corn pathway, 1bu of corn emits 2.40g NOx.



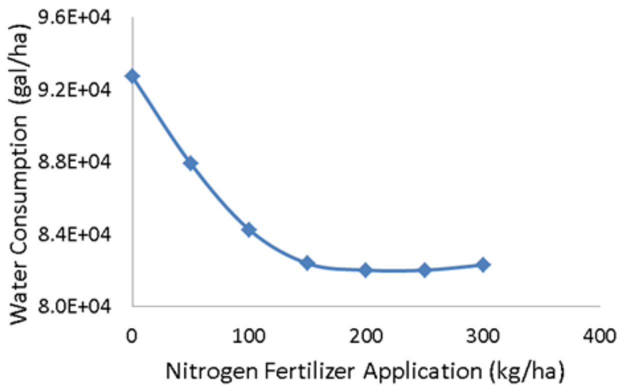
(a)



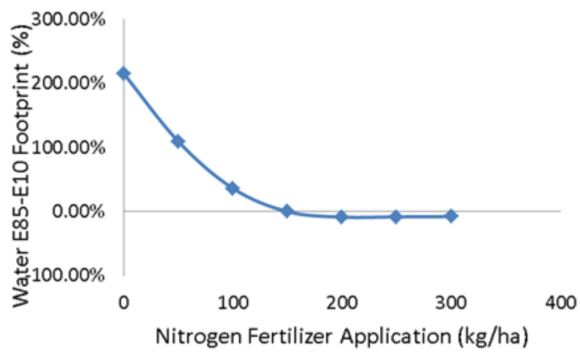
(b)

Figure 2.5 - E85-E10 criteria pollutants (a) total footprint and (b) percent footprint as compared to optimum of 150 kg N/ha of fertilizer application

Water consumption in the crop-biofuel system is influenced by irrigation amount and the amount of water used in the ethanol plant for producing ethanol. Processing water consumption for ethanol is greater than gasoline marginally by about 0.076 L/MJ. However, irrigation has the most significant impact and the practices that a decision maker has can greatly influence the water footprint of corn ethanol. In this scenario, irrigation is automated when needed. If the crops grow larger due to increased nitrogen, then more irrigation may be needed to maintain the growth and should reflect larger consumptive use. Figure 2.6a shows the total water consumption from the E85 pathway in relation to nitrogen application rate. Water consumption has a negative trend with nitrogen, even though yields are increasing and consumption is expected to rise. The results indicate that DSSAT may not be able to properly handle the relationship between nitrogen and water consumption. Climatic conditions influence how increased nitrogen levels impact crop physiology, yield, and evapotranspiration which is not a linear response. In this scenario, the annual precipitation is 731 mm which is high for this region. The percent footprint though does show a clear downward trend of water footprint with higher fertilizer. The increase in yield creates a lower water footprint and offsets the use from irrigation which does not change as much.



(a)

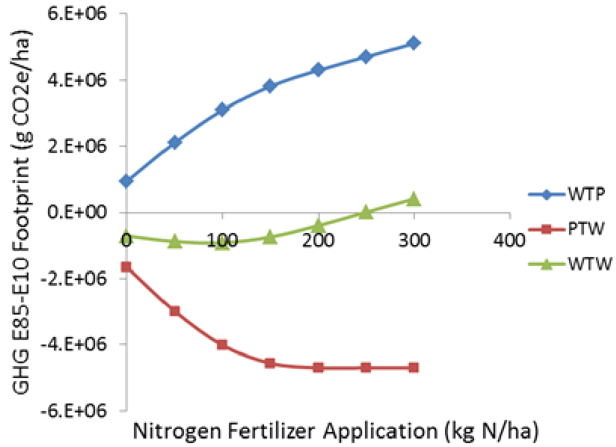


(b)

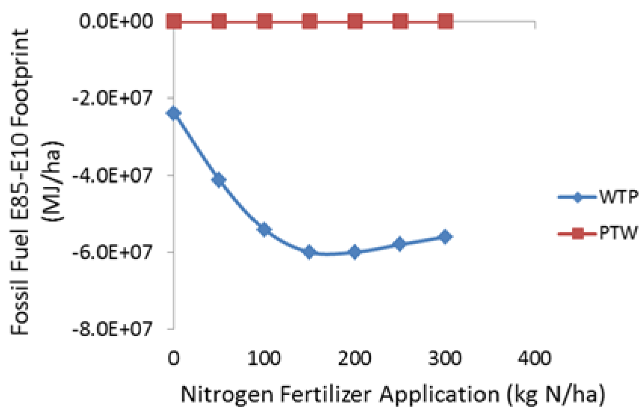
Figure 2.6 – (a) E85 total water consumption and (b) E85-E10 percent footprint compared to optimum of 150 kg N/ha

Figure 2.7 shows the breakdown of the footprints between the WTP pathway and the PTW pathway for GHG and fossil fuel categories. The production of ethanol emits more CO_2e than gasoline on a per MJ basis and that is reflected in the WTP results Where emissions increase as nitrogen use increases. Conversely, the GHG emissions for the PTW pathway decrease due to consumption of ethanol as E85 use emits much less GHG’s than E10 and offsets the GHG increase from the WTP pathway as seen in the full WTW pathway. E85 is a cleaner burning fuel than E10 so it emits much less GHG’s and offsets the detrimental impact caused from the WTP emissions. The footprint is negative through this range of nitrogen application but as it gets higher, the PTW footprint levels off and WTP footprint continues to increase at a near-constant rate. The total WTW pathway shows a net negative footprint for ethanol which shows the offsetting effects of clean consumption in vehicles.

PTW footprint does not have an impact on any of the other categories. The differences between E85 and E10 come only from the WTP pathway in all of these resources. This is because in the WTW analysis, the vehicle used for both E85 and E10 fuels are kept the same. Since the engine that is burning the fuel is standardized, there is no difference in energy, water, or air pollutant savings per MJ of E85 and E10. For example, Figure 2.7 shows that fossil fuel footprint only changes with the production of the fuel, not the consumption. GHG emissions is the only category where there is a difference between E85 or E10 consumption because of the composition of the fuel.



(a)



(b)

Figure 2.7 – Comparison of Well to Pump (WTP) pathway in E85 footprint to Pump to Wheel (PTW) pathway for (a) GHG emissions in a wet year and (b) fossil fuel use

2.3.2.2. Optimal plant population

Figure 2.8 shows the relationship between total resource and emissions footprint and plant population. The fossil fuel energy footprint steadily decreases with increase in plant population. This is because, based on the assumptions made within the DSSAT model, the increasing nitrogen application does not have as much of an offsetting effect on the energy footprint from producing with a higher plant population. GHG emissions footprint on the other hand is heavily influenced by nitrogen application and that shows in Figure 2.8a where it steadily increases. The GHG footprint levels off after 9 plants/m^2 because nitrogen levels are also leveling off as shown in Table 2.3. Much like in Section 3.1.1, the criteria pollutant footprints increase with plant population and are a net positive compared to using E10 gasoline. With this scenario analysis, the decision maker may weigh the environmental trade-offs when determining plant population as it has differing effects on these categories.

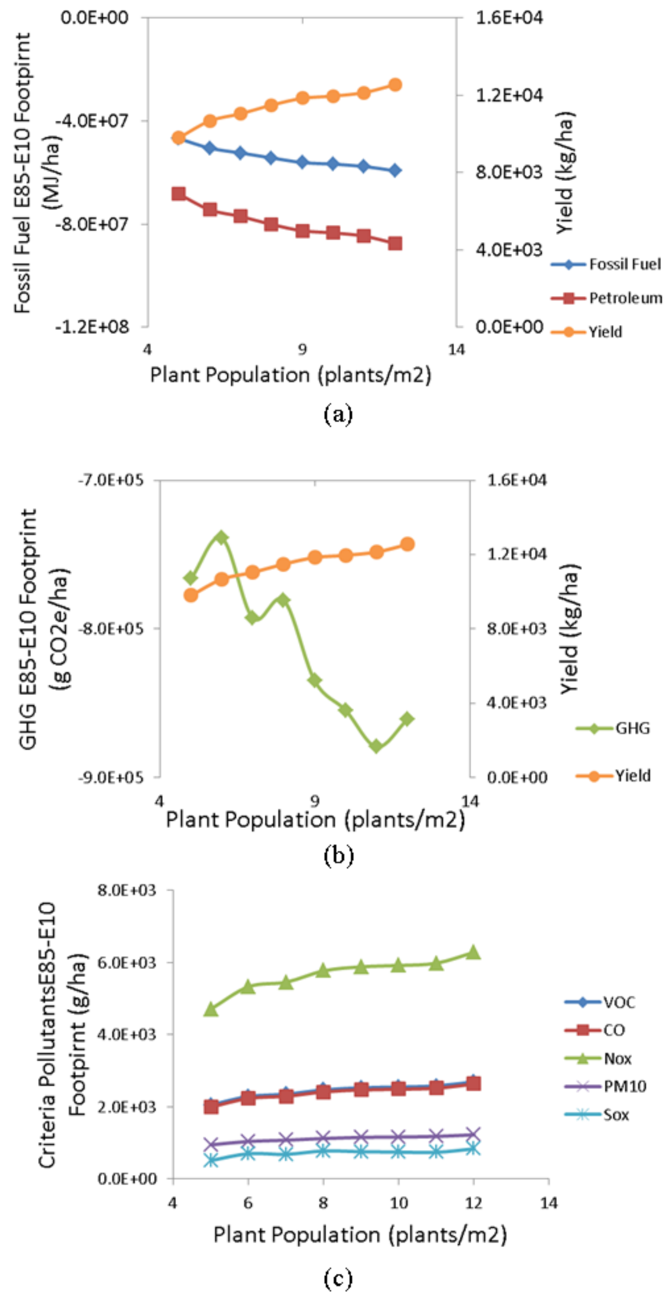


Figure 2.8- E85-E10 footprint by plant population on (a) GHG emissions, (b) fossil fuels, and emissions and (c) criteria pollutants.

While Figure 2.8 uses predetermined nitrogen values for each plant population, Figure 2.9 shows the relationships of GHG footprint to nitrogen fertilizer and plant population. The GHG footprint seems to be optimal with lower nitrogen application and higher plant population density. This seems to be the ideal decisions for nitrogen application and plant density to provide the best GHG footprint within the system. The GHG footprint is highest when the plant population is very low and the nitrogen application is very high. This is because the low population density is not producing enough ethanol to offset GHG emissions created by the high fertilizer use.

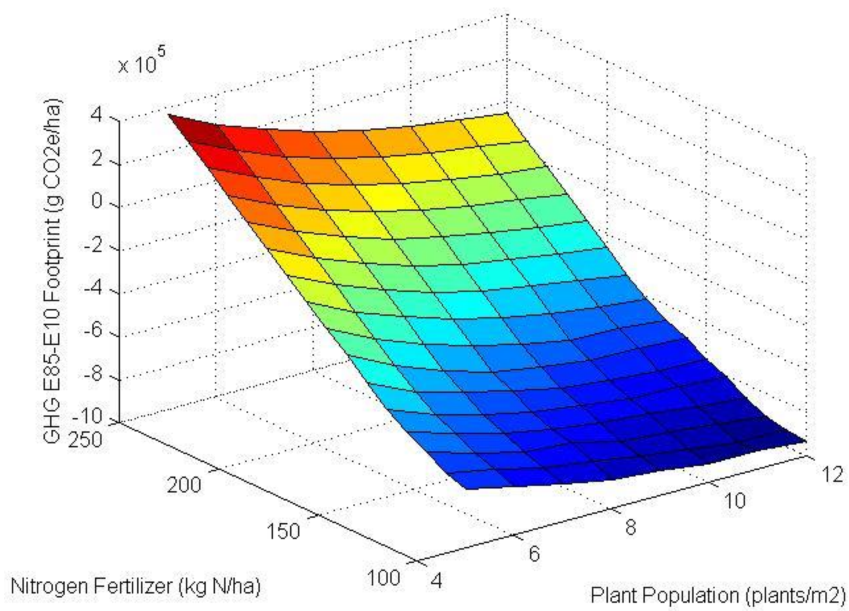


Figure 2.9 – GHG footprint vs nitrogen fertilizer application (kg/ha) and plant population (plants/m^2)

2.3.3. End user application

This program for integrating the crop and biofuel systems is primarily purposed as an environmental decision support tool. Both DSSAT and GREET have large user bases who use these tools to make informed decisions based on either production output or environmental impact (de Carvalho Lopes & Steidle Neto, 2011; Georgios M. Kopanos et al., 2017). Connecting the two creates a powerful tool that allows the user to do both and understand the impact that their decisions have on the integrated system. Many scenario analyses on the impacts of nitrogen fertilizer and plant population on corn growth have been done in the past. There are experimental field studies that test these variables against each other to determine their effect on grain yield for different years and different locations. (Blumenthal, Lyon, & Stroup, 2003) found a linear relationship between plant population density and grain yield and a quadratic relationship between total soil nitrogen and grain yield in Western Nebraska counties. (Ping et al., 2008) studied the relationship between site-specific nitrogen and population density management and economic performance which showed little impact, though it did increase nitrogen use efficiency. (Irmak & Djaman, 2016) concluded a positive relationship with plant population density and grain yield with mixed results for evapotranspiration. All of these results contribute heavily to understanding the effect that nitrogen application and plant population have on growth and economics of the farmer, but it is still in the closed system of the individual farming operation. This integrated tool provides a way to do these scenario analyses to understand not only how these variables can affect growth, but also the impact on emissions, resource use, and the environment when coupled with the ethanol system. This is a way to use the valuable crop research that is done to produce cropping models for the understanding of a larger system.

Likewise, LCA users will have a better understanding of the tradeoffs of using biofuels with a more functional corn farming pathway. GREET currently has a corn farming process included which is limited in inputs. The default values are derived from USDA NASS data which averages management practices from regions of completely different climates and land. Integrating the DSSAT model allows the user to make GREET location-specific which can be a valuable tool for businesses that operate close to biofuel plants in various regions. Future work can include scenarios that run in different locations to analyze how different areas affect the environmental impact of producing biofuels. This study is focused on corn ethanol production in the Midwest but the corn-ethanol system is also prevalent in further stretches of the Great Plains and the South. A database could be created of these various locations and based on the weather and land differences.

The model can also run scenarios for various other biofuels. It includes biodiesel from soybean oil and ethanol production from corn stover, sorghum, and forest residue feedstocks. DSSAT includes models for soybean and corn stover production so additional scenarios can be run to better understand how these systems are interconnected in comparison to corn ethanol and reformulated gasoline. Corn stover is an important addition to the system as it is tightly connected to both the corn production and biofuel systems. Cellulosic ethanol plants are commonly found in the Midwest United States and can result in further emission savings from corn production. Residue from crop yields can be simulated using DSSAT and distributed to have a more accurate understanding of the emissions within this integrated system.

There are limitations to this tool, some of which are inherently attributed to the individual models. DSSAT's large user base mostly consists of researchers and scientists who do not make field decisions in hopes of selling their product. DSSAT is also limited as an irrigation scheduling tool. The automated irrigation setting does not give the user many options to adjust for strategies such as implementing deficit irrigation. GREET also does not incorporate irrigation pumping costs when calculating GHG emissions and energy use for the corn ethanol pathway. Many producers consider irrigation pumping a large expense, especially for drier regions where irrigation is required. GREET is limited to calculating direct emissions from each system and as a result, indirect emissions were not taken into account for this study. A user can add emissions from indirect sources, but this study focused specifically on the capabilities of the two models used and allows for future work to explore the possibilities of adding indirect emissions from other models. GREET also does not consider methane emissions from irrigation and other agriculturally related emissions so those were left out of the scope of this paper.

This framework is also mainly a tool used for environmental assessment and does not include profitability. Decision makers are more likely to act based on their best financial interest even if there is an environmentally optimal solution. A more applicable tool will include economics in addition to environmental impact so that a user is more likely to use it.

Modelers and researchers have been developing and finding new ways to practically integrate agricultural production systems. This paper offers the methodology and framework for a functional tool that can connect two well-established models in their respective fields. In the generation where APIs and model wrappers are taking over the world of software and technology, it is important that agricultural models and software can keep up with this trend (Zhong et al., 2009). Programmers have made many tools to facilitate the connection of various programs which were utilized in this paper: the GREET API, the compiled DSSAT program, and the various Python packages used in the wrapper. The method also allows for the models to be automatically updated as the developers continue to work on the individual models. Other researchers may do similar studies and run their own holistic scenario analyses like how nitrogen fertilizer application was connected to total GHG emissions. This SOA offers users the ability to utilize these tools practically to make their own environmental assessments of corn ethanol scenarios. This framework makes the integrated model accessible for developers to create their own software, for decision makers to run their own scenarios, and for researchers to conduct analyses on this integrated system.

2.4. Conclusion

The DSSAT and GREET models were connected by running each program through APIs developed using Python. Several scenarios based on decisions that can benefit a user in studying what-if scenarios were run through this integrated model to identify the total environmental assessment of the full system. These scenario analyses can provide the user with a better understanding of the impact that certain key decisions, such as fertilizer application, can have on the environment and the rest of the system.

The DSSAT-GREET wrapper is not only a tool that can be used to evaluate and understand sustainability aspects of the system, but it also offers a step towards helping modelers and programmers make more effective decision support tools. Stakeholders in the crop and biofuel systems can better understand their effect on the other. Technology companies, large and small, develop APIs in the hopes of working together to make more powerful tools for society and a similar opportunity is available for environmental modelers. Future work will include integrating a model of a livestock system into the framework, incorporating other cropping systems, accounting for irrigation pumping costs, evaluating economic impacts, and developing an enhanced environmental impact assessment that includes other factors such as eutrophication and human health components. This integration will also be tested against long-term climate models and make system predictions for the future.

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Chapter 3
Developing an integrated model for the corn, ethanol, and beef systems using a loosely-coupled web framework

3.1. Introduction

With the global population rapidly increasing, the demand for essential food, energy, and water resources are projected to reach an unsustainable rate by the year 2050 (Godfray et al., 2010). Demand for food is expected to double by the year 2050 with an estimated population of 9 billion and preparing for which requires intelligent use of water and energy sources in the world's agricultural systems. We have developed strong understandings of how individual food, energy, and water (FEW) systems work on biophysical, economic, and environmental levels but these FEW systems are highly interconnected and understanding their interactions is essential to making more sustainable decisions within the nexus (Bazilian et al., 2011; Finley & Seiber, 2014). There is potential in using the FEW nexus approach to determine public policy for utilizing water and energy sources for more efficient use in agriculture. This can be used as a guiding principle on the local, national, or global level for quantifying economic and environmental effects of trading, tax plans, or technological innovation (Franz et al., 2017; Kurian, 2017; Pahl-Wostl, 2017).

Although much work has been done over the years to model food, energy, and water systems with high validity, these models have limited system boundaries and do not fully comprehend the impact it has to the full interconnected nexus. Recently however, researchers have become more engaged in interdisciplinary thinking to couple these FEW systems with Life Cycle Assessments (LCA) and integrated systems modeling. Some researchers take a general approach to quantify the FEW nexus impacts by performing visual model mapping (Zimmerman et al., 2018; Ziv et al., 2018). Another general way to quantify all resources is by balancing exergy inputs and outputs in local systems (Hang et al., 2016; Kılkış & Kılkış, 2017). Many FEW nexus tools that have been created so far use optimization algorithms to solve for the best decisions to make for a specific region and will carry out case studies. These models can function based on analyzing the best land use scenarios (Bieber et al., 2018; Chen et al., 2018; Chitawo & Chimphango, 2017), import/export scenarios (Andrew Berardy and Mikhail, V Chester, 2017; Daher & Mohtar, 2015; Owen et al., 2018), resource allocation methods (El Gafy et al., 2017), or any combination. Karan et al., (2018) stochastically generates scenarios to optimize the FEW nexus based on water and energy use to create a composite index. Kan et al., (2018) suggests using an accelerated global optimization method to solve multiple objective functions in the FEW nexus and demonstrates it on an integrated hydrological model, IHACRES. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) by the International Food Policy Institute (IFPRI) is a government project to do global integration of FEW systems and models to determine the world's capacity to solve climate change, food security, and sustainability issues (Robinson et al., 2015).

Most of these studies hope to find the best use of different types of water and energy sources to produce different types of crops and other foods that are available in that region. Many of the aforementioned studies rely on life cycle assessments to quantify the environmental impact and historical data to calculate the production in the agricultural systems. With many individual models already existing, some other researchers have attempted to couple specific agricultural systems by connecting agricultural models into a single tool. The Integrated Farm System Model (IFSM) combines crop farming and livestock production on a single operation to help farmers make optimal decisions based on the integrated system (Rotz et al., 2012). The Biofuel Energy Systems Simulator (BESS) is another systems model that does LCA on corn, ethanol, and beef systems using ethanol production as the functional unit. It integrates the different systems using a spreadsheet for all backend calculations (Liska et al., 2009). Coupling existing models as opposed to recreating systems models in stand-alone software is an alternative way to analyze specific system interactions that has not been incorporated as heavily.

Argent et al., (2004) reviews many different ways to computationally integrate models. Some of the challenges are differences in model context, programming languages, units, and technical feasibility. Service-oriented architecture (SOA) is a powerful way to integrate multiple programs together by allowing models to be exposed universally through a web service and connected in a functional pipeline according to the needs of the user. One would define this system as loosely coupled since their original models do not have any knowledge of each other prior to integration (Papazoglou, 2003). The loosely coupled framework is significant and appropriate for system integration because much like in the real world, each system can be viewed in a vacuum, but must have a layer of connection to understand the complete nexus. Many environmental researchers have used this methodology to connect environmental models (Vitolo et al., 2015). Some projects have used SOA to make multiple geospatial and hydrological models available through web services and propose a model workflow in the framework (Castronova et al., 2013; Granell et al., 2010). Researchers have attempted to develop smart web frameworks for connecting the user to the models and databases while incorporating an integration layer for these coupled environmental systems (Belete et al., 2017; Scott Dale Peckham, 2014). Two studies in particular create SOA for these models by exposing them using Representation State Transfer (REST) services (Granell et al., 2013; Jiang et al., 2017).

While loosely coupled web frameworks have has been used to connect environmental models, there has not been much work done in using it to connect agricultural models and assessing impact. Furthermore, most integrated nexus models are for general use and do not tie specific agricultural systems that have a large stake in a specific region. Every agricultural system is different in production and market interactions and it is difficult to generalize their interconnections and environmental impact based on single energy or economic balances. Once system interactions are better understood on a local level, more systems from other regions can potentially continue to be integrated for more comprehensive assessments.

In the Midwestern United States, corn, ethanol, and beef are produced in huge quantities and are significant parts of the regional and national economy. Over 75% of corn produced in the United States comes from states in the Midwestern region (National Agricultural Statistics Survey, 2018). They are also highly interconnected as corn can be used as inputs to ethanol and beef cattle, while ethanol byproduct can also be used for cattle feed. The Midwest holds the top 10 states in ethanol production and produces the most beef of any US region (Renewable Fuels Association, 2018). These systems are significant users of water and energy and it is crucial to understand how they are all interconnected to quantify the environmental impact and resource use in this corn, ethanol, and beef nexus. Each system has well-validated models that and can be loosely coupled. This paper proposes to link interconnected agricultural systems in the Midwest United States with the following 3 objectives:

1. Identifying system parameters and boundaries of corn, ethanol, and beef systems
2. Connecting the corn, ethanol, and beef production systems as a loosely coupled web framework
3. Simulating projected model scenarios to assess the system's ability to sustainably provide the world's corn, ethanol, and beef

3.2. Materials and Methods

3.2.1. Identifying and Wrapping Models

Each production system in the corn, ethanol, and beef nexus has many models and tools associated with it. The best models to use for this integrated model are widely accepted and easily useable in external shareable computational framework. Each model will be wrapped using Python script so that they can be run through the terminal (shell) and also fit the loosely coupled architecture.

Many cropping models exist that calculate yield and growth based on environmental and management parameters such as CERES, CROPGRO, and Hybrid-Maize (Boote et al., 1998; Jones et al., 1986; Yang, 2016). There are also software that wraps these models in related systems such as the Agricultural Production System Simulator (APSIM), Decision Support System for Agrotechnology Transfer (DSSAT), and CropSyst (Hoogenboom et al., 2015; Keating et al., 2003; Stöckle et al., 2014). DSSAT is the most widely used by researchers around the world and is calibrated in many different regions, including the Midwest US (Rao, 2002). It has high functionality with numerous inputs and has models for various types of crops, including corn. Furthermore, it is developer-friendly as there is a compiled version of the program called *DSCSM046.exe* that can be run in the terminal. The only argument the user needs to include when running the complied version is an experiment (.MZX) file. This experiment file is a text file that can be written using Python code based on input parameters defined by the user. This makes it easy to develop a workflow into the integrated model by writing the experiment file, running *DSCSM046.exe*, and returning desired yield values from the output files generated by DSSAT.

Many biofuel models exist in the form of Life Cycle Assessments (LCA) which evaluate the full impact of producing and consuming a product. Some LCA's for biofuels are the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) Model, SimaPro, and the Global Emissions Model for Integrated Systems (GEMIS) (Elgowainy et al., 2012; Fritsche, 2000; Pre Sustainability, 2017). GREET is a free software developed by Argonne National Laboratory that specializes in transportation fuels such as corn ethanol. It is sponsored by the U.S. Department of Energy is widely used, and much like DSSAT is developer-friendly. There is an Application Program Interface (API) made available through the website, written in C#, that wraps GREET's LCA functionality and allows developers to use it in their own program. The API can be compiled into a program that can be run in the terminal, much like DSSAT. The arguments needed to run this compiled version are the *.greet* file, the year being simulated, and the fuel pathway. A *.greet* file is a large Extensible Markup Language (XML) file that contains all necessary pathways, processes, and resources in the GREET database to perform LCA on any fuel. GREET accounts for technology changes based on the current year which is why that is also an input. The pathway is the fuel being simulated. GREET has a pathway for corn ethanol so the pathway ID corresponding to this fuel will be passed as an argument. The LCA will provide environmental parameters for the complete life span of the product from production to consumption (i.e. Well-To-Wheel). The default outputs are environmental impact values for energy usage, water usage, greenhouse gas emissions, and pollutant emissions on a per MJ basis of corn ethanol fuel.

While only a certain amount of parameters can be passed through the terminal to run GREET, the model can be further manipulated by modifying the *.greet* file. Instead of running LCA on a per MJ basis as default, the user can specify the amount of fuel in any unit by writing it into the XML input file. If there are any other resources or attributes in the pathway that the user would like to modify, these also can be written into the file as part of the program workflow. These inputs include nitrogen, chemical, and irrigation use in corn farming, as well as distance travelled by the product. Using Python, the program can parse the XML input file to find the appropriate line to write in these modifications. Thus, a Python wrapper for GREET in this integrated workflow can modify the *.greet* file, run the compiled program in the terminal, and collect environmental outputs from the results file.

To model the beef production, connecting a nutrition model that predicts weight gain is needed. There is one well accepted beef cattle nutrition model that is approved and developed by the National Research Council (Galyean et al., 2016). This model is composed of many equations that predict gain, methane emissions, water use, and other relevant environmental outputs of beef cattle given its daily diet, environment, genetics, and growth phase. Some researchers have used these equations for their models such as the aforementioned BESS and IFSM programs. However, a more accessible version of this model is useable in the Beef Cattle Nutrient Requirements Model (BCNRM) (Tedeschi et al., 2016). This model is available as a Microsoft Excel spreadsheet program which can easily be connected to Python using any number of Python-Excel libraries. Within the integrated workflow, the Python wrapper can attach to the BCNRM program, populate the form with inputs of the cattle's diet, weight, genetics, and environment, and retrieve gain, methane, and water use from the appropriate cell.

3.2.2. Integrated workflow

3.2.2.1. Input/Output Connection

Models are connected based on the intermediate inputs and outputs which must be converted into compatible units. The interconnections of the corn, ethanol, and beef nexus are illustrated in Figure 3.1. Corn is produced on fields and require inputs such as weather, irrigation, and fertilizer. This corn can either be distributed to ethanol plants or to beef operations to be used as feed. The ethanol plants not only produce ethanol, but also distillers grains and solubles (DGS) as byproduct which can be used as supplementary feed for beef cattle. Not shown in Figure 3.1 is that the corn can be further processed to be consumed directly by people. This system is also driven by the overall population growth and demand for FEW resources. The boundary is defined by the life cycle of corn from production in every acre of farmland to processing for either ethanol, beef, human consumption, or export. The LCA tracks the raw materials such as water, energy, and chemicals that go into corn and the environmental outputs such as greenhouse gases from each system. In this study, corn production and system usage is simulated on the county level and aggregated to the size of the region of interest; in this case, it is the state of Nebraska, but can be as large as the entire Midwest region or full United States.

The goal is to model this corn, ethanol, and beef system by simulating the interconnections described and using the individual models for each system. The general model pipeline that is developed using Python is described in Figure 3.2. The system starts with corn production where DSSAT simulates all the corn that the system is able to produce given cropping inputs and the amount of land allocated to corn growth. The system differentiates between irrigated and dryland (non-irrigated) corn fields as irrigated fields use more water and fertilizer.

The corn distribution is based on how it is processed or consumed within the boundaries of the systems. In this case, 1 of 4 things can happen to the corn: it can be used for human consumption, allocated to ethanol production, allocated to beef cattle feed, exported outside the system. In this model framework, the total corn production is first distributed to satisfy a certain amount for human consumption as that is currently assumed to be the top priority. Then, the remaining corn production is allocated to ethanol and beef simultaneously since beef production is very dependent on DGS from ethanol. The ratio of remaining corn allocated to either ethanol or beef is determined by the average feed ration defined in the input file. The feed ration consists of a certain ratio of corn to DGS and this determines the ethanol to beef ratio based on the conversion of corn to DGS in the ethanol production process. For these simulations, the feed ration is defined in Section 2.4.1 and is consistent for every county and year based on a typical feed ration for finishing cattle in the state of Nebraska. This is done so that the amount of

DGS that is produced in ethanol plants equals the amount that is taken by cattle. The allocated amounts are distributed until the capacities of either the ethanol or beef systems are met. Another ethanol loop is added if there is leftover corn from the beef system. Any remaining corn production is exported from the system which provides excess DGS to be exported. The usage of the exported corn is ambiguous since all of the use within the system is already accounted and therefore this model will only track how much is exported.

For this model to run, the user must feed an input using Comma-Separated Value (CSV) file that has attributes describing the system and are necessary for each model to run. DSSAT requires many inputs of a crop field in order to successfully run the model. Management inputs included for these simulations are crop type, cultivar, soil type, plant population density, irrigation amount, and fertilizer amount. Each DSSAT run also requires a weather file that describes the location’s daily precipitation, maximum temperature, minimum temperature, and solar radiation. GREET and BCNRM do not need any extra parameters to run.

The model calculates the production of a system split up into regions which, in this case, are counties. DSSAT only makes calculations on a per hectare basis so these outputs must be aggregated based on the total land size of the county. Since irrigated and non-irrigated fields have different environmental outputs, the input file must have data on the number of acres of irrigated vs non-irrigated land. The input file also contains information about how much corn each system uses that year. An amount of corn for human consumption needs to be defined, as well as the ethanol capacity and the feedlot cattle inventory of the system. Once all the attributes for each county in the system boundary are defined, the integrated model will run according the flow chart shown in Figure 3.2.

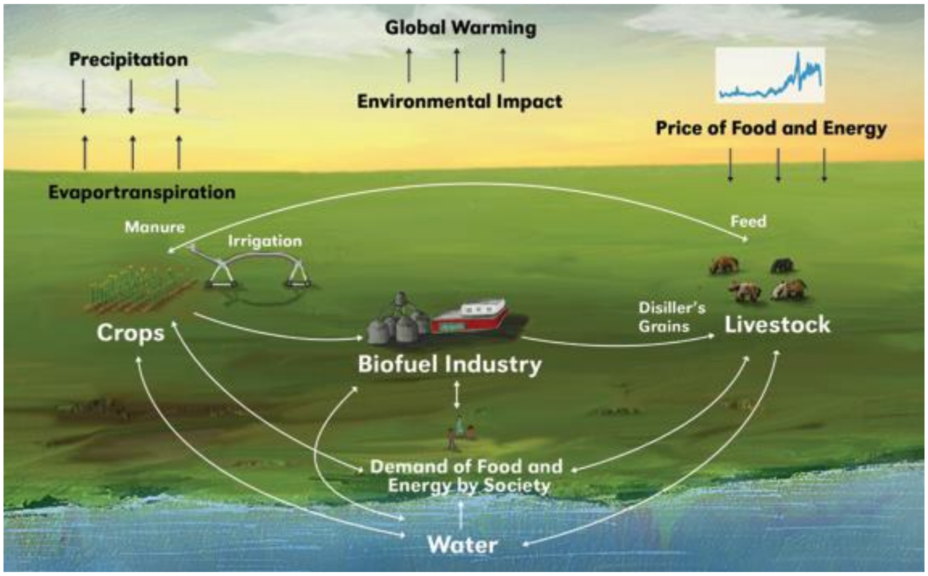

Figure 3.1 – Interconnections of the corn, ethanol, and beef nexus

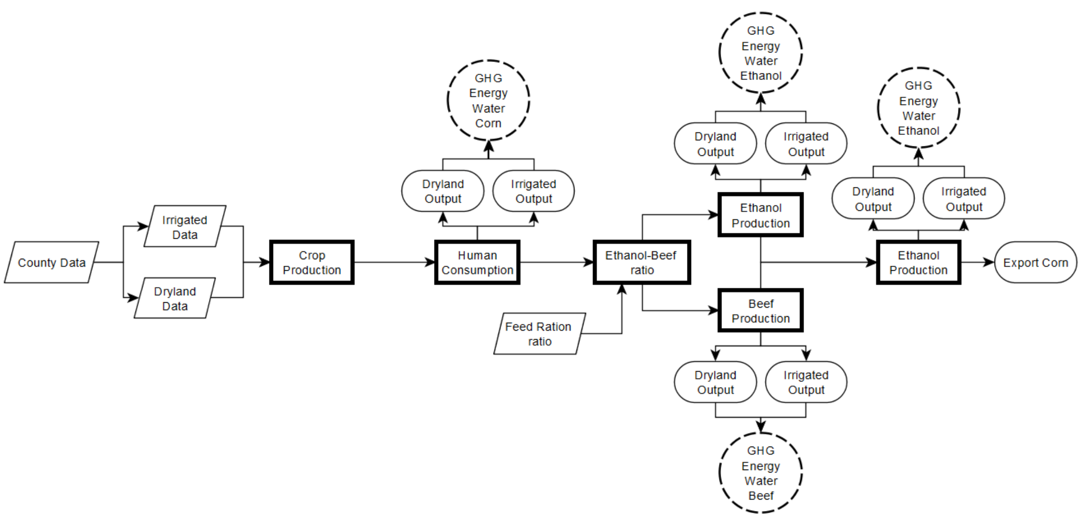

Figure 3.2 – Overall flow for integrated corn, ethanol, and beef models; Python wrappers for models are in bold rectangular boxes

Each Python wrapper function has a similar logic when distributing yield to satisfy the resource capacity for human consumption, ethanol, or beef. It iterates through the county and goes through the logic presented in Figure 3.3. The first full iteration will check if the county has any capacity for that resource in it (i.e. cattle or ethanol). If so, it will calculate if the corn production in that county satisfies the full capacity and if it does, the remaining corn will move onto the next iteration. The same check happens again if there is capacity in the district that the county is in. Districts are geographic groupings of counties that are assigned in the input file. If any corn is still remaining in the county, it will check again if there is any capacity left in the entire state which is the final check. The geographic level on which the corn is distributed determines the distance the product travels as an input into the GREET model which affects environmental impact. This step-wise iteration is performed to satisfy all resource capacity of the state and to more accurately define the average distance travelled.

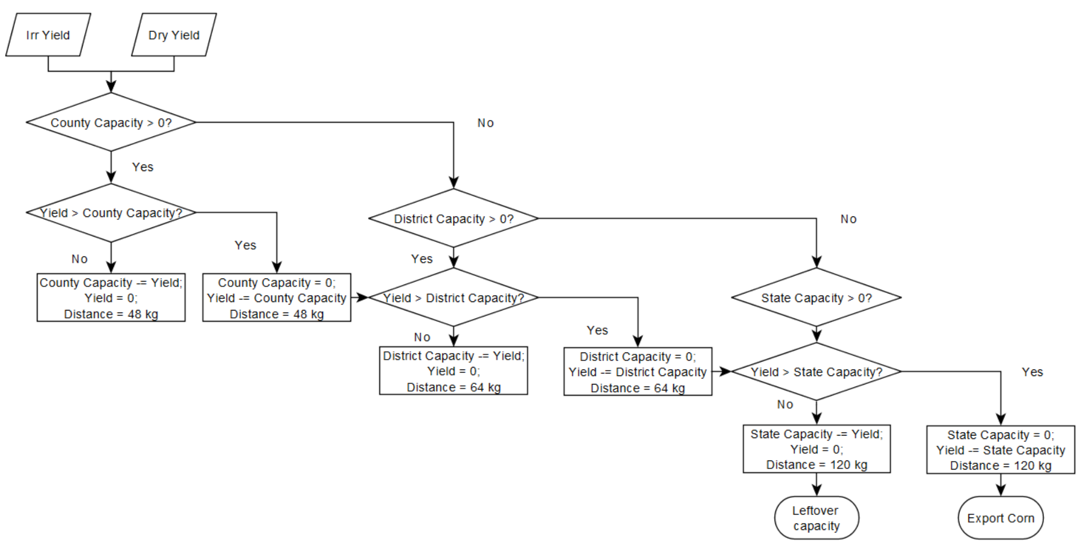

Figure 3.3– Logical flow for corn product in each Python wrapper

3.2.2.2. Environmental Outputs

GREET is a powerful tool for this model because it can calculate the environmental outputs for each use of corn in the integrated system. There is a pathway for corn farming in GREET so that can be used to calculate the full production to consumption footprint of certain parameters for corn. This is used in the Human Consumption function described in Figure 3.2 which removes a portion of the total corn production for human consumption and performs LCA on this amount. The environmental parameters of interest for the entire system are greenhouse gas (GHG) emissions, fossil fuel energy use, and water use. GHG are calculated in CO_2 equivalent based on global warming potential values of 1, 23, and 296 for CO_2, CH_4 and N_20 respectively (Wu et al., 2007). To accurately calculate these outputs, GREET needs all the data available from how the corn was produced. Irrigated and non-irrigated corn are calculated separately, because they have different water and greenhouse gas footprints. Any resource use that is specific to a field must be written into the *.greet* file as discussed in Section 2.1.

For the Ethanol Production function, GREET will be used once again but will instead use the corn ethanol pathway rather than the corn farming pathway to calculate the environmental footprint. This pathway includes the corn farming pathway in it and requires the same inputs such as fertilizer and irrigation use.

GREET does not have a pathway for beef, but LCA can still be done on the feed. Corn and DGS are both used in the feedlot rations here so those environmental parameters must be calculated. LCA can be done on the total amount of corn used with GREET in the same way as discussed previously. GREET already takes into account the benefits of DGS as a byproduct of ethanol and a feed for beef by crediting the amount of corn feed it displaces. If this displacement value is calculated based on the feed ration in the scenario and written into GREET, it will automatically perform LCA for the DGS byproduct.

Growing the beef cattle also has several environmental implications in itself. Beef cattle emit a large amount of enteric methane in its life span so this amount must be calculated using BCNRM. Current methane calculations do not include manure emissions due to the limitations of the model. Once the total methane emissions are calculated, it must be weighted by its global warming potential and added to the amount emitted from the feed. The amount of water that cattle drink is added to the feed water footprint. Water intake is sensitive to the average daily temperature which can be provided by the weather file.

3.2.3. Loosely coupled structure

Developing a web service framework will allow users to access these models and use them in the workflow as described in the previous section. The models and integration framework are loaded on to a server and exposed using Representation State Transfer (REST) services. A REST Application Program Interface (API) allows a client to communicate with the server using requests such as GET or POST commands (Richardson & Ruby, 2007). Once the user successfully sends a request to the server, it will be sent to the model layer which runs the appropriate model subroutines defined in Section 2.2.1. The server also has a data repository that can store and retrieve data as needed like the input and output files. While the model layer is running commands, it can interact with the data repository layer. After the subroutines are finished, the function will return output files that the user requested. The REST API takes this data and send it back to the client as a response.

Because the model integration is performed using Python, the web framework is also developed using Python. A REST server is created using CherryPy which is a Python web framework that is easily integrated with Python applications. When a request is sent by the user, the CherryPy server takes the parameters and automatically feeds them into Python framework.

With this loosely-coupled web framework, users can easily use the exposed individual models and the provided framework without needing to install any software. With the individual models exposed, users can either use the provided framework or build their own framework based on how they want the systems to be connected. Figure 3.4 shows the flow of the web framework where data files are stored in the data repository layer and the integration from Figure 3.2, is defined in the model pipeline layer.

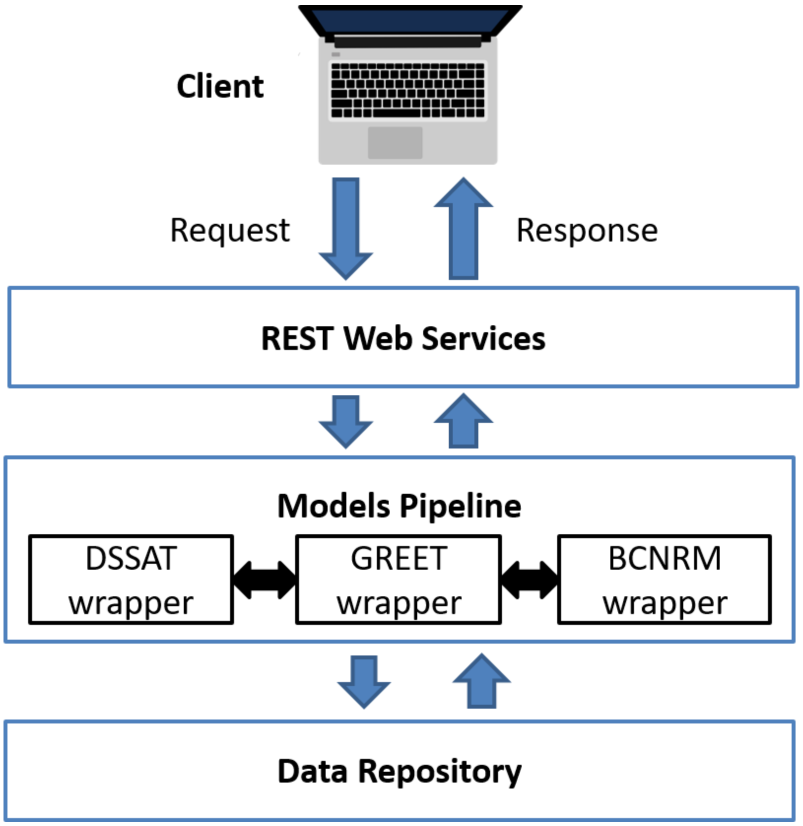

Figure 3.4 – Web framework for client interaction with models on server

3.2.4. Case study scenarios

3.2.4.1. Base scenario

Several scenarios of this model are run to evaluate its capability and understand how the integrated corn, ethanol, beef system behaves for a given region. In this case, the state of Nebraska is defined as the system boundary and the input file will include necessary parameters for all 93 counties in the state. Nebraska currently produces the second most cattle of any state and the third most corn of any state in the U.S. which makes this an appropriate case study for evaluating this integrated system (USDA National Agricultural Statistics Survey, 2018a; USDA National Agricultural Statistics Survey, 2018b). A base simulation is set for the state of Nebraska during the year 2017 where some parameters, including cropping acreage and beef cattle capacity per county, are provided by the National Agricultural Statistics Survey (NASS) for the U.S. Department of Agriculture (USDA) (USDA National Agricultural Statistics Survey, 2018a; USDA National Agricultural Statistics Survey, 2018b). The NASS data also separates Nebraska counties based on regions which is useful in geographically defining nearby counties. Ethanol capacity for each state is provided by the Renewable Fuels Association which displays where ethanol plants are and how much ethanol they can produce annually (Renewable Fuels Association, 2018). Weather data is taken from the nearest weather station provided by the High Plains Regional Climate Center (HPRCC) (HPRCC, 2018).

Many other input parameters were assumed based on common corn growing practices in Nebraska. All fields are assumed to be planted on May 1st and harvested on October 15th based on the growing season in Nebraska (USDA, 2010). While soil type varies across the state, it is assumed in this study that all farmers grow corn on arable land and is suitable for corn growth. DSSAT has many default soil files and the one most representative for the state of Nebraska is silty loam (Archer et al., 2017; Elder, 1969). The specific corn hybrid grown in each county is based on the appropriate Growing Degree Days (GDD) for that region. A map of the appropriate GDD for each corn hybrid is shown in Figure 3.5 and is based on the region's weather and sunlight hours (Pioneer, 2018). A typical plant population density for this area is 10 plants/m^2. All other inputs are similar to those used in the previous study integrating crop and biofuel systems (Anderson et al., 2018). The assumptions among the baseline values for the crop system are shown in Table 1.

Table 3.1 – Crop model assumptions

Parameter	Baseline Value
Plant Population	10 plants/m^2
Fertilizer material	Anhydrous ammonia
Fertilizer amount	120-150 kg N/ha
Fertilizer method	Banded on surface
Planting Date	May 1
Harvest Date	October 15
Irrigation	Automatic when Needed
Row spacing	75cm
Plant depth	5cm
Tillage	Drill, no-till
Soil	Silty Loam
Hybrid	Varies by GDD of county
Technology	Consistent through 2050

All of the above inputs are used for all fields. Some inputs are differentiated based on the fields that are irrigated versus those that are non-irrigated. DSSAT has a setting that allows the user to automatically fully irrigate the field throughout the season. The model applies water to the field based on evapotranspiration water stress. For the irrigated fields, this setting is selected. For the non-irrigated fields, this option is turned off and no irrigation water is applied. Because irrigated crops grow larger, they will need more nutrients than the non-irrigated crops. The amount of nitrogen fertilizer applied to each field in each county is based on the expected yield and the nitrogen requirement for that yield (Shapiro et al., 2008). Expected yield data were taken from the NASS dataset and rough approximations of 120 kg N/ha and 150 kg N/ha were chosen for all non-irrigated and irrigated fields respectively (USDA National Agricultural Statistics Survey, 2018b).

Figure 3.5 – Map of hybrids for each Nebraska county by GDD using 10°C as the base temperature

The amount of cattle produced in each state is already provided as input, but a feed ration must be defined for finishing feedlot cattle. Feedlot cattle are often fed with a high percentage of fat and concentrates such as DGS and corn grain so it is assumed that 25% of the ration's dry matter is DGS, 65% is corn, and the other 10% is hay for roughage. The total dry matter intake is 8.16 kg/day so that the cattle can achieve a daily gain of 1.36 kg/day. This model will output beef production in kg of beef rather than number of cattle finished so it is assumed that each cattle will grow from 408 to 567 kg mature body weight. The assumptions among the baseline values for the beef system are shown in Table 2.

Table 3.2 – Beef model assumptions

Parameter	Baseline Value
System	Finishing
Weight	`900 - 1250
Daily Gain	3 lbs/day
Ration % corn	65%
Ration % DGS	25%
Ration % roughage	10%
Sex	Steer
Breed	Angus

3.2.4.2. Long-term projections

The purpose of this scenario is to use this integrated corn, ethanol, and beef model to simulate Nebraska's ability to feed the world by the year 2050. These scenarios will use climate change and population growth projections to analyze whether or not Nebraska can continue to meet its contribution to an increasing global resource demand and what the environmental impact is. The contribution required is defined by the ratio of current Nebraskan cattle and ethanol inventory over the total world consumption. The proportion of corn used for human consumption is constant at 9.9% (Capehard & Liefert, 2018). While these ratios for each resource remain constant throughout the year, the total world consumption of each increases with world population. The product of the ratio and the world consumption will determine Nebraska's contribution for the resource in a given year. General practices will remain constant over the years for most inputs while weather and resource demand will change based on global climate models and population growth models.

Climate change has a significant impact on how each system behaves due to how weather affects crop and beef cattle growth. The increase in temperature affects how much water is consumed by beef cattle daily and can also negatively impact corn growth during the season. Because of this, the CSIRO climate model has been chosen to project daily weather up to the year 2050 (Jeffrey et al., 2013). This model has projected 3 paths, all of which differ in how extreme the CO_2 levels are expected to be: Representative Concentration Pathway 8.5 (RCP8.5), RCP6.0, and RCP2.5 where RCP8.5 is the worst-case scenario and RCP2.5 is a scenario with significant human intervention. These pathways are meant to predict the GHG forcings on the climate based on how the human population behaves environmentally. The model uses CO_2 levels to project what the climate will be like for each year. This global climate model has a daily temporal resolution and spatial resolution of 0.125 degrees latitude and longitude. The central coordinates for each county were approximated and used for extracting the daily weather data from the netCDF file provided by the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive. These files were converted into yearly weather files that can be read by the DSSAT model.

Population growth models dictate how much demand for resources there will be for each year up to 2050. The United Nations developed a growth model with high, middle, and low variants that predicts the global population size for the century (UN Population Division, 2017). Each of these three population projections are used in the scenario analysis. To determine whether Nebraska can upkeep its contribution to these resource demands, the beef capacity and ethanol capacity for each state will increase with the population. The current contribution of Nebraska is defined as the amount of resource that Nebraska produces versus the total amount that the world produces. When the population increases in subsequent years, the demand for beef and ethanol will increase and will adjust the input file accordingly by increasing the capacity in each county. Increased corn consumption is adjusted each year by increasing the parameter defined in the *ppl_corn.py* function that determines how much is used directly as human food.

With 3 climate change scenarios and 3 population growth scenarios, there are 9 total scenarios to simulate from the present year to 2050. 10 projections of each climate scenario were retrieved from the online CMIP5 climate projection archive (Maurer et al., 2007). The weather is volatile from year to year for a single projection which has a large impact on simulations and trends. Simulations for total production in Nebraska were run for each projection to determine if there was an optimal one to use. The total production was also calculated by averaging the yields from all the runs together. Finally, a final run was performed by averaging the weather files together to show what the resulting corn production looked like. The results, which are represented for the RCP4.5 projections, are shown in Figure 3.6. The filled part of the plot represents the variance of yield from all 10 projections. The Selected Projection shown in Figure 3.6 was the projection with the least variance from the mean and still shows high volatility. The simulation using averaged weather data appears to not be realistic as the yields are consistently higher than the rest. This is likely because rainfall is spread out evenly throughout the season as opposed to dispersed rainfall events which is realistic. The most representative simulation with the least variance is the one with averaged yield from all projections. Therefore, the model used average yield from all projections during this scenario analysis.

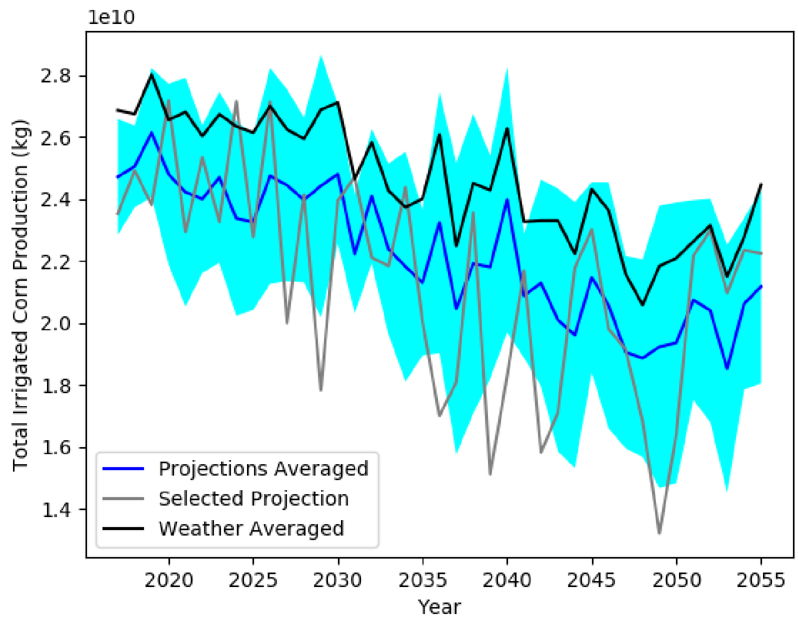

Figure 3.6 – Comparison of climate projections and methods for RCP4.5 to simulate total state corn production each year. Averaging yields from all projections provides less variance than using a single climate projection

Simulations are done every 5 years from 2020 and also including 2017 to show the present baseline scenario. Production outputs are compared in overall corn exported, corn for human consumption, pounds of beef produced, and gallons of ethanol produced. Environmental outputs are compared in (fossil fuel) energy used, water used, and GHG emitted per kg of corn produced. With these calculations, researchers can determine if the current practices in Nebraska are sufficient for contributing to the population growth and if it can do so in a sustainable and environmental manner despite climate change challenges.

3.2.4.3. Parallel Computing

Scenarios were done for 3 population projections, 3 climate projections, and 8 years so 72 total simulations were needed. Since GREET is computationally expensive and it is used throughout the integrated model, the scenario analysis was performed on a supercomputing cluster where all 72 simulations, which take over 12 hours to process, are run in parallel. To do this, the DSSAT program must be compiled in Linux using the original FORTRAN code and the GREET model must be compiled in run-time using Mono since it's API was developed in C# (*Mono*). Each simulation had its own folder with the input CSV file, DSSAT environment, GREET environment, and output files.

3.3. Results and Discussion

3.3.1. Weather and total corn production

To analyze how weather affects overall corn production and scenario results, the representative weather data from each year and each scenario were plotted in Figure 3.7. The average temperatures were averaged over the growing season across all projections and all counties to determine the average min and max temperature each year for that climate scenario. Precipitation data was summed over the growing season and across all counties but were averaged across all projections. This summary of weather data over each year does not fully explain yield values from DSSAT, but there are noticeable trends. Both minimum and maximum temperatures are rising steadily from 2017 to 2050 with moderate variation in between. Total growing season precipitation does not appear to have a clear trend but instead has significant variability throughout the years. For example, two pathways had completely different rainfall amounts in 2035 when RCP4.5 appeared to have a drought year while RCP8.5 experienced the highest rainfall.

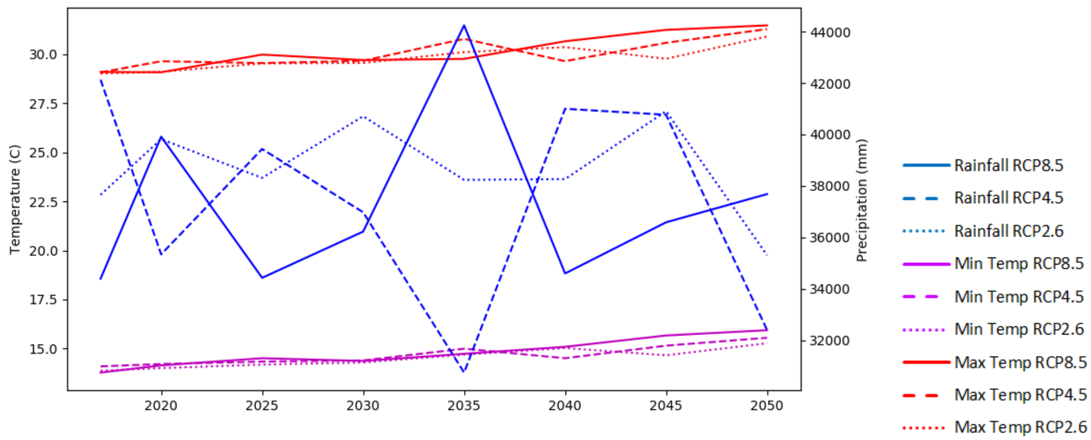

Figure 3.7 – Summary of weather data for simulations for maximum temperature (red), minimum temperature (magenta), and total annual precipitation (blue)

Total corn productions from DSSAT simulations are plotted in Figure 3.8. There is a negative trend for corn yields which mirrors the consistent rising temperature trends. There is some variation with noticeable low and high years for yield which can be attributed to weather trends. Year 2035 for RCP4.5 is a low year for yield which is related to what appears to be a drought year as shown in Figure 3.7. The yields are low for RCP8.5 in 2040 possibly due to a lower rainfall that year. To reiterate, annual weather summaries cannot fully explain variations in corn yields as timing of precipitation and temperature during the season also has great impact. However, this can provide some insight into overall yield and simulation results trends.

Planting and harvesting dates did not change from year to year which may be a reason for the lower yields. In reality, the increased temperature would increase the length of the growing season which may make corn yields appear higher than they are here. These projected yield trends are also not representative of historic yield trends as they have been increasing for a long time (USDA National Agricultural Statistics Survey, 2018b). This is due to improved technology throughout the years in equipment, irrigation, fertilizer, and genetics. These inputs assumed that technology did not change over the years and the same decisions and irrigation strategies would be made regardless of what year it was. This was done as a worst-case scenario and to project what corn production would look like without significant improvements in technology or crop breeding.

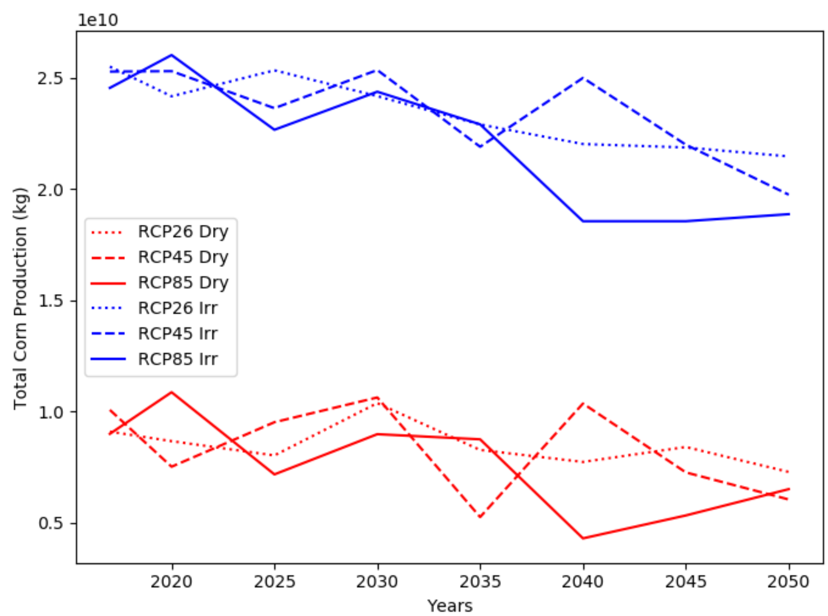

Figure 3.8 – Total dryland and irrigated corn productions for each year and RCP scenario

Irrigation water highly affects the total water use in the integrated system. The total amount of irrigation water used for pumping in each scenario is not well correlated with irrigated crop yield. DSSAT's automatic irrigation setting may not be able to properly handle the effects of different climatic conditions which is what is being varied in each scenario. Still, Figure 3.9 shows that irrigation water used is highly variable, even when set to the optimal settings.

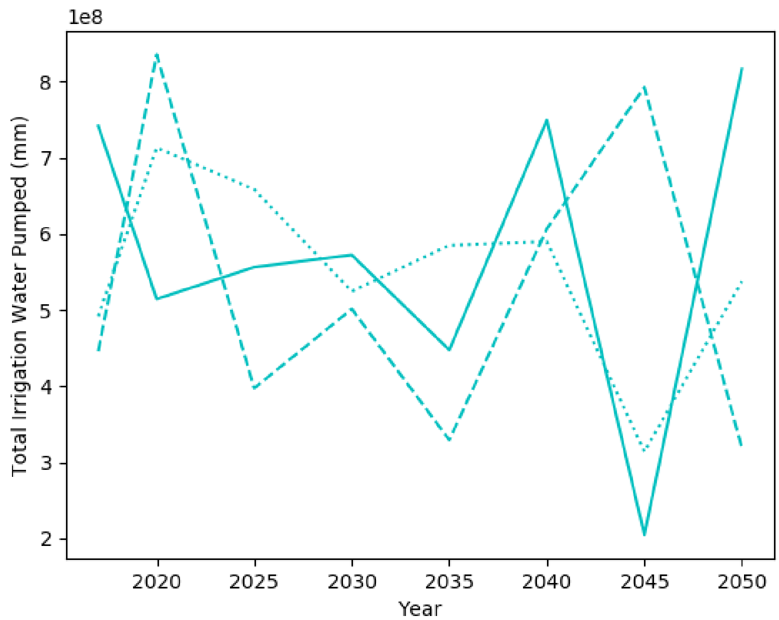

Figure 3.9 – Total water pumped for irrigation

3.3.2. Scenario Results

The simulation results of production outputs of the integrated system through 2050 are shown in Figure 3.9. There are 9 total scenarios grouped by each climate scenario and population model. After corn is produced, it first gets distributed to human consumption up to the amount required that year. Since corn requirement for human consumption has a direct relationship with the human population, the curve in Figure 3.9 will look similar to the population growth model if it completely fulfills requirements. In this case, all climate scenarios are able to meet each population requirement for human consumption.

After that, it is allocated to ethanol and beef production through a ratio defined by the feedlot cattle ration. Similar to human consumption, the requirement of corn to produce enough beef for the global population is met each year and for every population and climate scenario. For ethanol however, the population requirement for fuel is not met for every scenario. If corn for ethanol requirement is not met then the amount of ethanol produced will reflect how much corn production is remaining for the year. If corn meets the requirement then the ethanol produced for that year will be equivalent to the total ethanol capacity and the rest of the corn will be exported. If any corn is exported for a given year and scenario then it means Nebraska has met its requirements for all of these resources to provide for the global population. Figure 3.11 shows which scenarios fully meet the resource requirements. As previously stated, human consumption and beef requirements were met for all scenarios and years but it varied for ethanol. Generally, full requirements were met more often with lower projected population growth as 13 scenarios met full capacity in the low population variant, 12 scenarios met full capacity for the middle variant, and only 9 scenarios met full capacity for the high variant where much more resources are needed.

Variability in results due to climate scenarios are apparent and not as predictable. The ethanol production plot in Figure 3.10 shows large variability from year to year because of how sensitive corn production is to the changing weather. For example, the jumps in ethanol production in years 2040, 2045, and 2050 for RCP8.5 can be explained by corn production being low 2040, rising in 2045, and remaining stagnant in 2050 with a rise in other resource requirements. Corn production does not appear to have a clear relationship with the different climate change scenarios which is why some spikes in corn exports are for different scenarios and not just the best case, RCP2.6. For ethanol, there appears to be a general upward trend of production as it is meeting some population requirements but after 2030, the variability in corn yield is more intense and creates a lack of correlation. For corn exported, there is generally a downward trend through the years for each scenario but the variability in yields creates sporadic jumps such as in 2020 for RCP8.5 or 2035 for RCP4.5. This is further shown in Figure 3.12 where the ethanol production deficit in each year is generally increasing due to higher requirements.

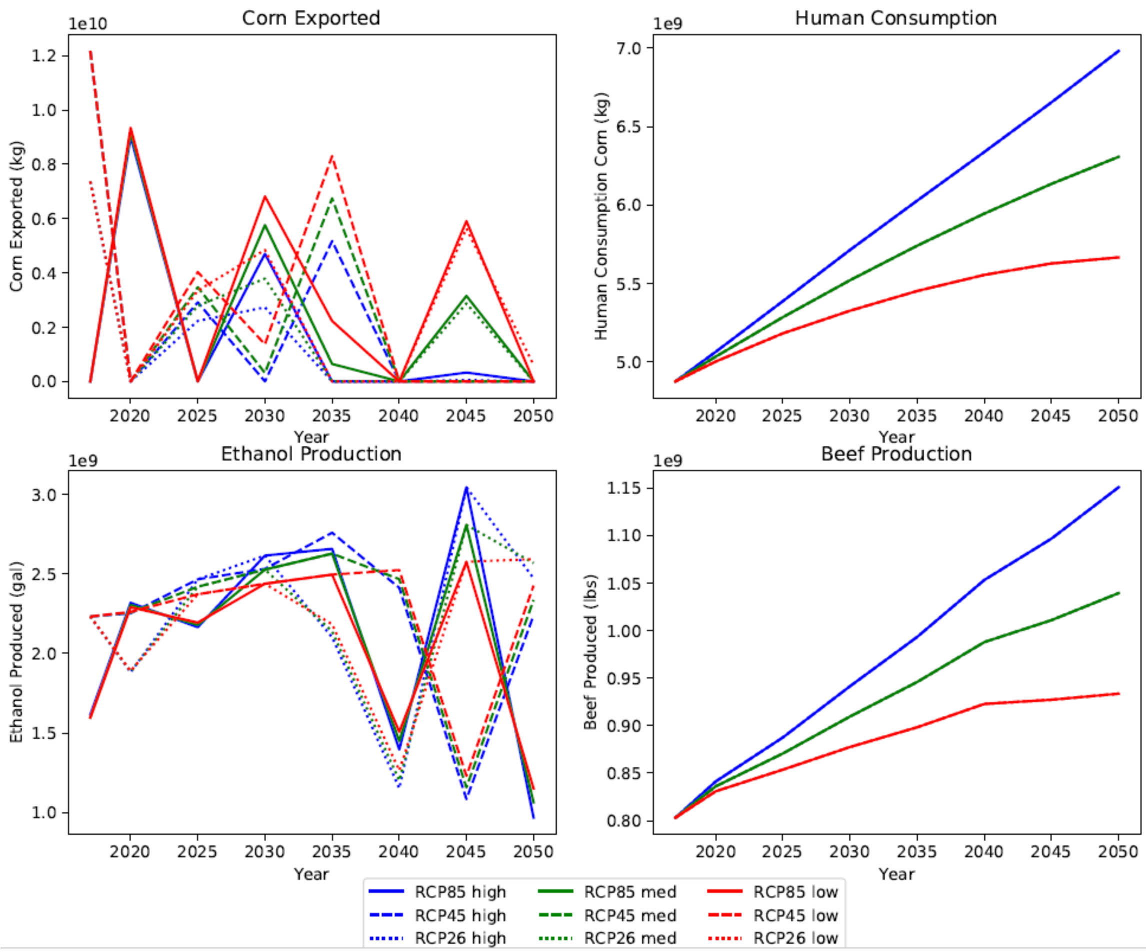

Figure 3.10 – Full simulation results of the integrated system for production outputs

Table 3.3 - Percent of years where resource demand was met

	High Population	Medium Population	Low Population
RCP2.6	33%	44%	55%
RCP4.5	33%	44%	44%
RCP8.5	33%	44%	44%

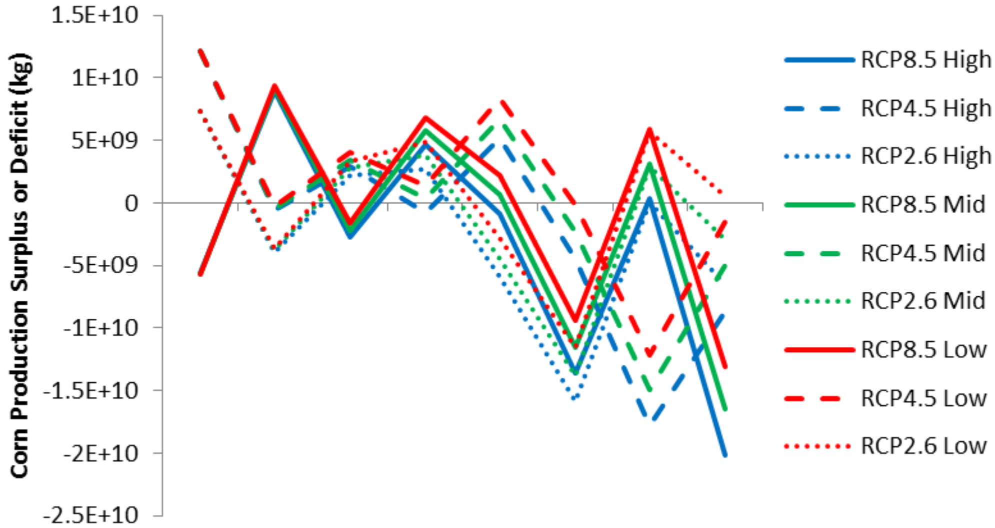

Figure 3.12 – Corn surplus or deficit for each year and scenario

The environmental impact of each scenario was measured per kg of corn produced because that is the resource used in all of these systems and it provides insight on the environmental efficiency of the system. Figure 3.12 shows environmental impact fossil fuel use, GHG emissions, and water use through 2050 which change due to usage in each system, transportation costs, and weather influence on crops.

The fossil fuel footprint is highly sensitive to how much the corn is transported which is especially prevalent in the jump from 2017 to 2020. In 2017, there are select counties that have ethanol plants based on current data so corn will not have to travel as much. In all other years however, ethanol production increases and it is assumed that it increases evenly in every county. Since every county would have some ethanol, corn will have to travel in every county to meet ethanol demands. The GHG footprint follows a similar trend to fossil fuel use. It generally is higher in years with higher production in other systems and where it has to travel longer distances.

Ethanol production has an inverse relationship with water use because of how GREET credits water use to DGS based on its displacement value to corn and soybean meal of livestock. In years that ethanol production is high, the water use is comparatively lower. Water use also changes year to year because of weather variations.

Generally, the footprints throughout the years are stagnant. A possible reason could be because an increase in beef and ethanol production as population increases does not have as much of an effect as the corn production pathway itself. The inputs to DSSAT, including fertilizer which is a large factor in emissions, do not change so therefore environmental impact is not being effected on a per kg corn basis in the corn production pathway. The only input that changes from year to year is irrigation which is sensitive to weather changes, not population growth.

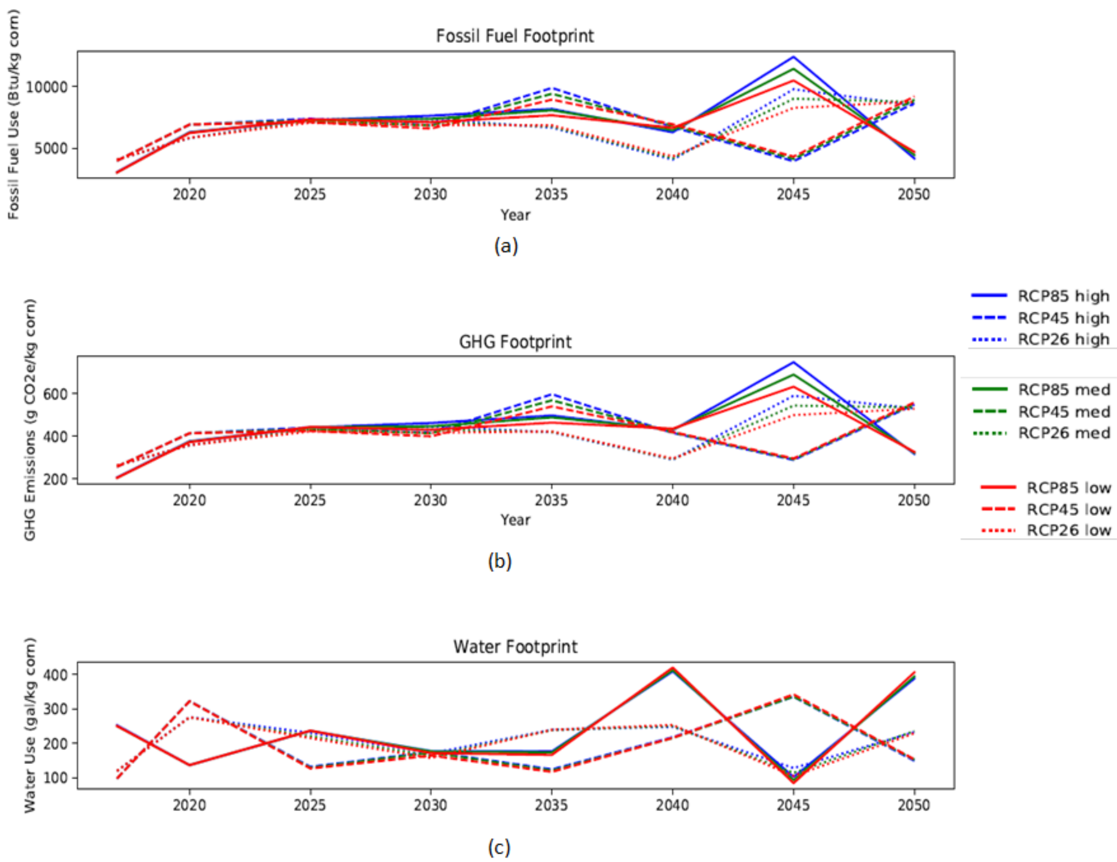

Figure 3.13 – Environmental impact of each scenario through 2050 per kg corn produced for (a) fossil fuel, (b) GHG and (c) water

3.3.3. End user application

The simulations performed in this study were possible because the models of each system were loosely coupled. After each model was wrapped using Python, a pipeline was created to connect each system based on how the integrated system behaves in real-life. With this pipeline, users can use it to decide which scenarios they would like to run to determine how Nebraska or any other region can contribute to producing corn, ethanol, and beef sustainably. To project into the future, different assumptions could be made about resource requirements, system inputs, climate models, or spatial boundaries. This can also be compared to historical data by plugging in known attributes to the input CSV file and validate against that.

This is also only one example of a pipeline that can be created. Other developers can use this loosely coupled web framework to create other pipelines in Python or other object-oriented programming languages. These models are exposed as API's using wrapper functions and can be connected in any number of ways to make simulations about the integrated system. Users can make scenarios based on different assumptions of system connections and inputs to make meaningful projections and interpretations. The resource demand for example could be different than the current method as beef demand could increase at a higher rate with the development of the middle class. Web services is a powerful technology that is currently being utilized heavily for integration of web apps related to social media, web search algorithms, and fitness tracking but is not as developed yet for use in agriculture.

The loosely coupled framework allows other developers to continue to build off of this framework and add more models and systems that are related to the nexus. Because the DSSAT model is loosely coupled, many other relevant cropping systems can be included for simulations such as soybean, wheat, forage, and sorghum which are related to biofuel and livestock feeding. DSSAT can also calculate residues from farming as it is relevant to producing cellulosic ethanol which is a growing industry in the Midwest U.S. GREET has several biofuel pathways such as the previously mentioned cellulosic ethanol and biodiesel which can be produced from soybean. Many of these additional crops can be turned into livestock feed such as forage, soybean meal, and corn stalks.

This particular scenario only simulated finishing feedlot cattle but BCNRM has the capability of calculating growth and other outputs for growing cattle, replacement heifers, dry cows, lactating cows, and yearling calves. The Midwest also has other livestock systems which can be simulated for growth including swine, chicken, and dairy.

The spatial boundaries of the system can also be expanded to the entire Midwest as this is the region for which this integrated system was built. As the boundaries are expanded further, it can continue to include other agricultural systems not native to the Midwest region as all of these systems are interconnected loosely in some way. The spatial resolution can also be increased for more accurate calculation of traveling distance of resources instead of grouping all inputs by county.

3.4. Conclusion

Corn, ethanol, and beef systems were simulated using existing, well-accepted models in their respective fields. Without any need to access the source code or recreate any formulas, they were connected to Python script in their existing software which allowed them to be loosely coupled. A model pipeline was created in Python to connect these loosely coupled models in a way that closely simulates real-world behavior in these industries in the Midwest US. Scenarios based on this framework were developed to determine Nebraska's ability to meet its contribution to producing enough corn, ethanol, and beef for the world population. Inputs for each year were based on different climate projections and population growth projections as both have large impacts on how sustainable the world will be.

Results showed that based on how the framework was structured, not all resources were able to be met every year. Both environmental and production results were also very dependent on variations of weather from year to year so building resiliency to climate in each of these systems is essential to creating a sustainable world. Integration of models using loosely coupled web services is a powerful tool because it does not require modelers to recreate any models but instead, allows them to take a well-developed model in its existing condition and work on simulating the meaningful interconnections. This allows for more meaningful impact assessments of how much food can be produced and how environmentally sustainable these methods are.

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