Simulating and Analyzing Use of Water and Renewable Energy in Agricultural Areas Using FEWCalc and DSSAT

By
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Jirapat Phetheet
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Chair: Mary C. Hill

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Randy L. Stotler

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Edward F. Peltier

____

Jonathan Aguilar

Date Defended: June 19, 2020

The thesis committee for Jirapat Phetheet
certifies that this is the approved version of the following thesis:

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Chair: Mary C. Hill

Date Approved: July 20, 2020

Abstract

As much of farmland in the middle USA is located in arid and semi-arid regions, agricultural practices depend primarily on irrigation. Widely prevalent large-scale groundwater extraction for agriculture began in the 1950s with the introduction of center pivot irrigation, each of which requires about 800 gallons/min, or 4,360 m^3/day. Groundwater supported irrigation was dependable for decades, but now many areas of the High Plains aquifer is at risk for over-extraction, and farming is facing difficult circumstances. On the positive side, Kansas recently became the fifth leading producer of wind energy, with solar power production growing in recent years. However, opportunities to use this locally produced energy to improve prospects for the farming community face scientific and engineering challenges and, communities are not aware of many potentially promising alternatives.

Food-Energy-Water Calculator (FEWCalc) is a freeware interactive computer program designed to inform farmers about economic and water resource consequences of land-use alternatives in the face of climate variability and long-term change. FEWCalc integrates the agricultural model, Decision Support System for Agrotechnology Transfer (DSSAT), and Agent-Based Modeling (ABM), and is novel in its attention to farm economy, groundwater quantity and surface water quality, and its ability to realistically account for arid climates.

FEWCalc is demonstrated and tested using data from Garden City, Kansas, USA. It allows users to define model parameters such as the acreage planted in four crops (corn, wheat, soybeans, and grain sorghum); the number of solar panels and wind turbines, and their financial variabilities; and one of four 50-year projected scenarios. FEWCalc results show high variability of net farm income due to price uncertainty and weather conditions. FEWCalc outputs also present how water

supplies threaten farm incomes and indicate that renewable energy development has the potential to support farm systems and provides economic opportunities to balance farming difficulties. Results from Scenario 1 (Repeat Historical) are repeated based on conditions from a 10-year base period (2008-2017) in sequence. For Scenario 2 (Wetter Future), FEWCalc can maintain irrigation operations for the entire 60-year simulation. Scenario 3 (Drier Future) resorts to dryland farming more quickly than other scenarios, but it produces the highest average annual net income. Scenario 4 (Climate Change) indicates increased challenges such as reduced crop yields and increased financial losses under climate change.

This finding addresses the challenges of the future and provides a tool for research and education. The existing human interaction capabilities of FEWCalc would be improved by adding human decision-making characteristics such as avoidance of risk, maximizing profit, and evolution of policies and governmental institutions.

Acknowledgements

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Chapter 1. Introduction

1.1 Research Motivation

Water resources are of considerable importance for human beings. Although the Earth is known as a Watery Planet, only about 0.3% of the world's water is usable by humans (Mullen, 2020). Apart from glaciers, freshwater stored in the subsurface as groundwater is a significant source for human water consumption, accounting for approximately 30% of the total global freshwater reserves (Shiklomanov, 1993). Even though water continuously circulates through the global hydrological cycle and is considered as a renewable resource, the amount of water is limited in a given time in any one region (Pimentel et al., 2004). Water can be used for many purposes, such as human and animal consumption, electricity generation, industrial uses, and agriculture. These uses seem to increase globally, posing challenges of widespread water scarcity and lack of access to water supply (Cooley et al., 2014). In today's world, water shortages affect agricultural production. Water use for irrigation shares about 70% of the global freshwater withdrawals, and is the largest consumer of its consumptive use of water – more than 90% (FAO, 2012). Some types of energy production also require large quantities of water. Though the use is not as consumptive as agriculture, thermoelectric energy production plants use more water than agriculture (Dieter et al., 2018).

This interaction between vital resources becomes more critical as the human population increases. The world's population is projected to increase to 9.1 billion people by 2050. Feeding this growing population would require a substantial increase in food production of 70% (FAO, 2009a, 2009b). Irrigated cropland contributes about 40% of the world's food; although, it is only 17% of the total cropland (FAO, 2000). To meet increasing food demand, groundwater resources are being extracted to support agriculture, leading to groundwater-related severe depletion. For instance, India is known as the world's largest groundwater user, using about 166 billion gallons (gal) a day (628 million cubic meters per day [m^3/day]) (World Bank, 2012). More than 60% of irrigated farmland in India depends on groundwater, causing water-levels to decline as much as 4 m between 2012 and 2016 (Chindarkar & Grafton, 2019; Department of Water Resources, 2019). In 2016, agriculture made up about 15.4% of Gross Domestic Product (GDP) in India, ranked second globally, followed by the United States (CIA, 2020).

Agriculture is a significant industry in the United States, contributing about 1 trillion US dollars to GDP in 2017 (Melton, 2019). As of 2017, the USA had about 396 million acres (ac) of total cropland, and approximately 15% was irrigated. Even though the number of irrigated farms decreased by 2% between 2007 and 2017, the total irrigated area increased by 2.5% (USDA, 2019). The United States' irrigation water use was 118 billion gal/day (447 million m^3/day), and nearly half of this consumption was from groundwater (Dieter et al., 2018). The Great Plains is a major agricultural area. The USA portion of the Great Plains includes all of North Dakota, South Dakota, and Nebraska; and parts of Montana, Wyoming, Colorado, Kansas, New Mexico, Texas, and Oklahoma. Extensive groundwater pumping for irrigation has caused substantial groundwater declines of the High Plains aquifer in the USA since 1950 (McGuire, 2014); as of 2013, groundwater levels in one location in the aquifer declined 256 feet (ft) (78 m) since 1950.

This study focuses on the state of Kansas, which is located in a subregion of the Great Plains called the High Plains, where the economic activity of the region is driven by agriculture (Hudson, 2020). In 2017, Kansas contributed 4.8 billion US dollars of USA agricultural production and ranked 7th among the 50 USA states (KDA, 2019c). Recently, Kansas is the leading producer of wheat and milo. There were about 22 million ac (8.9 million hectares [ha]) of cropland harvested in Kansas, and around 3.1 million ac (1.2 million ha) (14% of the state's cropland area) was in the Southwest region (KDA, 2019c), where this study was conducted. This region overlies the High Plains aquifer, which is the most crucial source of water for agriculture in Kansas. The region faces critical water-related issues due to groundwater overdraft. Groundwater levels have declined steadily in the western region since the 1950s (Buchanan et al., 2015).

Energy has typically been produced for human consumption in ways that adversely affect the environment (EPA, 2019). While no energy production capability is without some environmental impacts, renewable energy sources like wind and solar have the potential of creating considerably less environmental difficulties compared to fossil fuels. Western Kansas has considerable renewable energy production capacity. For example, the area has a very high capacity factor for wind power, with an average of 42% in 2018; in most areas of the USA, the capacity factor is about 25%, so that the same wind tower would produce, on average, about twice the electricity if installed in Kansas. The state of Kansas ranked 5th nationally in cumulative installed wind power capacity at the end of 2018. As a fraction of in-state generation, Kansas is a leader, with 36.4% of electricity generated in the state coming from wind (Wiser & Bolinger, 2019). The total solar installed capacity in the state was 46.7 megawatts (MW) by the end of 2019. Since Kansas has produced a small amount of electricity from solar, it ranked 47th among all states in 2019 (SEIA, 2020a). Such areas with abundant renewable energy resources could potentially support the local farm economy in communities where water nearly runs out or needs to be appropriately managed.

Local farmers are juggling the need for agricultural production and economic development in rural areas, the shortage of water, and the opportunity of renewable energy. A decision support system is needed to provide the technical information from the multiple disciplines involved. It is an example of interacting natural and human systems under the variability and complexity of climate, hydrology, economics, and policies. Food, energy, and water (FEW) mentioned above are linked to one another; therefore, one component can have effects on one or both of the other components.

This work introduces FEWCalc (Food-Energy-Water Calculator) as a decision-making tool for understanding FEW interdependencies with science and societal needs, assessing the risks of uncertain future, and providing knowledge of how renewable energy production might be considered at the farm-scale and if such development could improve the economics of rural areas. For more detailed understandings of food and water systems and more creative agricultural scenarios, Decision Support System for Agrotechnology Transfer (DSSAT), the most widely used crop growth model (Thorp et al., 2008), can simulate crop production and irrigation water use under given weather conditions in particular areas and has the potential to analyze and evaluate adaptive crop and water management strategies based on actual agricultural practices.

1.2 Research Questions

FEWCalc, supported by DSSAT, allows several research questions to be addressed. In this work, the following questions are of primary importance.

1) Could local renewable energy resources provide opportunities to the farm system?
2) What effect does climate change have on the farm economy in terms of water use and food production?

3) How do agricultural production and farm income respond to groundwater shortage?

4) How and how much does nitrogen fertilizer in agricultural areas impact the environmental quality of surface water?

1.3 Organization of Thesis

This thesis introduces a modeling tool to simulate a linkage among food, energy, and water systems and shows how these components affect the future by using FEWCalc. The organization of this thesis is as follows.

Chapter 2 provides background information on the study site and data used for the calculation. This chapter starts with a brief description of science for simulating FEW systems, followed by a location of the study area, surface and subsurface information, and historical and projected climate data. Finally, detailed documentation of food, energy, and water systems of the study area are included.

Chapter 3 presents a draft of a journal article, including an additional background of Integrated Assessment (IA) and Impacts, Adaptation, and Vulnerability (IAV), modeling methods for addressing research questions, and results from the simulations.

Chapter 4 discusses modeling results from DSSAT and FEWCalc, summarizes, and offers recommendations for the future works. There are four appendices including data used for calculations, outputs from the models, equations used in FEWCalc, and FEWCalc instructions.

Chapter 2. Background

Chapter 3 presents a draft article of study results. Here, more selected details to provide background for the problem addressed in the journal article draft in Chapter 3 are presented. These include greater detail about the study site, weather and climate data, and crop details applied in this work.

2.1 State of the Science for Simulating Integrated Food, Energy, and Water Systems

An enduring need is the ability of stakeholders to understand the dynamics of integrated systems and for scientists from the narrow component fields to gain a greater understanding of more extensive consequences. The food, energy, and water (FEW) systems involve both natural sciences (e.g., physical science and biological science) and social sciences (e.g., anthropology and economics). Integration across multiple disciplines in science provides new insights into the complexity of the FEW systems (Scanlon et al., 2017).

Studies of the nexus of FEW resources were mostly conducted at an academic level (Endo et al., 2017). Previous works focused on different aspects such as land use optimization (Nie et al., 2019), nutrient flows (Yao et al., 2018), environmental security for livelihoods (Biggs et al., 2015), food-energy tradeoff (Cuberos Balda & Kawajiri, 2020), and water-energy-food production and consumption (Guijun et al., 2017) using distinct analytical approaches (e.g., MATLAB Simulink, crop growth model, surrogate model, an agent-based model). However, some of these models and frameworks did not integrate all three resources.

The USA National Science Foundation's (NSF) Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS) program aims to advance the knowledge of FEW systems and understand how the systems affect the world under increasing stress (NSF, 2018b). The INFEWS program brings science and technology to seek innovative solutions for solving FEW critical challenges. The NSF's "FEWtures: Innovation Analysis Framework for Resilient Futures, with Application to the Central Arkansas River Basin" project, explores economically viable solutions by using renewable energy resources to sustain valuable water resources and produce ammonia in small town and rural (STAR) communities (Hill et al., 2019). Another INFEWS project, DS-WSND (Decision Support for Water Stressed FEW Nevus Decisions), provides a decision support tool for FEW systems to evaluate how climate change and increasing population affect the system and identify economic and environmental tradeoffs in water-scarce areas (McCarl et al., 2017). Characklis et al. (2016) propose solutions for understanding how each of FEW components affects the system. This INFEWS project introduces an open-source modeling framework for FEW systems with interactive virtualization, sensitivity analysis, and optimization tools.

2.2 Study Site

Garden City is located in Finney County, southwest Kansas, on the north side of the Arkansas River (Fig. 2.1). It is the center of an irrigated agricultural area of the Arkansas River Valley. As of the 2018 census, there were 26,546 people and 9,214 households residing in the city (U.S. Census Bureau, 2018). The city's economy is primarily driven by agriculture. As stated in the Kansas Department of Agriculture's (KDA) economic report in 2019, agriculture and ag-related sectors support about 5,000 jobs in Finney County, having a total direct output of approximately 2.80 billion US dollars (KDA, 2019a).

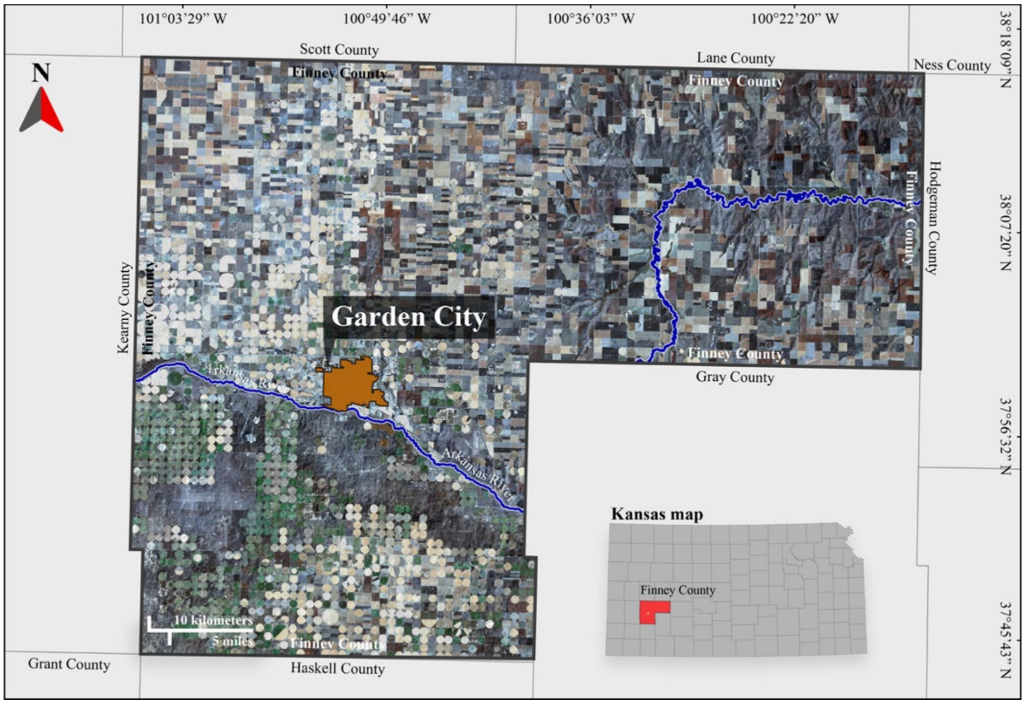

Fig. 2.1 Satellite image of the study site, Garden City, Kansas.

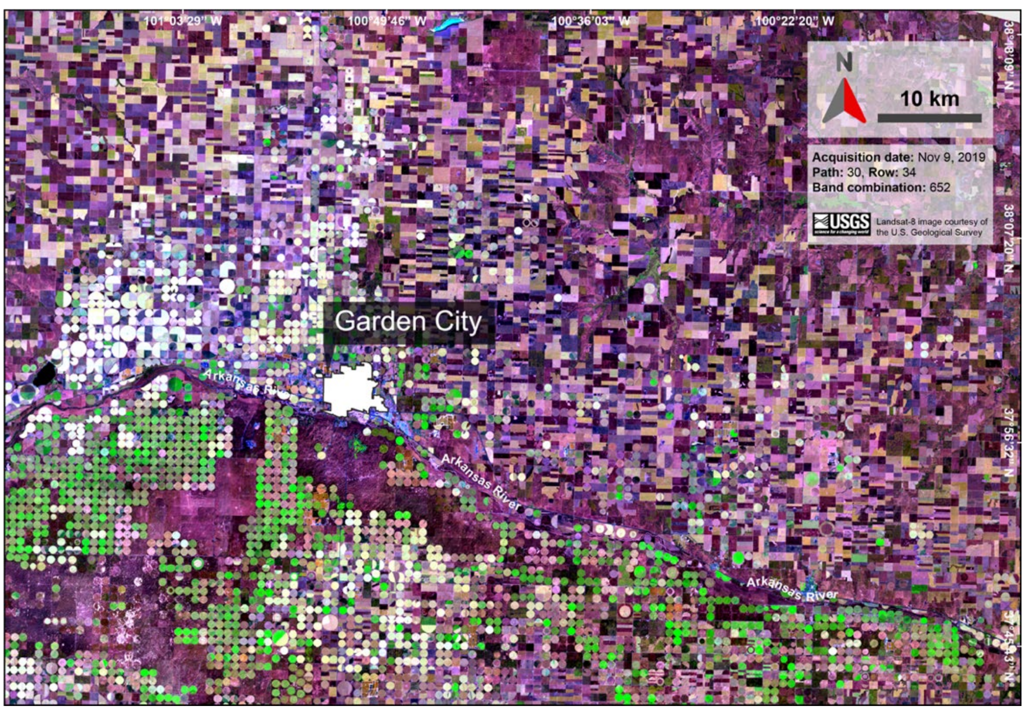

Fig. 2.2 Band combination (RGB 652) of Landsat-8 imagery showing agricultural areas in southwest Kansas.

As mentioned earlier, the state's financial resources rely on many agricultural businesses. Circular fields along the Arkansas River in Fig. 2.2 are areas irrigated with a center pivot irrigation system, which is a widely used irrigation method in Kansas (Rogers et al., 2019). Figs. 2.1 and 2.2 are the same NASA's Landsat-8 satellite image taken on November 9, 2019. Landsat provides high-resolution multispectral data of the Earth's surface (USGS, 2017). Each band of a multispectral image can be displayed as a combination of three bands (red, green, and blue) in a time called a color composite image, as shown in Fig. 2.2 (HSU, 2019). Band combinations are selected for several purposes. Fig. 2.2 uses a combination of band 6 (the shortwave infrared), band 5 (the near-infrared), and band 2 (the blue) as the visible red, green, blue components, respectively. In the figure, vigorous vegetation shows bright green, healthy vegetation appears as a darker green, while dull green represents stressed vegetation. Bare areas with sparse vegetation appear brown and mauve (Esri, 2019).

2.3 Geology, Hydrogeology, and Pedology of Study Area

Latta (1944) studied geology and groundwater resources of Finney County. Rocks that were exposed at the surface of the county are all sedimentary rocks. Ages of these rocks range from Cretaceous to recent. Geologic cross-sections (Fig. 2.3) extend from Scott County to the southern border of Finney County in south-north direction (section A-A') and from Kearny County eastward to the southeast corner of the Finney County panhandle (section B-B'). Section B-B' shows a broad, shallow depression known as the Finney basin with thick unconsolidated deposits, extending from Garden City to Scott County (Smith, 1940).

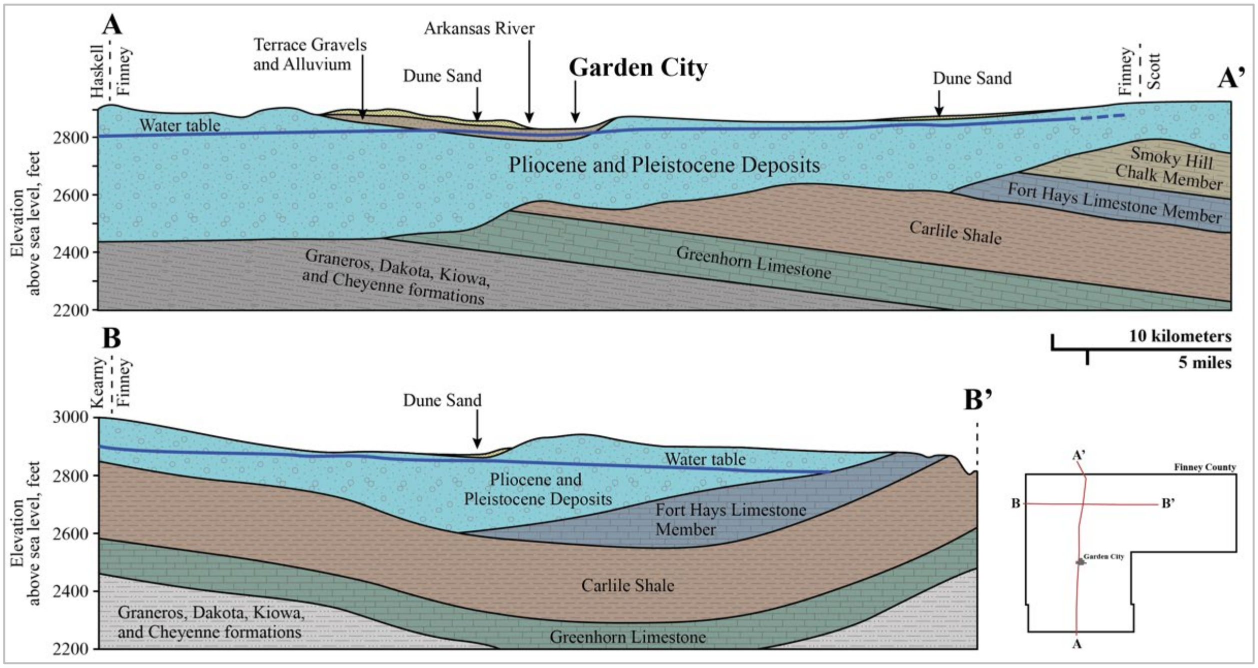

Fig. 2.3 Geologic cross-section through Finney County, Kansas (modified from Latta, 1944). The 1944 water table shown precedes the extensive groundwater pumping for irrigation in the area.

Upper Cretaceous rocks are the oldest rocks found in this area, which are parts of Carlile Shale and Niobrara formations. The upper series of the Cretaceous System is the Gulfian Series. The Carlile Formation consists of dark gray to black noncalcareous shale, deposited in the marine environment during the Turonian Stage (~93.9-89.8 Ma). Most parts of the Carlile Shale consist of low permeable materials. Thus, they supply little or no water to wells. Thick massive beds of chalk or chalky limestone of the Fort Hays Limestone, a member of the Niobrara Formation, overlie the Carlile Shale. The rocks are widely distributed in northeastern Finney County. The beds of chalky limestone are hard and brittlely fractured, so these fractures allow water to flow through the formation.

The Tertiary (Neogene) rocks, which overlie the Cretaceous beds, range in age from Lower Pliocene and possibly Upper Miocene (?) to Pliocene. These sediments were eroded and transported due to the tectonic uplift of the Rocky Mountains and deposited mostly by streams and in lakes. The Laverne Formation is the lower subdivision consisting of silty blocky clay and clay shale, overlaid by the Pliocene Series. The subsequent sediments of the Ogallala Formation, including gravel, sand, silt, clay, and caliche, are widespread over western Kansas. Due to thick deposits of unconsolidated sediments, they make up a vast underground reservoir and become the most critical water source in western Kansas. The maximum thickness of the unconsolidated deposits is approximately 350 ft (107 m), with an average of 125 ft (38.1 m). The Quaternary System is all nonmarine in origin and distributes widely over the state. The sediments include glacial, fluvial, and eolian deposits (Latta, 1944).

The Ogallala Formation is a significant groundwater reservoir in the High Plains region. The Ogallala aquifer is the western half of the High Plains aquifer (HPA) in Kansas (Buchanan et al., 2015). The HPA is in parts of eight states including Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, with the total area of approximately 111.8 million ac (45.24 million ha) (McGuire, 2014). In Finney County, groundwater generally moves toward the east, with different directions of movement and slope locally. Natural groundwater velocity measured by Slichter (1906) at around Garden City ranged from 1.3 to 10.3 ft/day (40 cm/day to 3.14 m/day), with an average of 6.6 ft/day (2.0 m/day). The average hydraulic gradient obtained from the same location is 1.42×10^{-3}. The aquifer is an unconfined water table aquifer, whose water surface is at atmospheric pressure. Therefore, the water table can fluctuate up and down, corresponding to changes in the volume of water stored and barometric pressure in the aquifer (Butler et al., 2013). A significant use of water withdrawn from the aquifer is for irrigation (more than 90%) (KGS, 2019). Other discharge of groundwater includes withdrawals for public and domestic uses, evapotranspiration, and seepage to the land surface (McGuire, 2014). In general, sources of recharge comprise precipitation, surface water seepage, irrigation return flows, and cross-formational flows from adjacent aquifers (Sophocleous & Merriam, 2012).

More than half of Finney County is covered by silt loam, which is a dominant soil type, followed by loamy fine sands and fine sands (Figs. 2.4 and 2.5b). According to a soil survey collected by the National Cooperative Soil Survey (NCSS), a silt loam soil has a higher percentage of silt than sand and clay, as shown in the soil texture triangle (Fig. 2.5a). A majority of soil series distributed in the north of Arkansas River is the Richfield series, accounting for approximately 180,000 ac (72,843 ha). The Richfield silt loam is well-drained and formed in calcareous loess. It commonly has a plane landform with a slope of less than 1%. The Richfield soil is well-suited to winter wheat and grain sorghum (NRCS, 2006). The Ulysses and Beeler silt loam are typical in the northwest and north-central regions, making up roughly 15% of the county area. Winter wheat and grain sorghum are principal crops for these soil series, but for the Beeler series, corn can be grown under irrigation. The Richfield series meets the criteria for prime farmland, defined by the U.S. Department of Agriculture (USDA), for economically producing high crop yields (NRCS, 2011, 2017).

Soils were derived mostly from eolian sands south of the Arkansas River and are excessively drained (NRCS, 2020a). They are grouped in the Valent and Vona soil series, which are on hills, ridges, and uplands. For the Valent fine sand, it was classified as “not prime farmland,” which is not suitable for farming. The Vona loamy fine sand, however, is considered to be “farmland of statewide importance,” which nearly meets the requirements for prime farmland (NRCS, 2020a, 2020b).

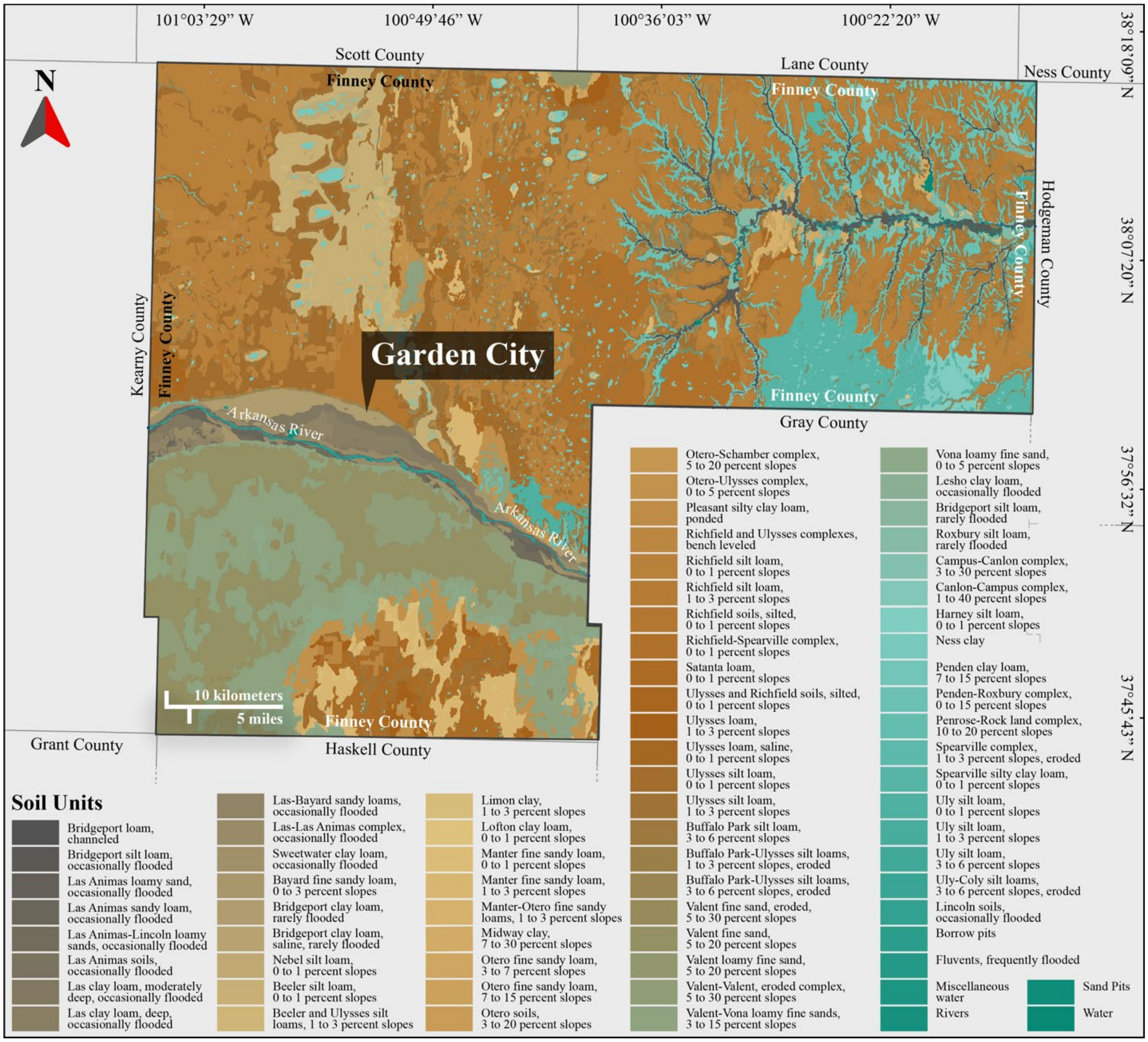

Fig. 2.4 Detailed soil map in Finney County, Kansas (modified from NRCS, 2020c).

Processes of soil data collection and analysis are not included in this study. The data consisting of physical and chemical properties collected from many stations across the world are provided within DSSAT. A soil database of a project on the "World Inventory of Soil Emission Potentials" (WISE) is one of the most comprehensive databases (Gijsman et al., 2007). The nearest soil station (37°37'08" N, 100°47'38" W) is located about 30 mi (48 km) south of Garden City, Kansas. Based on its composition in Table A.8, soil texture varies vertically from silt loam to silty clay loam, which corresponds to soil distribution in Finney County shown in Fig. 2.5b.

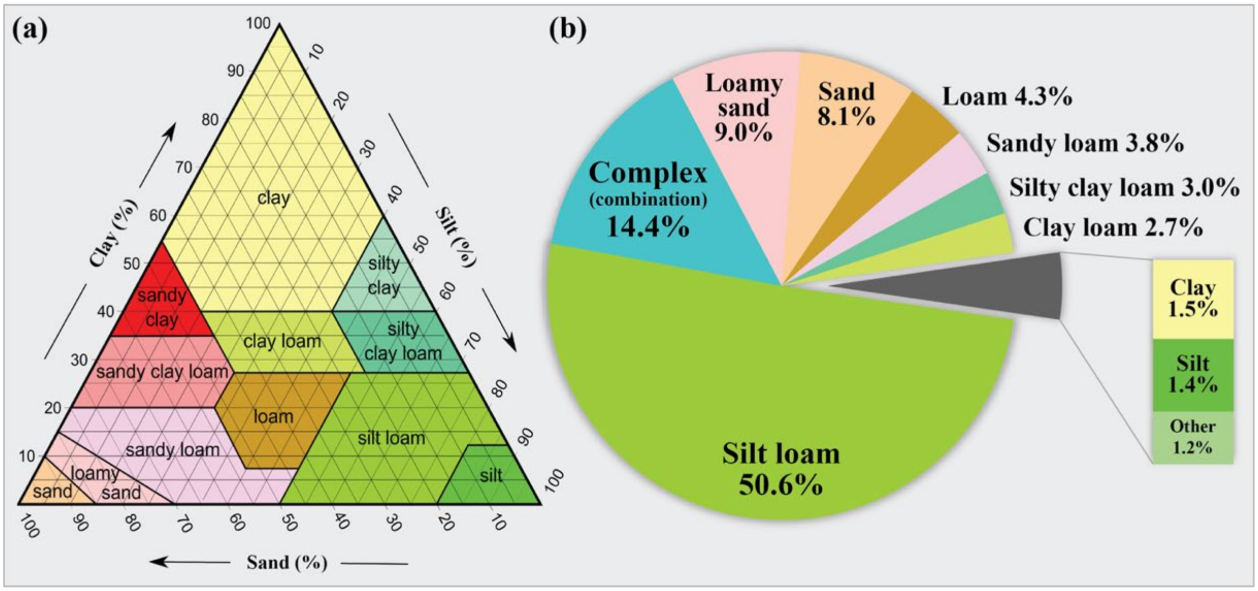

Fig. 2.5 (a) USDA soil texture triangle defining names associated with a combination of sand, silt, and clay. (b) The proportion of soil texture distributed in Finney County, Kansas.

2.4 Weather and Climate

In Garden City, the climate is classified as cold semi-arid based on the Köppen climate classification (Peel et al., 2007). It is situated in a region where precipitation rate is lower than potential evapotranspiration, but not as low as a desert climate. On average, the summers are hot with clear skies; the winters are very cold, dry, and partly cloudy; and it is windy year-round. The hot season lasts for 3.6 months, with an average daily high temperature above 83 °F (28 °C). The cold season is about three months long, with an average daily high temperature below 53 °F (12 °C). Over a year, the drier season lasts for 7.4 months, and the remaining months are typically wetter (Weather Spark, 2020).

2.4.1 Historical Data

Daily historical weather data considered in this study include minimum and maximum air temperature, precipitation, and solar radiation. The historical period from 2008 to 2017 (called base period in this work) was chosen because a generally complete set of weather and agricultural data is available, and it also represents wet, moderate, and dry years. The 10-year data were obtained from a weather station at Garden City Regional Airport, Finney County, Kansas (37°55'37.992'' N, 100°43'28.992'' W, elevation 2,882 ft [878.4 m]).

Temperature. In southwest Kansas, temperatures regularly reach 90 °F (32 °C) in the summer. An average low of 17.8 °F (-7.9 °C) is in January, which is the coldest month (Table 2.1). On average, air temperature falls below a freezing point for roughly five months a year. Based on records from NOAA's National Weather Service, the warmest temperature ever observed at Garden City Regional Airport Station was 110 °F (43 °C) on June 8, 1985. The lowest temperature hit -22 °F (-30 °C) on March 11, 1948.

Precipitation. Garden City receives about 19.5 in (495 mm) of precipitation throughout a year. By definition, the area where precipitation is below 20 in (508 mm) is considered a semi-arid region (Thornbrugh, 2007). Monthly precipitation changes from 0.4 to 3.0 in (10.2 to 76.2 mm), with a peak from May to August in the annual cycle.

Solar radiation. Solar radiation considered in this study is a Global Horizontal Irradiance (GHI). GHI is the sum of direct and diffuse radiation received on a horizon plane (SolarGIS, 2019). Garden City has an average monthly GHI of 212 watts per square meter (W/m^2) or 18.3 Megajoules per square meter per day ($MJ/m^2/day$). A peak of radiation would be between late spring and summer every year or from May to August, as illustrated in Fig. 2.6a. Solar radiation varies temporally and spatially. In Kansas, the higher irradiance values occur in the southwest region of the state (Fig. 2.6b).

Table 2.1 Annual and monthly average historical from 1950 to 2019, except solar radiation data are only available from 1998 to 2018.

	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMIN[1]	5.0	-7.9	-5.7	-1.5	3.9	10.0	15.6	18.5	17.5	12.5	5.3	-2.0	-6.6
TMAX[2]	20.7	7.2	9.9	14.6	20.4	25.5	31.4	34.0	32.8	28.4	21.9	13.7	8.0
P[3]	1.6	0.4	0.5	1.2	1.6	2.9	3.0	2.9	2.6	1.7	1.4	0.7	0.6
S[4]	209.0	111.1	148.1	201.4	246.5	289.4	312.5	309.0	274.3	225.7	167.8	122.7	99.5

[1]TMIN, minimum air temperature in degree Celsius; [2]TMAX, maximum air temperature in degree Celsius; [3]P, precipitation in inches; [4]S, solar radiation in W/m^2.

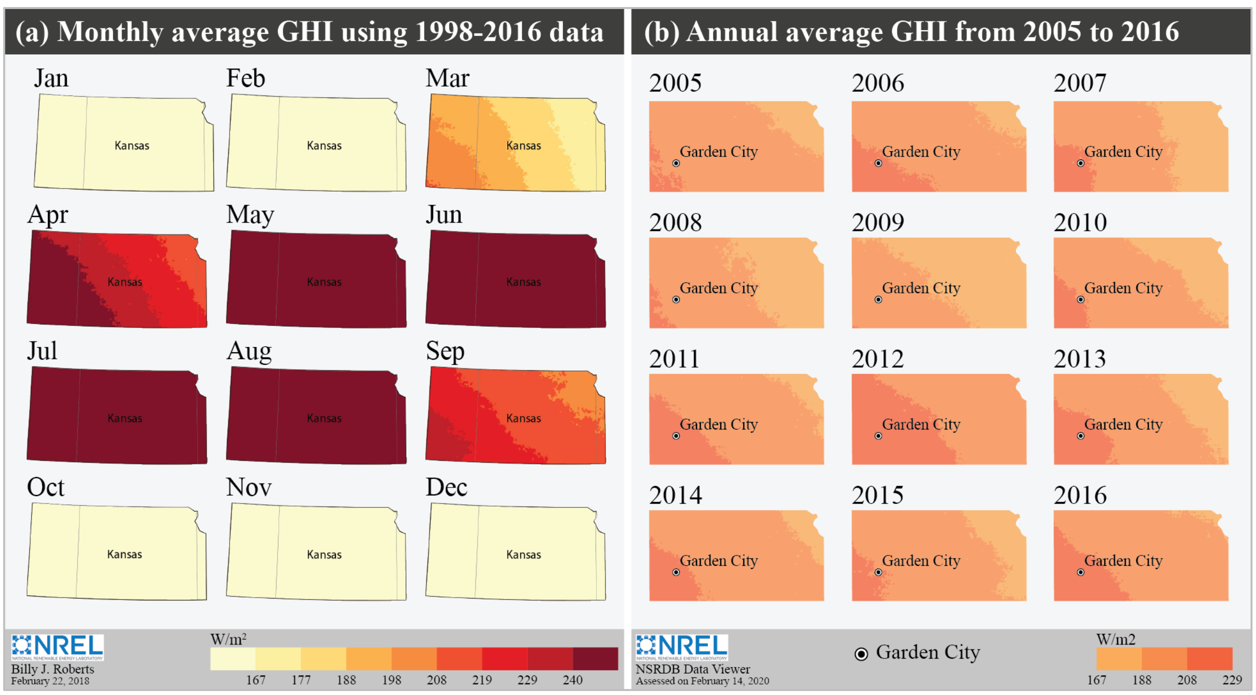

Fig. 2.6 Historical solar radiation showing (a) monthly average daily GHI using 1998-2016 data and (b) annual average daily GHI from 2005 to 2016 (modified from NREL, 2020; Roberts, 2018).

2.4.2 Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI) is the most well-known drought index used in the United States (Dai & National Center for Atmospheric Research Staff, 2019). The PDSI was developed by Palmer (1965) to estimate relative dryness. The severity index normally ranges from -10 (dry periods) to +10 (wet periods). Practically, the values below -4 or above +4 represent extreme conditions. Instead of using the original 11 classes (Palmer, 1965), the PDSI is simplified for this work into five categories: extremely dry, dry, normal, wet, and extremely wet conditions (Fig. 2.7).

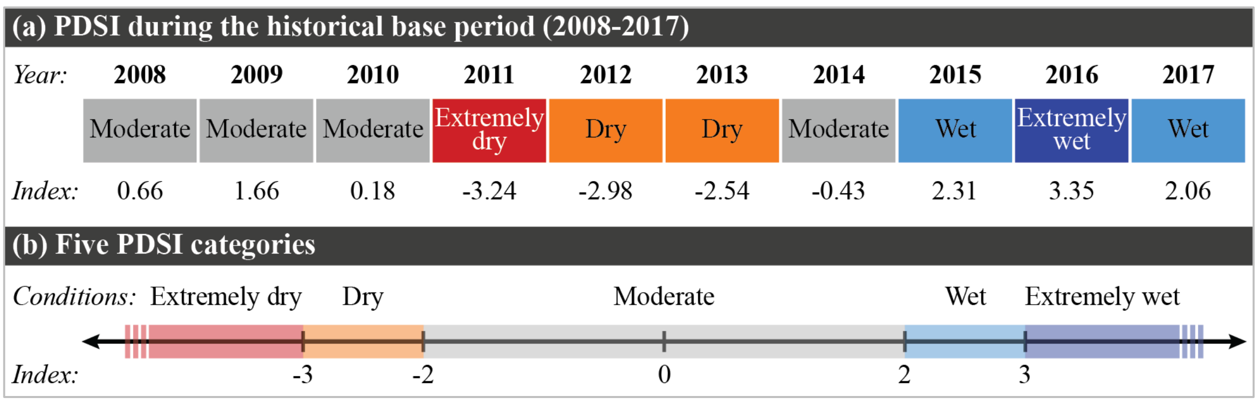

Fig. 2.7 (a) PSDI values and its classification during the 10-year base period. (b) Five PDSI classifications simplified for this this work.

2.4.3 Global Climate Models

To address gaps in understanding of long-term changes in climate, Global Climate Models or General Circulation Models (GCMs) are the primary tool for climate projections (Abatzoglou & Brown, 2012). Climate models apply mathematical equations to describe physics, biochemistry, and processes across the globe. The Coupled Model Intercomparison Project (CMIP) has worked worldwide to provide multi-model datasets as well as improve simulation capacities in the global models (Meehl et al., 2005).

The fifth phase of CMIP (CMIP5) provides more than 50 GCMs from 20 climate modeling research groups around the world. The recent CMIP5 includes two types of climate change modeling experiments: (1) near-term experiments (decadal time scale) and (2) long-term experiments (century time scale). The decadal prediction experiments are initialized based on observations and used to explore climate prediction of the climate system. These integrations focus on recent decades and predictions to the year 2035. For long-term simulations, the historical runs are forced by observed atmospheric composition changes covering from the mid-19th century to near present.

The long-term projections are driven by concentration or emission scenarios being consistent with representative concentration pathways, RCPs (Taylor et al., 2009, 2012). This set of runs considers 4 RCPs, including RCPs 2.6, 4.5, 6.0, and 8.5 (Table 2.2). The RCPs are scenarios of emissions and concentrations of greenhouse gases (GHGs) and aerosol, chemically active gases, and land use and land cover (Moss et al., 2008). Each of these scenarios represents a possible range of radiative forcing values described by the Intergovernmental Panel on Climate Change or IPCC (2014) and Moss et al. (2008).

- RCP 2.6 is a low so-called peak-and-decay pathway where radiative forcing peaks at roughly 3 W/m^2 before 2100 and then declines.
- RCPs 4.5 and 6.0 are an intermediate stabilization (without overshoot) in which radiative forcing is stabilized at about 4.5 and 6.0 W/m^2 after 2100, respectively.

- RCP 8.5 is a high pathway (rising pathway) for which radiative forcing reaches higher than 8.5 W/m^2 by 2100 and continues to increase for some time.

Table 2.2 The 4 RCPs.

Name	Radiative forcing	Concentration (ppm)	Pathway	Model[1]
RCP 8.5	>8.5 W/m^2 in 2100	>1,370 CO_2-equiv. in 2100	Rising	MESSAGE
RCP 6.0	~6.0 W/m^2 at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	AIM
RCP 4.5	~4.5 W/m^2 at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	GCEM
RCP 2.6	Peak at ~3 W/m^2 before 2100 and then declines	Peak at ~490 CO_2-equiv. (before 2100 and then declines)	Peak and decline	IMAGE

[1]Model providing RCP. *MESSAGE*, Model for Energy Supply Strategy Alternatives and their General Environmental Impact, International Institute for Applied Systems Analysis, Austria; *AIM*, Asia-Pacific Integrated Model, National Institute for Environmental Studies, Japan; *GCAM*, Global Change Assessment Model, Pacific Northwest National Laboratory, USA (previously referred to as MiniCAM); *IMAGE*, Integrated Model to Assess the Global Environment, Netherlands Environmental Assessment Agency, The Netherlands. (Moss et al., 2010).

Resolutions of output data from CMIP5 GCMs are at coarse scales (i.e., typically about 62-186 mi or 100-300 km on a side). Therefore, CMIP5 output must be downscaled at finer scales (to a higher spatial resolution) using statistical downscaling techniques (Abatzoglou & Brown, 2012; Cammarano & Tian, 2018; Taylor et al., 2012).

The GCM data has been downscaled using the method of Multivariate Adaptive Constructed Analogs (MACA) developed by Abatzoglou & Brown (2012). In addition to downscaling, MACA is applied for bias correction in data. MACA CMIP5 products were downscaled from 20 GCMs of CMIP5 listed in Table 2.3. They comprise one historical scenario (from 1950 to 2005) and two future RCP scenarios, including RCPs 4.5 and 8.5 (Hegewisch, 2016). The MACA dataset currently has data for ten variables with a resolution of 2.5 arc minutes represented in Table 2.4.

In Garden City, Finney County, annual average daily maximum and minimum air temperature is projected to increase by 41.8 °F (5.42 °C) and 41.2 °F (5.11 °C) by 2099, respectively, under RCP 8.5. Annual average precipitation varies throughout the period. On the other hand, solar radiation remains unchanged, with an average of 220 W/m^2 (19.0 $MJ/m^2/day$). Monthly average data are presented in Table 2.5 and the annual projections to the year 2099 are shown in Fig. 2.8.

Table 2.3 Downscaled 20 Global Climate Models from the Fifth Phase of the Coupled Model Intercomparison Project

Model Name	Model Country	Model Agency	Atmospheric Res. (Lon × Lat)
bcc-csm1-1	China	Beijing Climate Center, China Meteorological Administration	2.8 deg x 2.8 deg
bcc-csm1-1-m	China	Beijing Climate Center, China Meteorological Administration	1.12 deg x 1.12 deg
BNU-ESM	China	College of Global Change and Earth System Science, Beijing Normal University, China	2.8 deg x 2.8 deg
CanESM2	Canada	Canadian Centre for Climate Modeling and Analysis	2.8 deg x 2.8 deg
CCSM4	USA	National Center of Atmospheric Research, USA	1.25 deg x 0.94 deg
CNRM-CM5	France	National Centre of Meteorological Research, France	1.4 deg x 1.4 deg
CSIRO-Mk3-6-0	Australia	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia	1.8 deg x 1.8 deg
GFDL-ESM2M	USA	NOAA Geophysical Fluid Dynamics Laboratory, USA	2.5 deg x 2.0 deg
GFDL-ESM2G	USA	NOAA Geophysical Fluid Dynamics Laboratory, USA	2.5 deg x 2.0 deg
HadGEM2-ES	UK	Met Office Hadley Center, UK	1.88 deg x 1.25 deg
HadGEM2-CC	UK	Met Office Hadley Center, UK	1.88 deg x 1.25 deg
inmcm4	Russia	Institute for Numerical Mathematics, Russia	2.0 deg x 1.5 deg
IPSL-CM5A-LR	France	Institut Pierre Simon Laplace, France	3.75 deg x 1.8 deg
IPSL-CM5A-MR	France	Institut Pierre Simon Laplace, France	2.5 deg x 1.25 deg
IPSL-CM5B-LR	France	Institut Pierre Simon Laplace, France	2.75 deg x 1.8 deg
MIROC5	Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), the National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.4 deg x 1.4 deg
MIROC-ESM	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and the National Institute for Environmental Studies	2.8 deg x 2.8 deg
MIROC-ESM-CHEM	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and the National Institute for Environmental Studies	2.8 deg x 2.8 deg
MRI-CGCM3	Japan	Meteorological Research Institute, Japan	1.1 deg x 1.1 deg
NorESM1-M	Norway	Norwegian Climate Center, Norway	2.5 deg x 1.9 deg

Available at https://climate.northwestknowledge.net/MACA/GCMs.php

Table 2.4 Downscaled GCM Variables.

Variable	Description	Unit
tasmin	Minimum daily temperature near surface	K
tasmax	Maximum daily temperature near surface	K
rhsmax	Maximum daily relative humidity near surface	%
rhsmin	Minimum daily relative humidity near surface	%
huss	Average daily specific humidity near surface	kg/kg
pr	Average daily precipitation amount at surface	mm
rsds	Average daily downward shortwave radiation at surface	W/m^2
was	Average daily wind speed near surface	m/s
uas	Average daily eastward component of wind near surface	m/s
vas	Average daily northward component of wind near surface	m/s

Hegewisch (2016), Earth Engine Data Analog (2019).

Table 2.5 GCM projected weather data under RCP 8.5 scenario and changes in data compared to Table 2.1.

	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMIN[1]	7.6	-5.5	-3.5	1.0	6.3	12.8	18.7	21.5	20.9	15.5	8.1	0.2	-4.7
(Change)	(+2.6)	(+2.4)	(+2.2)	(+2.5)	(+2.4)	(+2.8)	(+3.1)	(+3.0)	(+3.4)	(+3.0)	(+2.8)	(+2.2)	(+1.9)
TMAX[2]	23.4	9.7	12.1	17.1	22.8	28.3	34.4	37.5	36.2	31.6	24.6	16.4	10.2
(Change)	(+2.7)	(+2.5)	(+2.2)	(+2.5)	(+2.4)	(+2.8)	(+3.0)	(+3.5)	(+3.4)	(+3.2)	(+2.7)	(+2.7)	(+2.2)
P[3]	1.6	0.5	0.6	1.6	1.8	2.9	3.0	2.6	2.1	1.3	1.1	0.7	0.7
(Change)	(0)	(+0.1)	(+0.1)	(+0.4)	(+0.2)	(0)	(0)	(-0.3)	(-0.5)	(-0.4)	(-0.3)	(0)	(+0.1)
S[4]	203.6	104.2	137.7	186.3	241.9	284.7	306.7	309.0	270.8	218.8	165.5	119.2	98.4
(Change)	(-5.4)	(-6.9)	(-10.4)	(-15.0)	(-4.6)	(-4.6)	(-5.8)	(0)	(-3.5)	(-6.9)	(-2.3)	(-3.5)	(-1.2)

[1]TMIN, minimum air temperature in degree Celsius; [2]TMAX, maximum air temperature in degree Celsius; [3]P, precipitation in inches; and [4]S, solar radiation in W/m^2, and average annual solar radiation from climate models slightly decreases over the projected period. However, this is affected by the direct and indirect effects from clouds and aerosols, which are some of the largest sources of uncertainty in the energy balance of global climate models (Boucher et al., 2013).

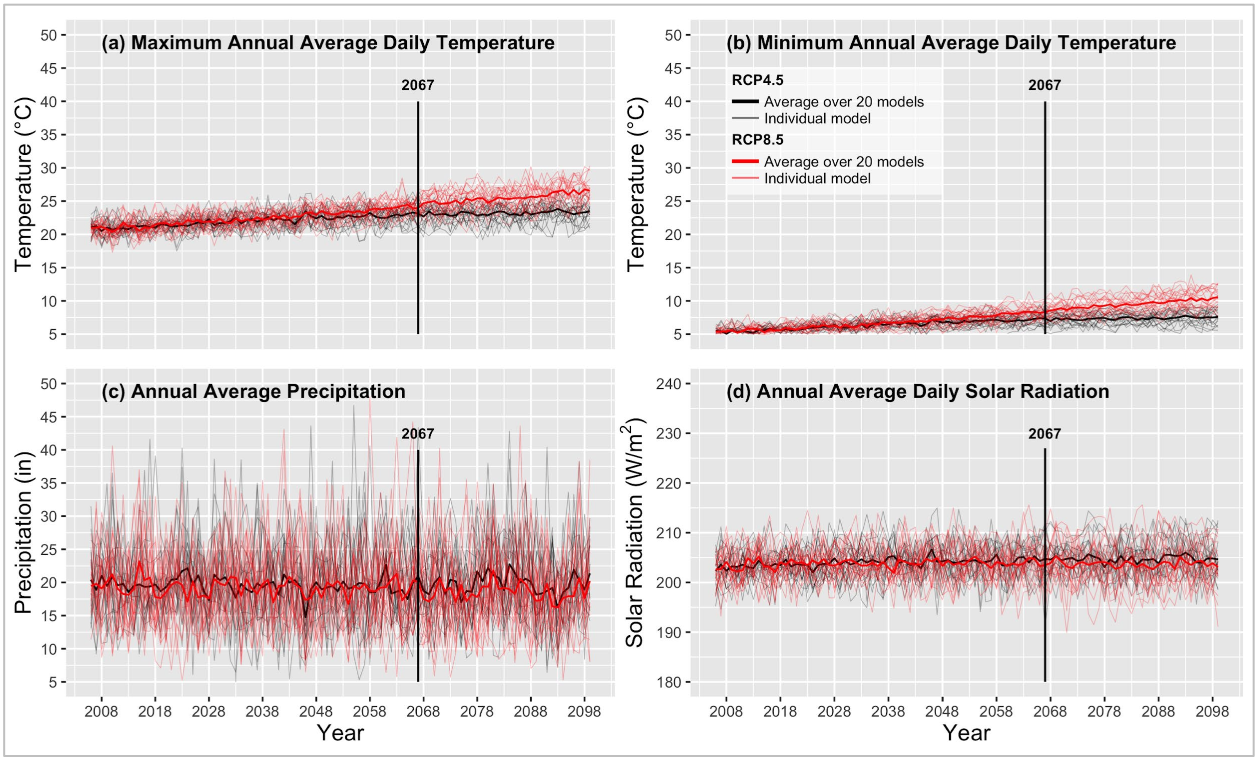

Fig. 2.8 Comparison of annual average projected weather data between the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios obtained from 20 downscaled global climate models between 2006 and 2099. The end of the FEWCalc simulations in this work, 2067, is marked.

2.5 Food

As the world population is expected to reach nearly 9 billion people by 2050, the projected demand for food would continue growing to meet requirements adequately (FAO, 2009b). The growth of the population puts pressure on the existing resources, and potential solutions for a sustainable food future must be addressed to support the projected population (Anderson et al., 2018).

In 2007, about a trillion US dollars produced from agriculture, food, and other related industries contributed to USA gross domestic product (GDP) (Melton, 2019). A huge change occurred in the mid-19th century when USA farms leveled off at about 2 million farms. The average farm size, on the contrary, has increased by roughly 180% since 1935. As a result, a decrease in the number of farms with increasing in farm size makes the total farm output in the USA tripled from 1948 to 2017 (Kassel, 2020).

2.5.1 Crops Grown in Kansas

Kansas has a strong tradition of agriculture, and its economy is largely driven by agricultural and agricultural-related sectors (KDA, 2019b). Many of the early settlers, who turned to the agricultural sector, faced tough issues from drought, wind, the severe grasshopper invasion in 1874, and a lack of operating capital. Even in the grasshopper year, there were 16 million bushels of corn compared with 10 million bushels of wheat. In the following year, Kansas farmers produced about 65 million bushels higher for corn, which was about a 400% increase. In the early 20th century, wheat acreage was about 500,000 ac (202,343 ha) greater than corn acreage. Since then, wheat has remained a major crop in Kansas (Hoover, 1957).

Nowadays, Kansas' largest crop is corn, accounting for 800 million bushels. Wheat production has become the second-largest crop since 2000. In 2019, Kansas produced approximately 340 million bushels of wheat. Grain sorghum and soybeans are other valuable crops in Kansas (NASS, 2019). Even though corn is the most produced crop in the state, Kansas' wheat and grain sorghum production are of the first rank in the United States (KDA, 2019c).

Corn (known as *Zea mays*) is a cereal grain. It is widely cultivated and has become a staple food throughout the world. In the United States, corn is the largest crop, both in the number of corn acreage and revenue of crops produced (KFAC, 2018). In 2018, Kansas contributed 4.7% of the corn produced for grain, among the top ten corn-producing states in the USA. Yellow dent corn is a predominant type grown in the state. About three-quarters of the corn produced in the United States is fed to livestock. Corn is also used to produce ethanol, which was consumed roughly 5.6 billion bushels in 2018 (Capehart, 2020).

Wheat (known as *Triticum aestivum*) is a cereal grain which is a worldwide staple food. It is an important source of carbohydrates. The first record of wheat growing in Kansas was in 1839. Wheat considered in this study is winter wheat, which is a major variety of wheat grown in Kansas. It is a cool-season crop and grows best under moderate temperatures, usually planted in the fall and then harvested in the summer or early fall of the next year. Roughly half of the production of wheat is exported for food use. Another 36% is consumed for food production within the USA.

Soybeans (known as *Glycine max*) are legumes. Soybeans have symbiotic bacteria that can fix atmospheric nitrogen, depositing it into the soil through its root systems. Processes of separating and extracting oil from soybeans create soybean meal, which is the largest source of protein feed for livestock. Over 90% of soybean meal consumed in the USA is fed to livestock. Above half of the soybeans used by livestock is fed to poultry, followed by swine for another 26%.

Grain sorghum (known as *Sorghum vulgare*) is one of the most important dryland crops stretching from Texas to South Dakota. About 87% of grain sorghum produced in the United States is for livestock. Kansas also feeds over 80% of the state's production to livestock. Common varieties of grain sorghum planted in Kansas are yellow and red grain sorghum.

2.5.2 Agricultural Planting Practices

Understanding how these crops grow, develop, and produce grain is crucial to identify factors that affect crop growth and maximize yield at the end of the season. Actual planting practices summarized in Table 2.6 were mainly retrieved from crop production handbooks from Kansas State University Research and Extension. Values applied in this study are summarized as follows.

Table 2.6 DSSAT parameters for crop simulation.

	Corn[1]	**Wheat[2]**	**Soybeans**	**Grain sorghum[4]**
Cultivar	2750-2800 GDD[5]	NEWTON[5]	M. GROUP 4[3]	W. AFRICAN[5]
Planting date *DSSAT simulation starts a week before planting date.	April 15	October 1	May 5	May 15
Population at seeding: • Irrigated	30,000 plants/ac (7 plants/m^2)	1,250,000 plants/ac (310 plants/m^2)	185,000 plants/ac (46 plants/m^2) [6]	100,000 plants/ac (25 plants/m^2)
• Dryland	13,000 plants/ac (3 plants/m^2)			
Planting depth	2 in (5 cm)	1.2 in (3.0 cm)	1.2 in (3.0 cm) [6]	0.8 in (2 cm)
Row spacing	15 in (38 cm)	6 in (15 cm)	30 in (76 cm) [6]	22 in (55 cm)
Applied N Fertilizer[7]	160 lb/ac [8] (180 kg/ha)	85 lb/ac [8] (95 kg/ha)	No N fertilizer [3]	80 lb/ac [8] (90 kg/ha)

[1]Kansas State University Research and Extension (2007); [2]Kansas State University Research and Extension (1997); [3]Kansas State University Research and Extension (2016); [4]Kansas State University Research and Extension (1988); [5]Araya et al. (2017); [6]Sharda et al. (2019); [7]Applied rates of nitrogen fertilizer listed here are needed to satisfy DSSAT-calculated nitrogen demand. [8]Leikam et al. (2003).

Corn: In southwestern Kansas, corn is suggested to plant between April 15 and May 10 since temperature and other conditions are appropriate. The speed of germination and emergence depends on planting depth and soil temperature. During these periods, soil temperature would reach about 55 °F (13 °C), which is optimal for planting at a depth of 1.5- to 2-in (4- to 5-cm). Recommended plant populations generally depend on yields and environmental conditions such as availability of water across the state. Most irrigated corn ranges from 28,000 to 36,000 plants/ac (7 to 9 plants/m^2). A suitable population for dryland farming is between 16,000 and 25,000 plants/ac (4 and 6 plants/m^2). Corn typically grows in 15- to 30-in (38- to 76-cm) rows. Narrow rows can enhance weed control and reduce plant competition. Applying narrow rows, although, can have an advantage, it needs to modify planting and harvesting equipment, resulting in rising operation costs eventually.

The amount of nitrogen fertilizer is capped at 300 lb/ac (336 kg/ha) for irrigated corn, whereas dryland production is at most 230 lb/ac (260 kg/ha). At the time of the silking stage (about 60 days after emergence), corn uptakes nitrogen about 60% of the total nitrogen needed during the growing season. It indicates this is the best time for nitrogen application since most of the nitrogen has been taken up.

Wheat: A recommended planting date varies greatly due to climate conditions across the state. In Finney County and surrounding areas, the optimum planting date is between September 15 and October 20, with an optimal planting depth of 1 to 2 in (2.5 to 5.0 cm). A seeding rate in western Kansas, where rainfall is low, ranges from 600,000 to 900,000 seeds/ac (150 to 220 seeds/m^2). With irrigation, the seeding rate may be higher, ranging from 900,000 to 1,350,000 seeds/ac (220 to 330 seeds/m^2). This rate, however, can be adjusted upward by 10 to 20% if conditions are good. Nitrogen recommendations rely on the expected yield, cropping system, and available profile nitrogen. The rate and timing of application depend on growth stages. During a jointing stage, spring applications that normally occur in early to mid-March would increase the grain's protein content.

Soybeans: Soybeans should be planted when the soil temperature reaches at least 60 °F (15 °C). In southwest Kansas, an optimum planting date ranges from May 5 to June 10. Sharda et al. (2019) suggest that the optimal plant population at seeding is about 185,000 plants/ac (46 plants/m^2) planted at a depth of 1.2 in (3.0 cm) in rows 30 in (76 cm) apart. Under normal conditions, soybeans can be grown without nitrogen fertilizer because bacteria can fix enough nitrogen through the process of biological nitrogen fixation for optimum growth.

Grain sorghum: Planting dates should be considered to avoid the hottest and driest periods during a growing season. Optimum planting date for grain sorghum in southwest Kansas is typically applied when the soil temperature reaches 70 °F (21 °C) between May 15 and June 20. A planting depth of 1 to 2 in (2.5 to 5.0 cm) is satisfactory. Planting populations vary depending on climate and growing conditions. With irrigation, an optimum value of plant population is 100,000 plants/ac (25 plants/m^2) planted in 30-in (76-cm) rows. Nitrogen fertilizer can be applied at various times with comparable results on most soils. By boot stage (about 50 to 60 days after emergence), grain sorghum has taken about 65 to 70% of the total nitrogen. Under a yield goal of 100 bushels/ac, the nitrogen recommendation is about 81 lb/ac (90 kg/ha).

2.6 Energy

The United States produces and consumes several types and sources of energy, such as primary energy sources (fossil fuels, nuclear energy, and renewable energy) and secondary energy sources, which are electricity generated from primary energy. Fossil fuels, including petroleum, natural gas, and coal, provided about 80% of the USA total primary energy consumption in 2019. Roughly 11% of the entire nation's energy originated from renewable energy, accounting for 11.5 quadrillion British thermal units (BTUs) (EIA, 2020b). In comparison, renewable energy consumption is relatively low; however, it is projected to increase annually to nearly 20 quadrillion BTUs by 2050 shown in Fig. 2.9 (EIA, 2020a).

In Kansas, fossil fuels are currently the major source of energy generated in the state (KCC, 2020). As of 2017, Kansas' total energy consumption was 1,073 trillion BTUs, which ranked 30th nationally. Natural gas supplied the highest proportion of the state's energy consumption, contributing about 280 trillion BTUs, followed by coal. Moreover, Kansas shared about 20% of USA renewable energy consumption (EIA, 2019).

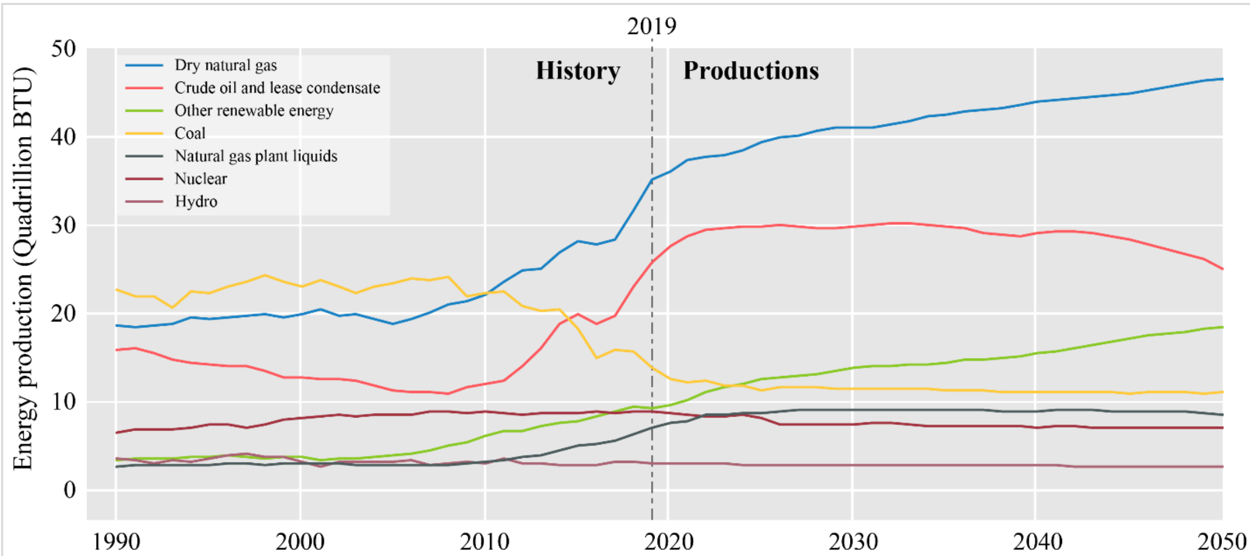

Fig. 2.9 The United States' historical energy production and projection to 2050 by sources (EIA, 2020a).

2.6.1 Wind Energy

Almost all of Kansas's renewable energy production is from wind power. The state is located within the Interior region, which is the area with the highest wind speeds (Fig. 2.10) and, therefore, the highest production potential (EERE, 2019). In this region, an average capacity factor in 2018 was highest at 43.1% (Wiser & Bolinger, 2019). The state's net capacity factors (NCF) among 29 wind projects built recently range from 25.9 to 51.2%, with an average of 42.1% (Berkeley Lab, 2019; Wiser & Bolinger, 2019). On a cumulative basis, Kansas was one of the top five states with the highest total wind energy generation, which was 5,653 MW by the end of 2018.

As a fraction of in-state generation, Kansas is the leading state, with about 36.4% of electricity generated in the state coming from wind (Wiser & Bolinger, 2019).

2.6.2 Solar Energy

Kansas also has solar energy resources. Kansas is one of the ten sunniest states in the USA, but it has little utility-scale solar generation (EIA, 2019). Commercial-scale solar capacity installed in the state for each site is relatively small, compared to the wind capacity depicted in Fig. 2.11. As of 2019, solar energy production ranked the state 47th in the nation, with a total solar installed capacity of 46.69 MW. In 2019, Kansas installed 22.52 MW of solar capacity, which was about 0.14% of the state's electricity generation (SEIA, 2020a). Kansas is one of the lowest-ranked states installing solar energy in agricultural operations. As of 2011, farm-scaled solar photovoltaic capacity was, on average, 408 W/farm (Xiarchos & Vick, 2011).

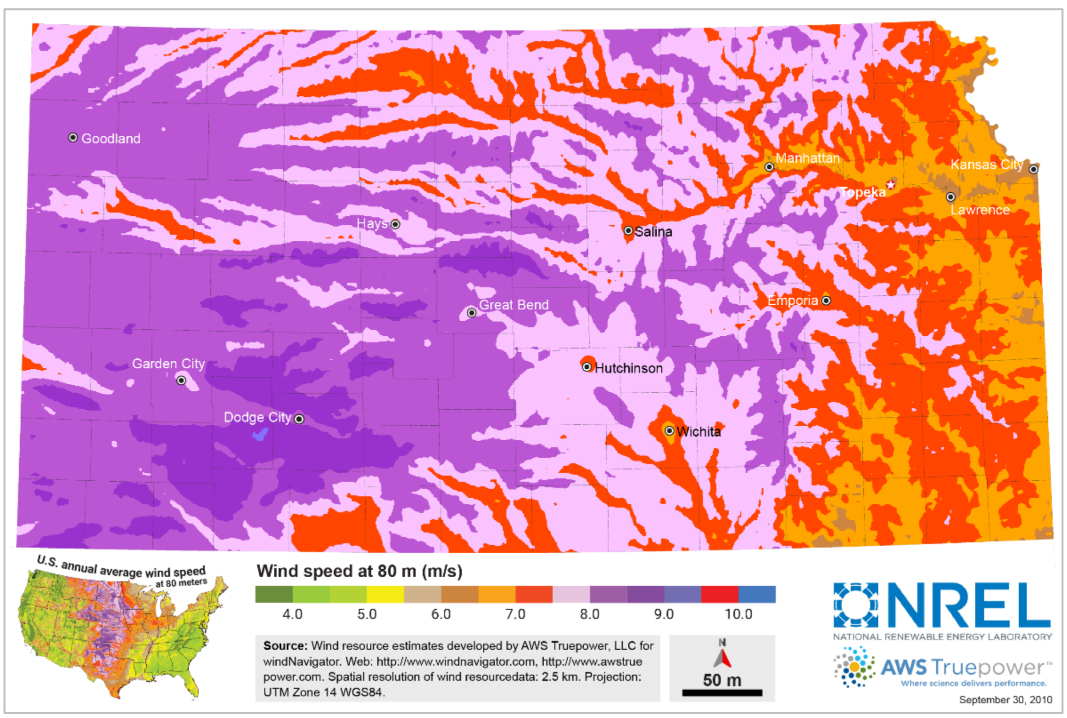

Fig. 2.10 Kansas annual average wind speed at 80 meters (modified from NREL, 2010).

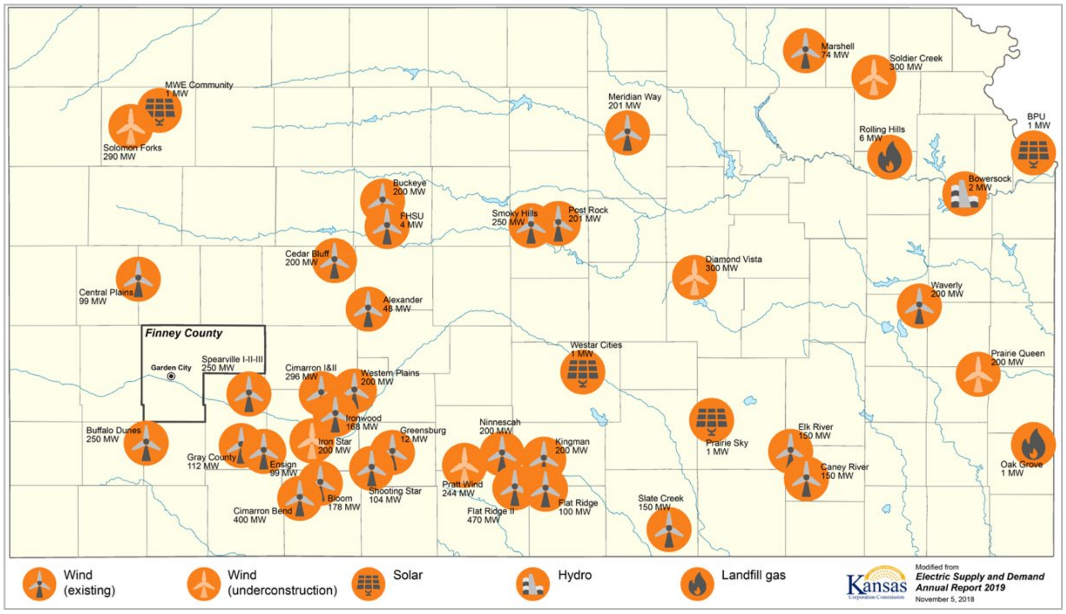

Fig. 2.11 Commercial-size renewable energy generation showing the distribution of wind, solar, hydro, and landfill gas sites in Kansas, with its project name and capacity (modified from KCC, 2019).

2.7 Water

In addition to energy, water is another critical resource. Irrigation water use is a significant driver of global water scarcity. By 2050, total irrigated areas, by implication, are projected to reach 796 million ac (322 million ha) globally (Alexandratos & Bruinsma, 2012).

In 2017, the USA total irrigated areas were 58 million ac (23 million ha), which had increased by 4% from 2012 (USDA, 2019). The total irrigation in 2015 was 118,000 Mgal/day (447 million m^3/day), an increase of 2,314 Mgal/day (8.759 million m^3/day) from 2010 (Dieter et al., 2018). Under the effects of future climate, changes in the total withdrawal from 2005 to 2060 are projected to increase by more than 50% in the Arkansas-White-Red and Lower Mississippi water-resources regions. In the west, the projected total water use is primarily driven by future irrigation withdrawals due to the increases in irrigated areas and potential evapotranspiration (Brown et al., 2013).

2.7.1 Irrigation in Kansas

As noted in Section 2.2, Kansas relies on groundwater as a primary source of irrigation water. As of 2015, the state ranked 6th in the USA in total volume of irrigation withdrawn from aquifers. Kansas consumed about 2,560 Mgal/day (9.69 million m^3/day) of groundwater for irrigation, which was roughly 20 times higher than surface water (Dieter et al., 2018). The primary irrigation system type applied in Kansas (Fig. 2.12) has changed from surface flood irrigation to sprinkler irrigation since the late 1980s (Rogers & Lamm, 2012). In 2015, irrigated areas of approximately 3,000 ac (1,214 ha) were irrigated with sprinkler systems in Kansas, ranking third nationally (Dieter et al., 2018). Center pivot systems became the most common sprinkler irrigation systems in Kansas because of their high efficiency. These systems were used for more than 95% of the irrigated areas across the state in 2017 (KDA, 2017; Waller & Yitayew, 2016).

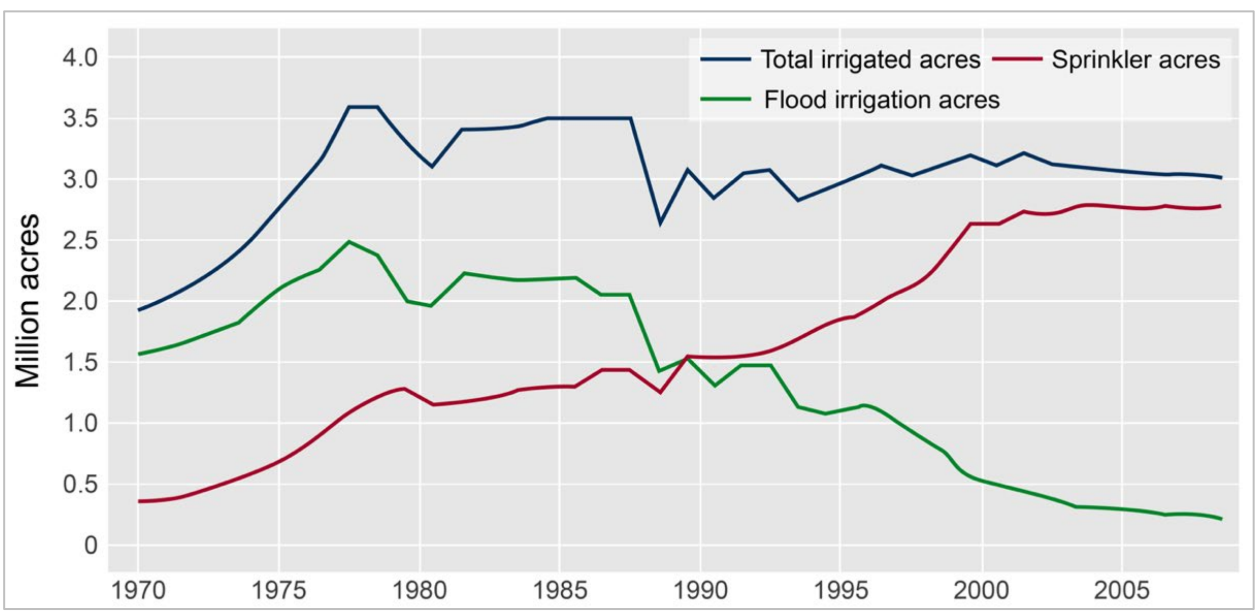

Fig. 2.12 Major irrigation system in Kansas since 1970 (modified from Rogers & Lamm, 2012).

A standard 125-ac (50-ha) center pivot system has been successful and widely adopted to irrigate almost all crops, especially traditional field crops, under a wide range of conditions (Evans, 2001). The system is a pipe structure with sprinkler outlets, rotating around a point that is connected to a water supply (Waller & Yitayew, 2016). Most machines are powered by electricity, driving a gearbox on each wheel from the electric motor. The pivot's speed can be controlled at the opposite end of the pivot point (Government of Saskatchewan, 2014). The pumping flow rate and size of the sprinkler (i.e., radius of the pivot circle) fix the water application. Therefore, a large amount of water irrigates to the field when the rotation speed is low. Minimum rotation times (with maximum speed) typically range from 14 to 20 hours (Evans, 2001).

In general, the pumping flow rate is about 800 gal/min (4,360 m^3/day) with a range of pressure at the pivot point from 15 to 80 pounds-force per square inch (psi) (Government of Saskatchewan, 2014). Though this system applies a considerable amount of water and leaves a lot of unused spaces, it has the potential for highly efficient and uniform water application; saves human labor; covers large areas; and needs low capital, maintenance, and management costs (Evans, 2001; Waller & Yitayew, 2016).

2.7.2 Impact of Groundwater Withdrawals for Irrigation in Kansas

In the mid-twentieth century, the beginning of substantial irrigation development using groundwater in Kansas had impacts on groundwater-level declines in parts of the High Plains aquifer (Buchanan et al., 2015; McGuire, 2014). In particular, the onset of center pivot irrigation systems in the 1960s caused the considerable expansion of irrigated farmland in the state. Since cultivated areas with sandy soils, where were not previously irrigated under gravity irrigated systems, could now be irrigated with the center pivot systems (Rogers & Wilson, 2000). Since predevelopment in many areas has been reported levels of groundwater, overlying the High Plains aquifer has declined by more than 60% (Buchanan et al., 2015). As of 2013, the water level in Kansas, on average, decreased by 25.5 ft (7.77 m) with a change in storage of 67.5 million ac-ft (83.2 billion m^3) compared to predevelopment or about the year 1950 (McGuire, 2014).

Groundwater is being consumed for irrigation with several hundred gallons per minute in western Kansas. How long will the aquifers support large-scale pumping? Kansas Geological Survey (KGS) projected a lifespan of the High Plains aquifer in western Kansas based on past rates and patterns of water use (Schloss & Buddemeier, 2000). An estimated usable lifetime map conducted by KGS (2007) shows the number of years remaining for the aquifer. Saturated thickness of 30 ft (9 m) is likely to be impractical for large-scale irrigation, municipal, and industrial pumping. Hence, a thickness of 30 ft (9 m) or more is considered as a usable aquifer for the projection. In Finney County, especially in the northern part of the county near Scott County, many areas are already below a minimum threshold. The number of years remaining varies spatially. In the South, groundwater could be used at most 50 years; however, it might be last more than 250 years in some areas near the western border.

Chapter 3. Relating Agriculture, Energy, and Water Decisions to Farm Incomes Using 50-Year Projections from FEWCalc and DSSAT

Jirapat Phetheet[a*], Mary C. Hill[a*], Robert W. Barron[b], Benjamin J. Gray[c], Hongyu Wu[d], Vincent Amanor-Boadu[e], Wade Heger[f], Isaya Kisekka[g], Bill Golden[e], Matthew W. Rossi[h]

[a] Department of Geology, University of Kansas, Lawrence, KS, 66045, USA

[b] Department of Industrial Engineering and Engineering Management, Western New England University, Springfield, MA, 01115, USA

[c] Department of Society and Conservation, University of Montana, Missoula, MT, 59812, USA

[d] Electrical and Computer Engineering, Kansas State University, Manhattan, KS, 66506, USA

[e] Department of Agricultural Economics, Kansas State University, Manhattan, KS, 66506, USA

[f] Environmental Studies Program, University of Kansas, Lawrence, KS, 66045, USA

[g] Department of Air, Land, and Water, University of California, Davis, CA, 95616, USA

[h] Earth Lab, University of Colorado, Boulder, CO, 80303, USA

[*]Corresponding Author: Jirapat Phetheet jirapat.p@ku.edu, or Mary C. Hill mchill@ku.edu

Abstract

FEWCalc (Food-Energy-Water Calculator) is a new freeware model with the novel ability to project farm incomes based on crop selection, irrigation practices, groundwater availability, renewable energy investment, and environmental conditions. FEWCalc's Agent-Based Model (ABM) architecture accepts user-specified inputs and integrates simulated crop production and irrigation water demand from DSSAT (Decision Support System for Agrotechnology Transfer) with added arid-region dynamics. Demonstrations with data from Garden City, Kansas, USA,

illustrate energy and agricultural production and farm profitability given (1) continuation of recent (2008-2017) ranges of crop prices, farm expenses, and crop insurance, (2) continuation of recent (2015-2019) renewable-energy economics, technology and government incentives, (3) four example temperature, precipitation, and solar radiation futures, including global climate model projections for Representative Concentration Pathway 8.5, and (4) groundwater-supported irrigation and its limitations. Surface water nitrate loads are reported. FEWCalc addresses scientific, experiential, communication, and educational gaps between global- and local-scale FEW research communities and local stakeholders, and improved understanding of how near-term choices and solutions can be crafted to create a more advantageous future.

Highlights

- Crop production and water use results from the DSSAT model with arid regions package
- ABM adds renewable energy, water quantity and quality, climate change, farm incomes
- FEWCalc enables users to relate current choices to near- to long-term implications
- Intuitive GUI makes FEWCalc accessible to non-technical stakeholders

Keywords

Food, energy, and water; Climate scenarios; Freeware; Renewable energy; Integrated Assessment (IA); Impacts, Adaptation, and Vulnerability (IAV)

3.1 Introduction

Small town and rural (STAR) agricultural communities produce much of the food for an increasingly urban and suburban world, yet face serious challenges including declining populations and reduced affluence driven by long-term crop price declines and production cost (fuel, seed, fertilizer, and so on) increases. Many of these areas also have rich renewable-energy resources such as wind and solar. Local residents seek ways forward to support their livelihood and communities. FEWCalc (Food-Energy-Water Calculator), which is presented in this work, seeks to assist in this process. This introduction reviews challenges considered in FEWCalc, how FEWCalc fits into existing research, and choice of development methods.

Climate-change driven increases in water and food insecurity pose emerging and long-term challenges. Surface temperatures are rising and historically extreme weather conditions are becoming more frequent (Campbell, 2020; Lesk et al., 2016). Increasing temperatures are already increasing crop water requirements and shifting precipitation patterns (Dore, 2005; Li et al., 2019; Zhang et al., 2019), and may directly affect global food supply quantity and quality (Wheeler & von Braun, 2013). Moreover, shifting regulations and restrictions on carbon emissions may alter the menu of available adaptation options. FEWCalc enables users to evaluate the impact of climate change by including future global climate model (GCM) results for representative concentration pathways (RCPs) and/or other scenario-based impacts on agricultural production.

Water scarcity is an immediate and enduring challenge in many regions, which can in part be addressed with groundwater reserves. Irrigated areas currently produce 30-40% of the world's food, and 70% of global water withdrawals are for agriculture (FAO, 2014; Kovda, 1977; WWAP, 2012). Groundwater is important: for example, it accounts as much as 70% of irrigation in some locations of China's dry northern region (Calow et al., 2009); groundwater accounts for 70-80% of the value of irrigated production and supports 90 million rural households in India (World Bank, 1998; Zaveri et al., 2016); and in western and central USA, groundwater from the Central Valley aquifer of California and the High Plains aquifer (HPA) supply as much as 16% and 30% of the nation's irrigation water, respectively (Dieter et al., 2018; Maupin, 2018; Maupin & Barber, 2005).

Most agricultural use is consumptive – that is, the water used for irrigation is transferred to plants or other parts of the hydrologic cycle such as the atmosphere, and, thus, only a small percentage is available to serve local water needs again. FEWCalc includes irrigation derived from groundwater, resulting resource depletion, and effects on agricultural production.

Challenges to agricultural, energy, and water systems are addressed in part by current and evolving local, regional, national, and international policies, the practices of supporting institutions and businesses, economic and socio-cultural attitudes, and subjective perceptions (Cash et al., 2006). Example studies in the USA include the Columbia-Snake River Plain (Adam, 2017) and southern California (Faunt et al., 2016; Kaufman, 2017). The consequences of policies and decisions can be unexpected, and may support or diminish system resilience – the ability of systems to recover utility after disruption. Unanticipated, negative externalities include economic disruptions and resulting price and profit instability, and depletion of natural resources such as soil and water (Aeschbach-Hertig & Gleeson, 2012; Wu et al., 2018; Zivin & Perloff, 2012). Promising efforts to promote sustainable groundwater use include California's 2014 Sustainable Groundwater Management Act (SGMA) and northwest Kansas' 2013 Sheridan-6 (SD-6) Local Enhanced Management Area (LEMA) (KDA, 2018; KWO, 2020). FEWCalc includes two types of policies: agricultural support in the form of crop insurance and selected renewable energy incentive programs.

Many STAR community residents recognize the challenges to their predominantly agricultural way of life and the need for action. However, consensus on paths forward is elusive, in part because the scale, complexity, and economic importance of the issues make it difficult for individual stakeholders to answer the question: "What could this mean for me?"

Renewable energy production from wind and solar is an alternative, but deciding whether and how to become involved in a fast-changing, unfamiliar industry is difficult. Recent research into Food-Energy-Water (FEW) systems has generated new understandings (e.g., Allan et al., 2015; Endo et al., 2017), however, this knowledge is largely unavailable to frontline stakeholders most directly affected by STAR community challenges, and whose choices most directly impact local resources such as water and national to global concerns such as food and energy security. Even scientific and engineering experts are often limited to one of the component fields. Moreover, effective, enduring solutions require community knowledge, perspectives, and values in addition to scientific and engineering expertise. Both knowledge and engagement gaps pervade many STAR communities trying to address the risks that confront them.

To close these critical gaps, we have developed FEWCalc as a tool for research and education. FEWCalc can be used to relate present agricultural, energy, and water decisions to long-term dynamics and consequences. Including renewable energy production addresses, in part, the concern that agricultural production alone may not be able to maintain STAR communities given resource challenges and competitive global markets. An advantage is that alternative energy production from wind and sunlight that exist in these regions may be developed by the community without placing greater demands on already challenged water resources.

3.1.1 The Prior State-of-the-Art

The development of FEWCalc can be viewed as advancing existing scholarship on the multi-scale, multi-stakeholder issues within the FEW nexus. First, consider the research in Integrated Assessment (IA) and Impacts, Adaptation, and Vulnerability (IAV) (Table 3.1). IA has a high-level interdisciplinary viewpoint and is commonly used to evaluate the impacts of climate policy choices on global scales (Weyant, 2017). The IAV community analyzes climate change effects and responses at sub-national to local scales (Absar & Preston, 2015; van Ruijven et al., 2014). These research streams have been converging as the value of integrated, multi-scale approaches to climate research has become apparent. As a tool focused on bringing longer term perspectives to present-day decision makers, FEWCalc bridges the gap between the IA and IAV communities.

Table 3.1 Summary IA and IAV approaches to technology and policy analysis.

Description	IA (Integrated Assessment)	IAV (Impacts, Adaptation, and Vulnerability)
Geographic Scale	Regional (U.S. State) – Global	Local (town, farm, ecosystem)
Temporal Scale	Long-term up to ~100 years	Few years or less
Scenario (assumptions about the future) and Policy (adaptations) Development	Global scale, cross-cutting, generalized, little inclusion of stakeholder values.	Narrower focus, more detailed, often has explicit representations of stakeholder values.
Interdisciplinary Focus	Broad	Narrow
Perspective	General impacts and adaptation possibilities. Projection/qualitative results.	Specific impacts and adaptation measures. Prediction and quantitative results.

Second, the standardized, multi-scale Shared Socioeconomic Pathways (SSPs) scenario framework (O'Neill et al., 2014) relates economic and technological choices to carbon emissions, and are thus closely related to RCP levels. As such, SSPs research supports research in the IA and IAV communities. FEWCalc supports carbon emission mitigation through developing greater local familiarity with renewable energy production and greater research-level familiarity with the challenges of local stakeholders.

Finally, the USA National Science Foundation (NSF) Coupled Natural and Human (CNH) systems program complements IA and IAV. Fig. 3.1 (NSF, 2018a) shows how the major components of the FEW system considered in FEWCalc forms a natural and human system that can be thought of as a collection of heterogeneous and autonomous individuals interacting cooperatively and competitively with one another and the environment (Bert et al., 2015; Hu et al., 2018).

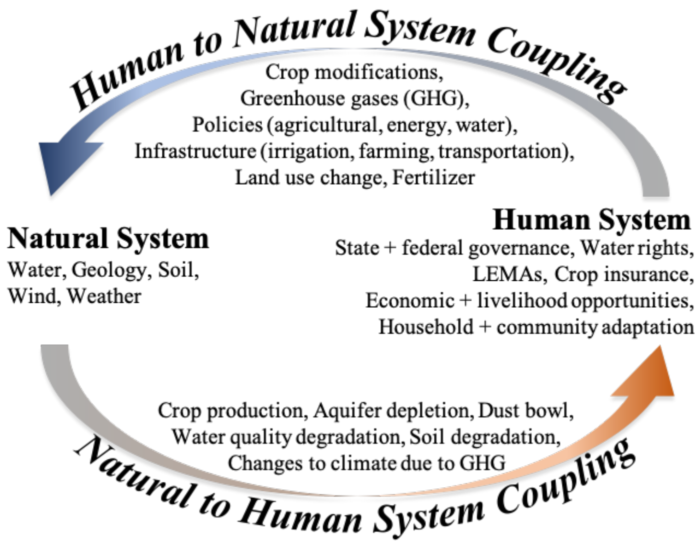

Fig. 3.1 The linkages between natural and human systems relevant to FEWCalc (Modified from K. Rogers, East Carolina University, Coastal Studies Institute, written communication, 2017; NSF, 2018a). LEMA (Local Enhanced Management Area) is a governance structure used in the state of Kansas, USA, to limit water use from a depleted aquifer.

3.1.2 The Knowledge and Engagement Gap

Many of the communities facing groundwater depletion have economies based almost entirely on agriculture. Farmers recognize that they have the choice of working together to extend the usable lifetime of local water resources by reducing irrigation rates or face a future in which declining water availability jeopardizes their livelihoods. In the absence of an organized policy framework, the tragedy of the commons could prevail (Hardin, 1968) unless the knowledge and engagement gap is addressed.

The knowledge and engagement gap is highlighted by the different approaches to scenario development taken by the IA and IAV communities (Table 3.1). The divergent approaches are unfortunate, because the complex multi-scale, multi-stakeholder problems these farmers face require participatory, systemic solutions that address stakeholder values. Despite recent convergence (Absar & Preston, 2015; de Bremond et al., 2014; Huber et al., 2014; Kraucunas et al., 2015; Rosenzweig et al., 2014), unresolved scale and human connection issues still limit the utility of IA and IAV models. Couplings within the multi-scale system may create synergistic or antagonistic relationships between different participants and processes (Ericksen, 2008; Ericksen et al., 2009; Vervoort et al., 2014). For example, national policies could be rendered ineffective for want of local-level adaptation and mitigation options, and local level efforts could be stymied by national policy or global market conditions. However, with the proper support, coordinated action such as the Local Enhanced Management Areas (LEMAs) in Kansas is possible. Climate, weather, hydrology, politics, energy, and economics are all important and interact across multiple societal scales, including jurisdictional, institutional, and managerial ones (Cash et al., 2006). Thus, the issues addressed by FEWCalc exist within the context of national- and global-scale dynamics (Ericksen et al., 2009).

As a farm-scale assessment framework that integrates issues related to agriculture, energy, water, and climate, FEWCalc leverages the momentum of the IA/IAV convergence with CNH-style advances. Farm-scale engagement and analysis is needed for regional-scale and global-scale policy to work. The FEWCalc model can thus be thought of as addressing three key needs identified by Vervoort et al. (2014): (1) engage diverse stakeholders across multiple levels; (2) move beyond analysis of single interventions towards system-wide measures that act across multiple spatial, temporal, and geographic scales; and (3) develop long-term capacity for collaborative decision making.

3.1.3 The Opportunity

A possible adaptation to water scarcity is to expand the economic base of STAR communities. Diversifying local economies could enable investment in emerging agro-technological solutions and improved use of the limited water resources. A promising opportunity for community economic diversification is renewable energy. Many water-stressed areas of the world are also rich in renewable energy resources. For example, in the central USA, renewable energy exported to existing load centers has been profitable for farmers through participation in land-lease programs from which they can derive considerable annual income (Weise, 2020).

One example of economic diversification based on renewable energy, and the one FEWCalc is designed to investigate, is for landowners, such as farmers, to invest directly in renewable energy production by owning wind turbines and solar panels, and thus take on both additional risk and greater income potential (Epley, 2016; Hill et al., 2017; Phetheet et al., 2019). In the area used to demonstrate FEWCalc, wind turbines tend to be more profitable than solar panels. However, solar panel profitability depends on what are currently changing price and policy conditions, and solar panels produce electricity on hot summer days that often have little wind and may be important to off-grid operations. To allow users to consider both technologies, wind turbines and solar panels are included in FEWCalc.

Another example of diversification is to power new local industries and businesses. One ongoing study is exploring the possibility of using renewable energy locally for water treatment and ammonia production (Hill et al., 2019). FEWCalc provides a foundation upon which such analyses could be made available to local stakeholders.

3.1.4 The Challenge

Potential solutions to the difficult problems faced by farmers in western Kansas are not easy, and often require difficult, high-stakes choices in the near term to reduce financial costs and risk in the long term. Ideally, these choices should be made in a coordinated way using robust, inclusive decision-support tools. However, there is currently no effective way for local stakeholders to understand how their individual situation is likely to be affected by their choices, collective action (or lack thereof) with their peers, and national- and global-scale factors, such as crop choice, depleting resources, and climate change.

3.1.5 A Solution (Or at Least Part of a Solution)

FEWCalc addresses the identified challenges, making expertise accessible to local decision makers who will bear most of the consequences of climate change and resource limitations. This article introduces FEWCalc and demonstrates how it provides users with a sense of tradeoffs and possibilities. As presented here, FEWCalc is applicable directly to farmers in arid regions of the middle part of the USA looking for new ways forward. The design of FEWCalc has broad applicability for agricultural-energy-water system decision support research and education. Applicability to other regions requires local data, development of a DSSAT model, and adjustment of the FEWCalc input variable values. Little or no programming would be required.

FEWCalc calculations are based on a conceptual view of the processes – statistical approaches in the component fields involved have not achieved a great deal of success so far (for example, see an energy example in Ulrich et al., 2019), and application to the integrated system considered in this work would be even more difficult. A conceptual-based approach and related process-based modeling is a 2020 state-of-the-art solution.

Technology has been the single-most important ingredient in agricultural and energy progress for centuries. Over the past 70 years, the Green Revolution (Sumberg et al., 2012), herbicides (Hamence, 1966), tillage systems (Carr et al., 2013), biotechnology (Bajaj, 1986), satellite technology (Negula et al., 2017), and big data analytics (Bronson & Knezevic, 2016) have had radical cumulative impacts on agricultural productivity. Over the same time period, energy has seen advances in transmission grids, transportation, manufacturing, and computing (DOE, 2015). Technical evolution will continue to address challenges and scarce resources. By default, FEWCalc simulations represent continuation of technologies of the last decade, and results illustrate the challenges of the future. Users can explore the impacts of hypothetical advances by altering agricultural and energy input variables during the simulation using the "Go once" option.

Sections 3.1.5.1 and 3.1.5.2 below provide an overview of DSSAT and agent-based modeling with NetLogo, as used to develop FEWCalc.

3.1.5.1 Simulating Agrosystems with DSSAT

Agricultural system science is a broad interdisciplinary field that has contributed models able to represent the water-crop-soil-nitrogen dynamics of complex agricultural systems (Foster et al., 2017; Holzworth et al., 2014; Jones et al., 2003). Model components and their interactions are described by mathematical equations that are integrated daily or hourly to predict the time evolution of crop growth, nutrient uptake, water use, and crop yield (Boote et al., 2010). Predictions are approximate, and careful modeling and use of available data and well-characterized processes are needed to produce useful insights.

For FEWCalc, a freeware model with global reach was needed. The Decision Support System for Agrotechnology Transfer (DSSAT) model (Araya et al., 2019; Jones et al., 2003; Jones et al., 2017a, 2017b; Sharda et al., 2019) was chosen for this work based on its capabilities and popularity. DSSAT requires daily weather data (maximum and minimum air temperatures, precipitation, and solar radiation), soil data (physical and chemical properties of soil profile horizons), and crop management practices (cultivars, planting practices, irrigation, fertilization, etc.). DSSAT produces the simulated values of crop yield, irrigation rates, and fertilizer demand used in FEWCalc.

Of interest in this work is the utility of DSSAT in tools such as FEWCalc. That is, when used for future projections, are the DSSAT results reliable enough for FEWCalc to fulfill its goals?

3.1.5.2 Simulating Economics, Agricultural, Energy, and Water with ABM

Agent-based models (ABMs) can include process-model calculations, and discrete and/or stochastic processes. ABMs are designed to integrate complex real-world systems and evaluate future policy decisions (Anderson & Dragićević, 2018; Guijun et al., 2017). NetLogo is a popular ABM construction platform (Hu et al., 2018; Tisue & Wilensky, 2004; Wilensky, 1999) and was used to construct FEWCalc.

ABM had its roots in business (Forrester, 1971; Morecroft, 2015), before migrating to urban problems (Sterman, 2000) and environmental challenges (Meadows, 2008); its use in the FEW nexus has emerged recently (Al-Saidi & Elagib, 2017; Memarzadeh et al., 2019; Schulterbrandt Gragg et al., 2018). Most of this recent research has been conceptual or focused on regional applications; focus on individual stakeholders, such as farmers, is needed (Ravar et al., 2020; Shannak et al., 2018). Studies of some urban systems have focused on stakeholders (Bieber et al., 2018; Guijun et al., 2017). Bieber et al. (2018) also describe how optimization can be used to identify advantageous choices for variable inputs. None of these models include the complex agricultural and renewable energy production, and water challenges represented in FEWCalc. In this sense, FEWCalc is novel and contributes to the emerging ABM literature.

In this article, we focus on how the unique aspects of FEWCalc are accomplished and the utility of the results they enable. In particular, we consider how future alternative climate scenarios are likely to affect agricultural production and farm income.

3.1.6 Case Study from the High Plains Aquifer

FEWCalc is developed and tested using data from Finney County, Kansas, USA (Fig. 3.2). The High Plains aquifer (HPA) consists of the Ogallala aquifer and its overlying aquifer units. The area's water problems are typical of arid agricultural regions around the world: Large-scale irrigation over many decades has depleted groundwater resources and produced now dry irrigation wells (Buchanan et al., 2015). The region's potential to develop renewable energy, its declining water resources, and its rich, 70-year-long time series of historical data makes it an ideal candidate for exploring opportunities to sustain farmers' economic well-being under alternative agricultural and energy production choices using FEWCalc.

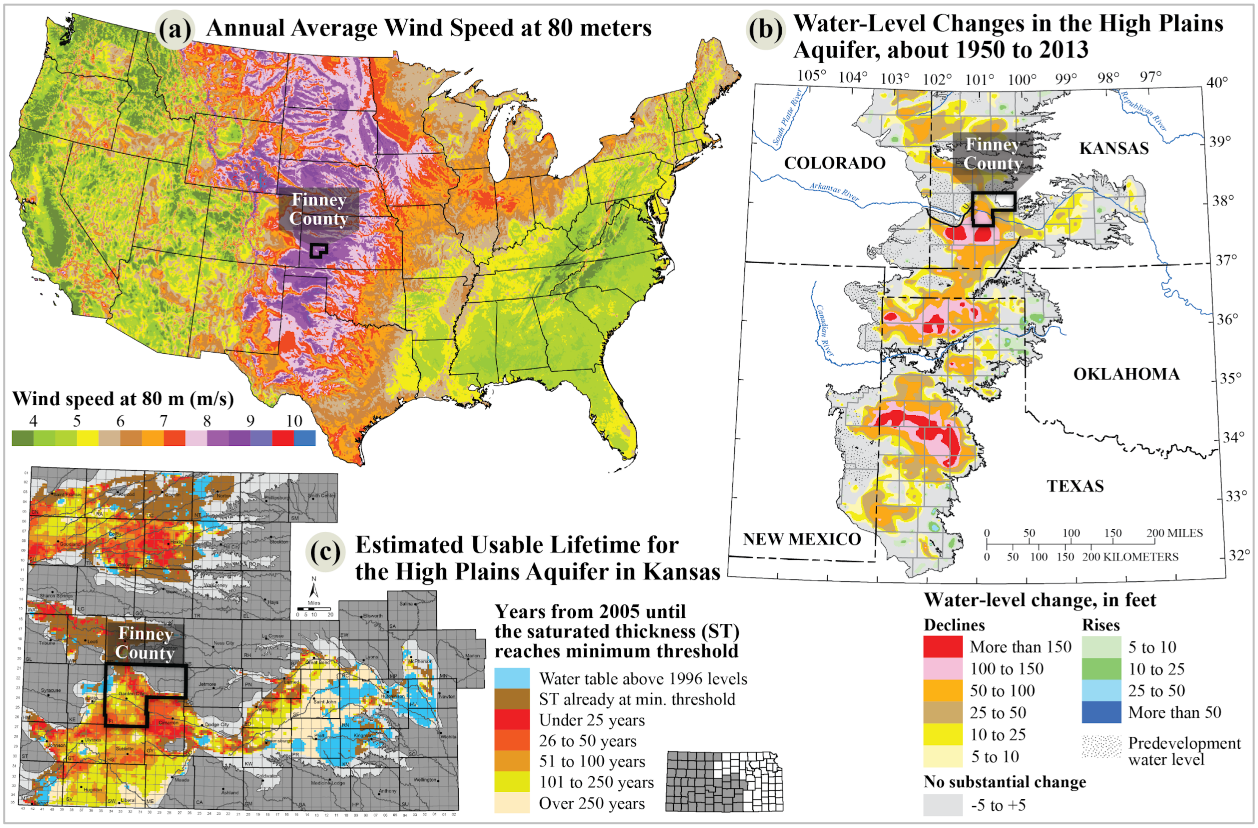

Fig. 3.2 (a) Average annual wind speed map for the Continental United States (modified from NREL, 2011). Finney County has very high average wind speeds and moderate solar energy supplies (not shown). (b) High Plains aquifer water-level changes (modified from McGuire, 2014). (c) Southwest Kansas estimated aquifer utility (Butler et al., 2013; KGS, 2007).

3.2 Methods

In this section, the FEWCalc workflow is briefly introduced, and each component and related equations are described. DSSAT and FEWCalc inputs and outputs are listed here and in Appendices A and B. FEWCalc equations are described here and in Appendix C. Default values for user-controlled FEWCalc variables are provided in Table D.1. As programmed, all costs are in US dollars.

3.2.1 Workflow

The workflow of FEWCalc with inputs from DSSAT is shown in Fig. 3.3. Components representing agriculture, energy, and water are identified in the figure; details are described in the following sections and in Appendix A. Climate data is entered using the weather data DSSAT input (top left in Fig. 3.3). DSSAT needs to be executed prior to running FEWCalc. DSSAT output files in a comma-separated values format (CSV files) are read by FEWCalc. The final results are presented in graphs identified by eight boxes at the bottom of Fig. 3.3. The time discretization of DSSAT is one day; in FEWCalc, time is incremented annually. Simulation length is defined by the user, with simulations of 60 to 90 years being common.

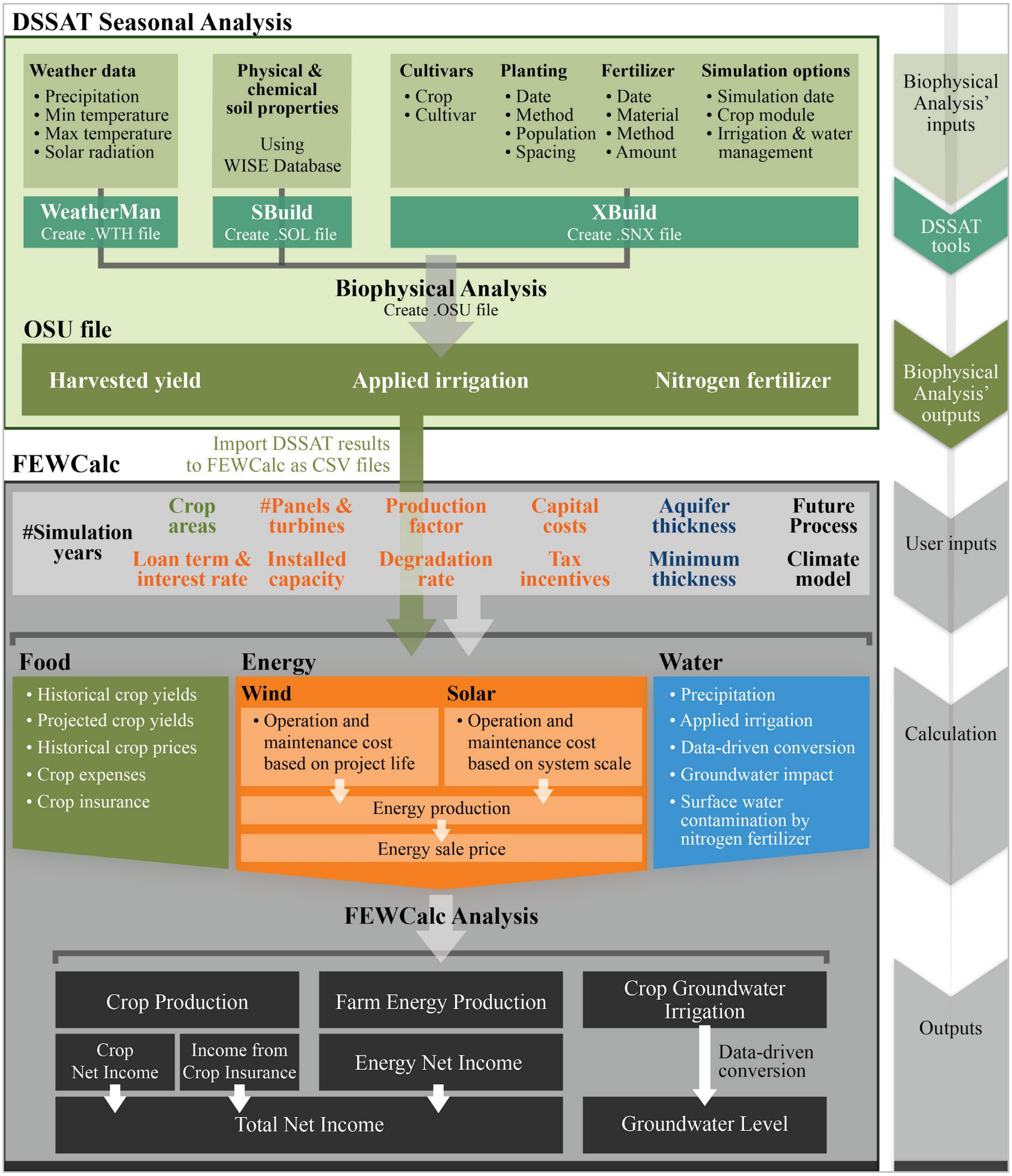

Fig. 3.3 Workflow diagram showing the flow of data and a listing of results. Seasonal Analysis, Biophysical Analysis, Weatherman, SBuild, and XBuild are routines within DSSAT.

DSSAT is tested by comparing calculated values for crop production and irrigation to observed field data (see Appendix A) obtained from the United States Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS), Kansas State University's (KSU) Department of Agronomy, and the Kansas Department of Agriculture (KDA). FEWCalc is tested through comparisons with values obtained through the literature and expert elicitation.

3.2.2 Weather, Climate, and Projections

Daily weather data for air temperature, precipitation, and solar radiation are used as input to DSSAT (Tsuji et al., 1994) and acquired as described in Appendix A. WeatherMan (Pickering et al., 1994) is used to import, harmonize, and error-check this daily weather data.

A 10-year period from 2008 to 2017 is used as the historical base period for this work. This 10-year period is presented in the context of data since 1950 in Fig. 3.4, in which wet and dry periods are identified using the Palmer Drought Severity Index (PDSI) (Palmer, 1965). The base period was chosen because a generally complete set of weather and agricultural data is available, and because wet, moderate, and dry years are included in that period of time (see Fig. 3.4). This variability is used to create future climate scenarios.

The four 60-year long scenarios used to demonstrate FEWCalc are listed in Table 3.2. All scenarios have the same 10-year (2008 to 2017) temperature, precipitation, solar radiation, and agricultural price conditions, and differ for the following 50 years. **Scenario 1**, Repeat Historical tests the time progression in FEWCalc, and allows users to focus on the impact of groundwater declines and energy production. **Scenarios 2 and 3** are dominated by wetter or drier years to create wetter and drier "futures". The weather data are chosen from the 10-year base set of years. So, for example, if those 10 years are numbered 1, 2, …, 10, years 8, 9, and 10 are wet (Fig. 3.4). Going forward, 7 of each 10 years will be selected from the three wet years. The other 3 of each 10 years are chosen from the 4 moderate base years (years 1-3, and 7). The random sequence of moderate to wet years results in increased crop production with no significant loss of yield. **Scenario 4** is based on 20 global climate model projections out to 2098 (Fig. A.2), though only the values through 2067 are used in the FEWCalc demonstration provided in this work. Projected crop prices are described in Section 3.2.3.2.

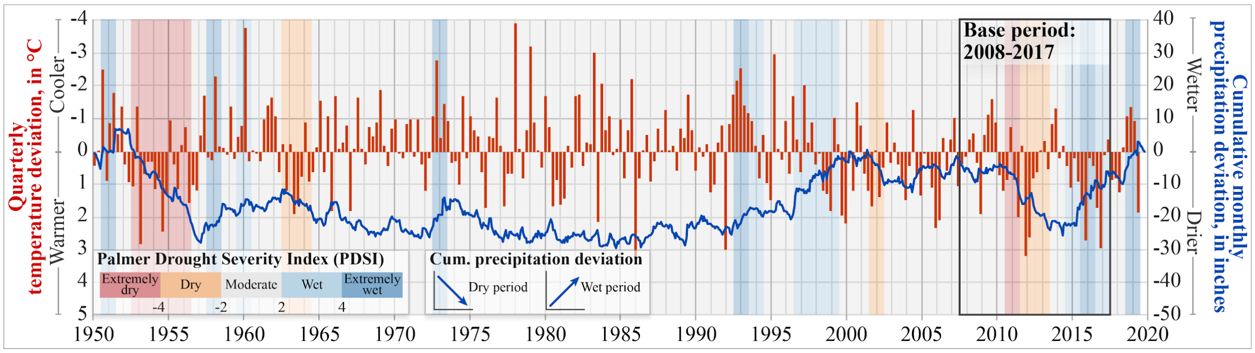

Fig. 3.4 Annual average PDSI, monthly cumulative precipitation deviation, and quarterly temperature deviation data from January 1950 to September 2019. Monthly and quarterly base values are listed in Table A.12. The 2008-2017 base period used in this work is highlighted. The axes for precipitation and temperature deviation are scaled so that conditions producing drought (high temperature and low precipitation) produce downward pointing bars of temperature deviation and downward sloping trend of cumulative precipitation deviation.

Table 3.2 Simulation scenarios used to represent climate conditions in DSSAT for the 50-year projection period (2018-2067) that follows the 2008-2017 historical base period in the FEWCalc simulations.

Name	DSSAT Temporal Progression of T, P, and S[1]
Scenario 1. Repeat Historical	Repeat conditions from 2008 to 2017 for all 50 years of the projection period.
Scenario 2 & 3. Wetter/Drier Future	Use more wet or dry years from 2008 to 2017, respectively to create a correlated random 50-year projection
Scenario 4. RCP 8.5 T, P, and S Changes	Apply GCM-simulated[2] climate for the 50-year projection period

[1]T, temperature, in degree Celsius; P, precipitation, in inches per year (in/yr); S, solar radiation, in watts per square meter (W/m^2). [2]GCM, global climate change under RCP 8.5 scenario.

Scenario 4 uses DSSAT results in which runs use projected air temperature, precipitation, and solar radiation from 20 downscaled GCMs to represent years 2018 to 2098 (Taylor et al., 2009, 2012). Results from the 20 DSSAT runs are averaged and used in FEWCalc. RCP 4.5 and 8.5 results are available in FEWCalc – see Appendix A for a discussion of RCP. FEWCalc results using the RCP 4.5 and 8.5 scenarios are compared in Phetheet et al. (in review). Results from the more severe RCP 8.5 are presented in this article.

3.2.3 Calculations for Agriculture

FEWCalc simulates crop yield, crop income, and crop insurance. To communicate results to stakeholders, this article presents both English and metric units. DSSAT uses the metric system. In this section, metric units or appropriate conversion factors are listed to facilitate cross-referencing to DSSAT results.

FEWCalc starts with the assumption that the decision-maker is already in business as a farmer, producing crops in the Garden City area of Finney County, Kansas. The farmer is considering investments in renewable energy as a diversification strategy to improve farm incomes, which have been extremely variable in the last decade. The environmental conditions and resources are as described in Sections 3.2.2 and 3.2.5. Therefore, the focus of FEWCalc is on-farm operations and on renewable-energy investment decisions.

3.2.3.1 Crop Production

The crops commonly produced in Kansas are corn, winter wheat (called wheat in this work), soybeans, and grain sorghum, all of which FEWCalc incorporates into the simulations (Table 2.6). Fig. 3.5 shows the crop production, planted acres, crop prices, and, to represent expenses, gasoline prices in Kansas from 1866 to 2019. The increase in productivity per acre is apparent by comparing Figs. 3.5a and 3.5b. In Finney County, soybeans are not commonly grown, due to soil conditions and heat-caused pod shattering. Soybeans are maintained in FEWCalc and mentioned briefly in this work because soybeans are a common crop in other parts of the region.

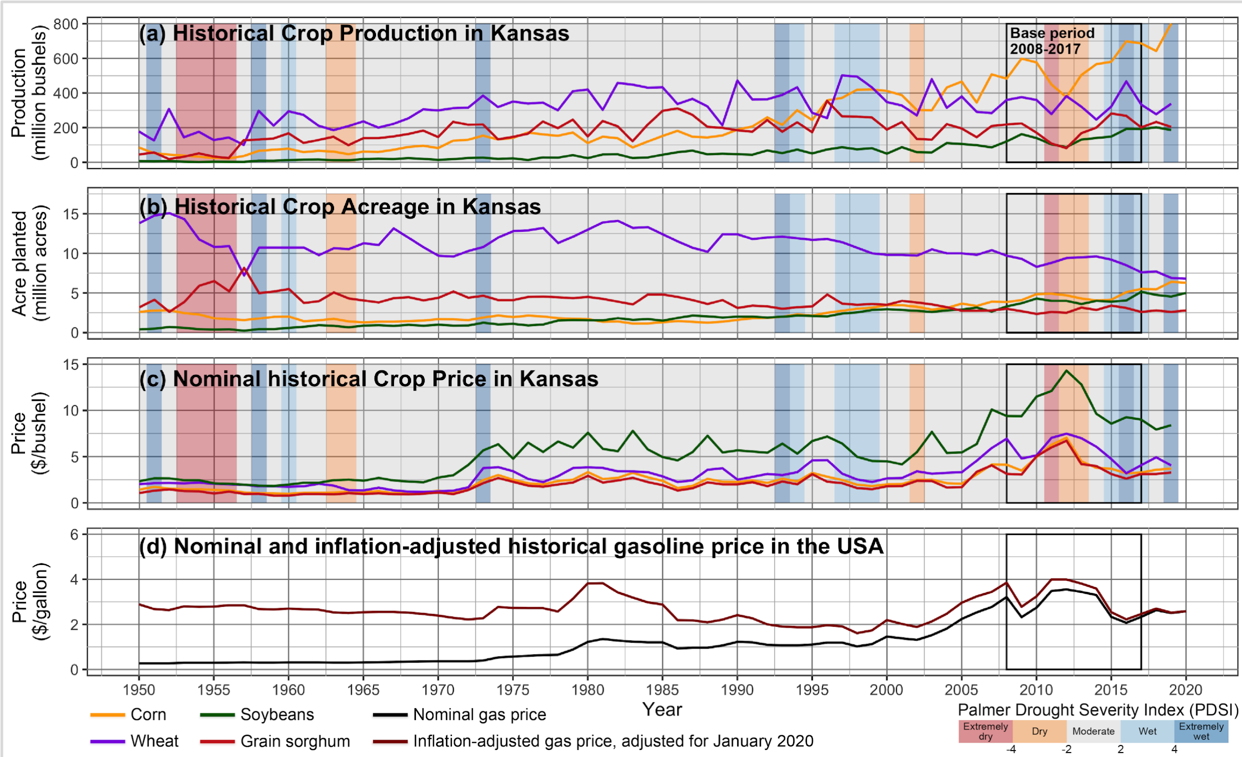

Fig. 3.5 Kansas (a) historical crop production (NASS, 2019), (b) historical crop acreage (NASS, 2019), (c) nominal historical crop prices (NASS, 2019), and USA (d) nominal and inflation-adjusted historical gasoline price (McMahon, 2020). The rectangular area in each plot shows the base period (2008-2017) used in this work to aid in comparison with historical data. Conversion factors: 1-bushel corn or grain sorghum is 56 lb or 25.4 kg, 1-bushel wheat or soybeans is 60 lb or 27.2 kg, 1 ac equals 0.4 ha, and 1 gal equals 3.8 liters.

DSSAT simulations are conducted using a one-day time step. Results are accumulated to produce annual results for FEWCalc. Datasets are prepared using DSSAT built-in software programs XBuild and SBuild (Fig. 3.3). XBuild allows users to specify management options such as cultivars, planting date, and plant population. SBuild assembles physical and chemical soil data. The International Soil Reference and Information Centre (ISRIC) developed a soil database for the project “World Inventory of Soil Emission Potentials (WISE).” The WISE database included in

DSSAT is one of the most comprehensive soil databases, with well-distributed soil stations globally (Gijsman et al., 2007).

In this work, the DSSAT Seasonal Analysis is used and simulations represent individual growing seasons. In this mode, by default, DSSAT starts each spring with soil water content at field capacity (SDUL). However, for this area, drier conditions are likely. As such, for this study, DSSAT is started each year with soil water content equal to (SDUL + SLLL)/2, where SLLL is the water content at the wilting point. The simulations are started one week before planting to allow the precipitation record to affect soil moisture at planting.

The long periods of interest in this work were simulated using the DSSAT Biophysical Analysis part of the Seasonal Analysis option. Outputs such as harvest yield, applied irrigation, and applied fertilizer are calculated based on parameters defined in Table 2.6; the values were chosen based on the cited references.

3.2.3.2 Crop Net Income

Farm net income is income after production expenses. Income is based on crop prices. For future projections, it is difficult to determine income accurately because crop prices vary over time, as shown in Fig. 3.5c, due to complex global trade and policy interactions (USDA, 2020). No attempt to project this process is made in FEWCalc; prices from 2008-2017 (Fig. 3.5c, boxed area) are used to produce prices for the projections as described in the following paragraphs.

For corn and grain sorghum, the region in and around Kansas produces a large enough percentage of world supply that local conditions largely control world prices (USDA, 2020, p. 20). In FEWCalc, high corn and grain sorghum prices tend to be high during regionally dry years (Fig.

3.5c) when crop production tends to decline (Fig. 3.5a). For wheat, the region does not exert control over world crop prices (USDA, 2020). These relations are represented in FEWCalc as follows.

The FEWCalc base period 2008-2017, which has three wet and three dry years, is used to create projected climate conditions as described in Section 3.2.2 (Fig. 3.4, boxed portion).

For corn and grain sorghum, the following procedure is used. In Scenario 1, 2008-2017 prices are repeated in sequence along with the temperature and precipitation data five times to create the 50-year projections. For Scenarios 2 and 3, the 10-year base period is used to define 10 sets of annual climate and crop-price data and selections are made from this 10-member set (with replacement) to create wetter and drier futures. For Scenario 4, prices are assigned based on precipitation: Less than 17 inches of precipitation is considered to be a dry year and price is selected randomly from one of the three dry years; 20 inches or more is treated as a wet year and price is selected randomly from one of the three wet years.

For wheat, local conditions do not dominate world crop prices, so prices do not remain associated with the local climate data. The 10 annual prices from 2008-2017 are assigned to each year for the period 2018-2067 randomly and independently of the climate data.

Total annual crop net income is computed as:

$$Income_C = \sum_i [(Yield_{C_i} \times Price_{MKT_i}) - Expense_{C_i}] \quad (1)$$

where $Income_C$ is crop net income earned for each year in US dollars per acre, i identified an acre, $Price_{MKT}$ is crop market price in US dollars per bushel, $Expense_C$ is crop production expenses in

US dollars per acre, and includes the cost of irrigation, fertilizer, herbicide, pesticide, labor, rent, crop insurance, and depreciation (Tables A.4 to A.7), and $Yield_C$ is annual crop yield for a given crop in bushels per acre from DSSAT.

3.2.3.3 Crop Insurance

Agricultural farm income support takes many forms which may or may not improve financial stability (Mishra & Cooper, 2017). FEWCalc includes the option of insurance for crop yield. General characteristics of crop-yield insurance are described by Edwards (2011) and RMA, (2020). Crop-yield insurance is purchased to protect against potential losses of crop yield from natural disasters, and especially droughts. In practice, insurance companies will increase premiums if indemnities are high, so over the long term, farm incomes will not be increased by crop insurance. However, the insurance does mitigate income declines in exceptionally bad years. In FEWCalc, the crop prices and premiums from the 2008-2017 base period are maintained, and years and values of indemnities are noted. How crop insurance is represented in FEWCalc is described in Appendix C, Eqs C.1 to C.4.

3.2.4 Calculations for Renewable Energy

Renewable energy calculations for wind turbines and solar panels are calculated in FEWCalc. Users control the number and installed capacity of wind turbines and solar panels, and their degradation rates, lifespan, capital costs, and tax credits.

The version of FEWCalc presented here considers farmer-owned energy production facilities that serve both local electric loads and electricity sale to the grid. These are not represented explicitly, the FEWCalc input is simply the resulting average value obtained from the electricity produced. Section 3.2.4.1 describes this process.

3.2.4.1 Energy Net Income

Energy net income for year *t*, $Income_{E\_t}$, is the sum of total net income from wind production (Eq. C.11) and total net income from solar production (Eq. C.21):

$$Income_{E\_t} = Income_{W\_t} + Income_{S\_t} \tag{2}$$

Calculating $Income_{W\_t}$ (income from wind energy for year *t*) and $Income_{S\_t}$ (income from solar energy for year *t*) requires *Energy_value*, the monetary value of all megawatt-hours (MWh) of electricity produced, and used in Eqs. C.13 and C.23. Users can control the average value obtained for that electricity. Usually this value should be greater than the wholesale price of electricity, which in Kansas and surrounding states is presently (2020) US$20 to US$40/MWh. Higher values would be expected because some of the electricity is worth retail because it allows the generator to avoid retail purchase of energy to, for example, run electric water pumps, or qualifies for net-metering. In the Kansas region, retail is presently US$100 to US$130/MWh. In addition, with some restrictions, farmers can enter into Power Purchase Agreements (PPAs) to sell electricity at prices that tend to be between wholesale and retail prices. While electricity prices tend to be less volatile than crop prices, they are still difficult to predict. FEWCalc uses a default *Energy_value* of US$38/MWh.

The effects of equipment depreciation on net income is simulated using a CSV file that is read by FEWCalc and defines the percent of installed cost to be depreciated, the depreciation taken each year, and the tax rate of 20% to be applied. For example, a US$3M installed cost (68.8% of the installed cost is a capital cost) would yield a US$206,400 reduction in taxes with a 50% depreciation rate (see Appendix A). This deduction may require a third-party financial partner.

This tax savings can be used to increase farmer income or reduce the loan to cover the renewable energy costs.

In Eqs. C.5 and C.15, installed costs for energy production are financed over a period defined by the user as a fraction of the life of the equipment (*Nyearsw* or *Nyearss*) and an interest rate (*APR*) that is also defined by the user.

3.2.4.2 An Overview of Energy Production and Regulatory Environment

The regulatory environment of renewable energy, including wind and solar, are complex and evolving. Here we provide a few comments to establish some context for the range of solar and wind energy resources that FEWCalc supports. References for additional information are noted.

Regulation of solar production can depend on capacity, and policy is not well established. Commercial size installed solar capacity is about 1 MW in Kansas (KCC, 2019); capacities under 3MW are commonly classified as small (Green Coast, 2019). States with less total solar capacity tend to have smaller installations: in the three lowest ranked states (including Kansas), solar installations for agricultural use average around 0.4 kW or 0.0004 MW per farm (Xiarchos & Vick, 2011). In 2019, Kansas had 47 MW of installed solar (SEIA, 2020a). In contrast, neighboring Missouri, with less solar potential but more solar-friendly policies, had 258 MW of installed solar capacity (SEIA, 2020b). The smallest solar installation FEWCalc can represent is 10kW.

FEWCalc supports the installation of up to 2.4 MW of solar installed capacity, which would require 8,000 solar panels with a combined area of 16.6 ac (6.7 ha) (Ong et al., 2013). In southwest Kansas, where average *PSH* is 5.6 hours per day, Eq. C.21 suggests that these solar panels would produce about 4,906 MWh of electricity per year. Eq. C.11 indicates that it would require about 0.7 2-MW wind towers and 0.9 ac of land (0.4 ha) to produce the same output per year (Denholm et al., 2009). The net revenue gained by this land use would need to be compared with crop revenues as part of deciding whether to make the renewable energy investment. FEWCalc provides the results needed for the user to produce such a comparison.

3.2.4.3 Financial Assumptions – Energy Equipment Tax Incentives and Depreciation

Tax incentives and equipment depreciation can produce large tax deductions that exceed what some owners can deduct from their taxes. It can thus be advantageous to contract with a third-party financial partner, called a Tax Equity Investor, who can claim the credit and return much of the value to the owner, depending on the agreement made; typical cost is 6-7% (M. Gilhousen, written communication, 2020). In FEWCalc, use of the tax incentives (ITC or PTC; see Eqs. C.13, C.15, and C.23) and depreciation often imply that such third-party arrangements are involved. The transaction fee is not included, and the entire value of any tax credit and deduction is applied to the owner as income in the year it is incurred. It could be accumulated to defray the cost of updating equipment, but FEWCalc does not provide for this.

The applicability of ITC and PTC has changed over time and differs with installed capacity and whether wind or solar equipment is installed. FEWCalc includes an adjustable range of options.

3.2.5 Calculations for Water

The only water use represented in FEWCalc is irrigation to support the farm production simulated using DSSAT. The current version of FEWCalc satisfies all water demands using groundwater, and it is assumed that dryland farming is the default production method when groundwater levels are too low. Simulation of crop production and irrigation demand in the arid region considered in this work required modification of the distributed version of DSSAT, and this modification is described below. This is followed by a description of how DSSAT results are used in DSSAT to simulate impacts on groundwater levels and surface-water quality.

3.2.5.1 DSSAT Irrigation Calculation for Arid Regions

Irrigation requirements and frequency of application vary as a function of crop type, crop management, soil properties, and weather conditions (Salazar et al., 2012). In DSSAT, the default irrigation calculations provided too much water and restrictions were needed to match measured water-use data. This was addressed by using the fixed amount automatic mode in DSSAT, as described by I. Kisekka (University of California, Davis, written communication, 2019) and as used by Sharda et al. (2019). The approach is described in Appendix C.

3.2.5.2 Calculating Groundwater Levels Based on Water Use

In FEWCalc, it is assumed that all irrigation water comes from groundwater. The simplest way to relate the irrigation use per crop area produced from DSSAT to groundwater level change is to divide by specific yield. However, this neglects spatial changes in specific yield, groundwater recharge, and other hydrologic processes, and was found to produce unrealistically fast dewatering of the aquifer. When available, historical data can provide an alternative. Butler et al. (2016) and Whittemore et al. (2016) show that in parts of Kansas, groundwater declines are linearly related to total groundwater pumpage and discuss the circumstances under which this would occur.

For FEWCalc, a two-step process was developed using two linear regressions and reported Finney County data from B. Wilson (Kansas Geological Survey, written communication, 2019). The first step (Fig. 3.6a) relates DSSAT-simulated areal average irrigation demand (converted from mm to ft) to reported groundwater use (divided by the county area, 833,900 ac = 337,500 ha

= 1,303 mi²). The second step (Fig. 3.6b) relates the groundwater use results of step 1 to reported annual county-average groundwater-level declines. The graphs, R-squared and p-values shown indicate that largely linear relations were obtained. This approach assumes that the temporal patterns in groundwater use simulated by DSSAT are, on average, replicated over the county and region.

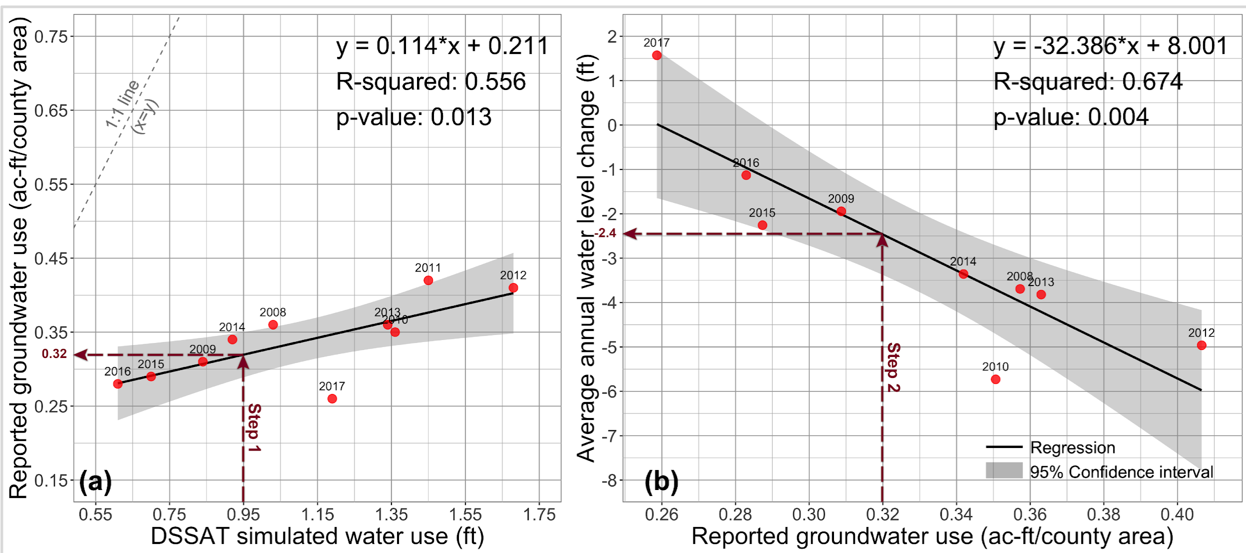

Fig. 3.6 A two-step data-based process used to relate DSSAT reported water use to average annual water level change for groundwater derived using data from 2008-2017. (b) is modified from B. Wilson, written communication, November 2019. Data are from the Kansas Geological Survey WIMAS database. Conversion factors: 1 ac-ft is 1,233 m^3, 1 ft is 0.3 m.

Dryland farming is simulated if the two-step process from Fig. 3.6 imposed over many years reduces aquifer thickness to less than a user-defined value; the default is 30 ft (9 m), based on the work of Schloss & Buddemeier (2000). During dryland farming, groundwater levels increase due to groundwater recharge, and the increase is calculated by extrapolating the linear regression in Fig. 3.6a to a DSSAT water use of zero (y-intercept = 0.211 ft = 0.0643 m). Fig. 3.6b then yields an annual water-level increase of 1.17 ft (0.357 m). FEWCalc simulates irrigated agriculture again when the saturated thickness is restored to 60 ft (18 m).

3.2.5.3 Nitrogen Concentrations in Surface Water

When nitrogen is applied to fields, a percentage of it remains in the soil until it is moved into surface-water bodies by large storms (USGS, 1999). In the study area, about 10% of the applied nitrogen is thought to be retained for silt loam soil and typical soil temperatures during fertilizer application (Kansas Mesonet, 2017; Sawyer, 2011). Individual storm data are not available, so nitrogen is moved to surface water in wet and extremely wet years as defined using PDSI. For Scenario 4, PDSI data are not available, and nitrogen is moved when annual rainfall exceeds or equals 20 inches. The equations used are presented in Appendix C.

Nitrogen is represented in FEWCalc using rust-colored dots that accumulate on fields during extremely dry, dry, and moderate years. The number of particles is determined using the NetLogo command "Round" where 0.5000 is rounded in a positive direction. Each particle represents 10,000 lb (4,500 kg) of nitrogen.

3.2.6 FEWCalc Interface

FEWCalc's NetLogo interface (Fig. 3.7) is divided into three main areas; large images of each are shown in Figs. D.5 and D.6, and in Section 3.3; Fig. D.8 is annotated. From left to right, the areas include (1) sliders, input boxes, and dropdown menus that allow users to vary model parameters and control the simulation (see Fig. D.5). In Fig. 3.7, all inputs are at default values (Table D.1) except ITCs is set to 30%. (2) In the center, a NetLogo World area shows circular cultivated areas, solar panel and wind turbine installations, and groundwater (GW) quantity and surface-water (SW) quality impacts, and a fraction of energy produced from solar and wind (see

Fig. D.8). (3) Eight output plots on the right show FEWCalc results evolving over time (see figures in Section 3.3).

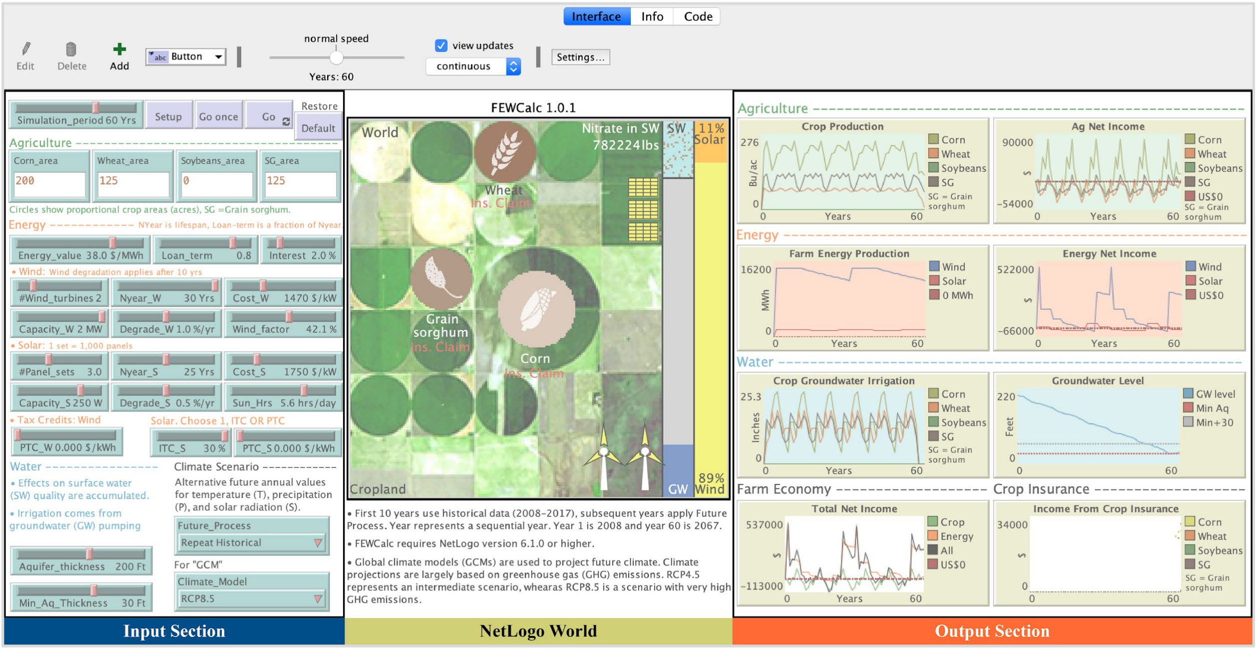

Fig. 3.7 NetLogo interface of FEWCalc upon completion of a run showing (from left to right) the input, World, and output sections.

In years that production conditions trigger an insurance claim, the text "Ins. Claim" appears next to the related crop in the World. The indemnity is shown in the lower right graph. The brown dots are used to represent nitrogen concentrations (see Section 3.2.5.3). Groundwater levels vary as irrigation is applied each year as described in Section 3.2.5.

FEWCalc is flexible enough to handle a wide range of inputs. However, all years use the same inputs unless changes are made over time. This can be accomplished by clicking the "Go once" button to increment time manually in FEWCalc – one click represents one year. For example, realistic adaptations to crop choices that lose money for a number of years are not automatically adjusted by the current version of FEWCalc, but could be changed annually.

Potential changes to renewable energy equipment costs and production degradation rates cannot be set up to change automatically, but could be changed when new equipment is installed.

In addition to the variables controlled by the user shown in Fig. 3.7, values related to crop insurance can be changed under the Code tab in the NetLogo interface after the declaration of global variables. See the Code button at the top middle of Fig. 3.7.

3.3 Results and Discussion

For the results presented here, the input values are those shown in Fig. 3.7, except that the future process is modified for Scenarios 2 through 4. The solar panels occupy about 5.2 ac (2.1 ha), and a similar area is occupied by the wind turbines (Denholm et al., 2009).

Results comparing DSSAT simulation with historical results are presented in Section 3.3.1. The four subsequent sections show results from the four climate scenarios listed in Table 3.2 and support an analysis of climate impacts on crop income in the context of potential farm energy capacity development. The scenarios do not include technological, crop management, or energy production changes that would be expected to occur. Thus, these results reflect the climate- and market-related pressures to which such changes would need to respond to maintain crop production and farm incomes. Finally, Section 3.3.6 focuses on financial results from all simulations.

3.3.1 Comparison with Historical Data

Crop production and irrigation water use simulated by DSSAT for 2008 to 2017 are compared to historical data in Fig. 3.8. Colors based on PDSI are used to identify dry and wet years. Fig. 3.8 suggests crop yields and water use are reasonably well represented using DSSAT, though in some years the differences are substantial (for example, non-irrigated grain sorghum yield in 2010). For non-irrigated corn, the simulated yield was unrealistically large during some wet years, and it was suspected that the plant population per acre was too high. Fig. 3.8(c.1) shows the effects of accounting for the plant population at seeding for corn under dryland farming. In this work, a plant population of 13,000 plants/ac (3 plants/m^2) was used. Overall, the DSSAT results are expected to be adequate for the analysis of renewable energy development and agricultural performance given potential future climate scenarios for which FEWCalc was developed.

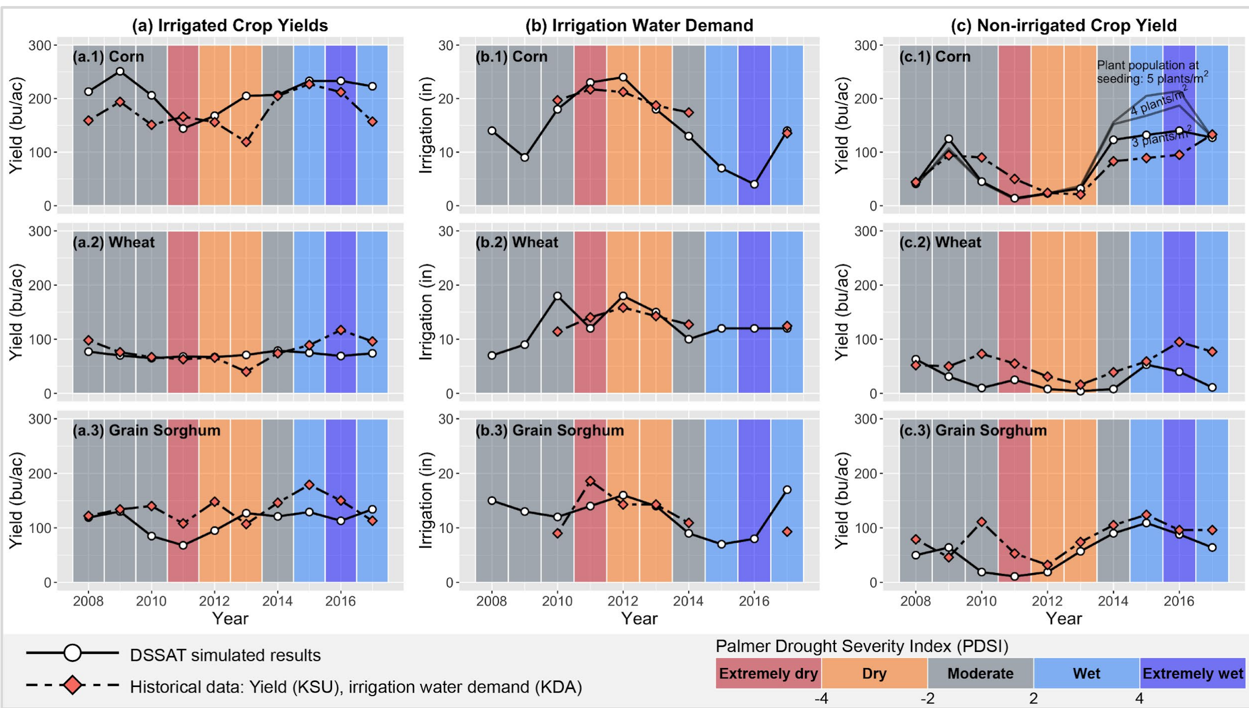

Fig. 3.8 Comparison of the DSSAT results (solid lines) and historical data (dashed lines) between 2008 and 2017 for corn, wheat, and grain sorghum. (a) Irrigated crop yields, (b) Irrigation water demand, (c) Non-irrigated crop yields. (Crop yield data from the Department of Agronomy, KSU, irrigation data from KDA, and simulated results are in Tables A.3, A.10, B.1, and B.2). Conversion factors: 1 bu/ac corn or grain sorghum = 62.77 kg/ha, 1 bu/ac wheat = 67.25 kg/ha, and 1 in = 2.54 cm. Moisture adjustments have been applied (see Table A.9).

3.3.2 Scenario 1: Repeat 10 Historical Years to Create the 60-year Simulation

Six ten-year long base periods of precipitation, temperature, and crop prices are repeated consecutively to create the 60-year FEWCalc simulation. The repetition allows analysis for a repeated known historical period; the duplication of results every 10 years indicates that FEWCalc progresses through time correctly. The only change is when groundwater is depleted toward the end of the simulation when dryland farming begins.

Energy solutions are the same for all scenarios and are presented with the Scenario 1 results. Income for wind is high in the first year of operation when tax policy allows 50% of capital costs to be depreciated. Solar income is high after the loan is paid.

Losses of crop yield occur during dry periods (Figs. 3.4 and 3.8). However, wheat yield remains stable for almost all simulation years. Wheat and grain sorghum are rarely profitable, and corn is the most profitable crop under the Repeat Historical scenario (Fig. 3.9).

Irrigation water use results in continuous groundwater level decline and dryland farming starting in 2065, 58 years into the simulation. Crop yields decline after switching from irrigated to dryland cultivation. However, average non-irrigated crop net returns are higher than irrigated net incomes because dryland farming expenses for all three crops are low enough to make up for lost crop sales. For corn and grain sorghum, the tendency of prices to increase globally when local yields decline could prove even more advantageous than indicated. During the dryland simulation, groundwater level rises from recharge as described in Section 3.2.5.2.

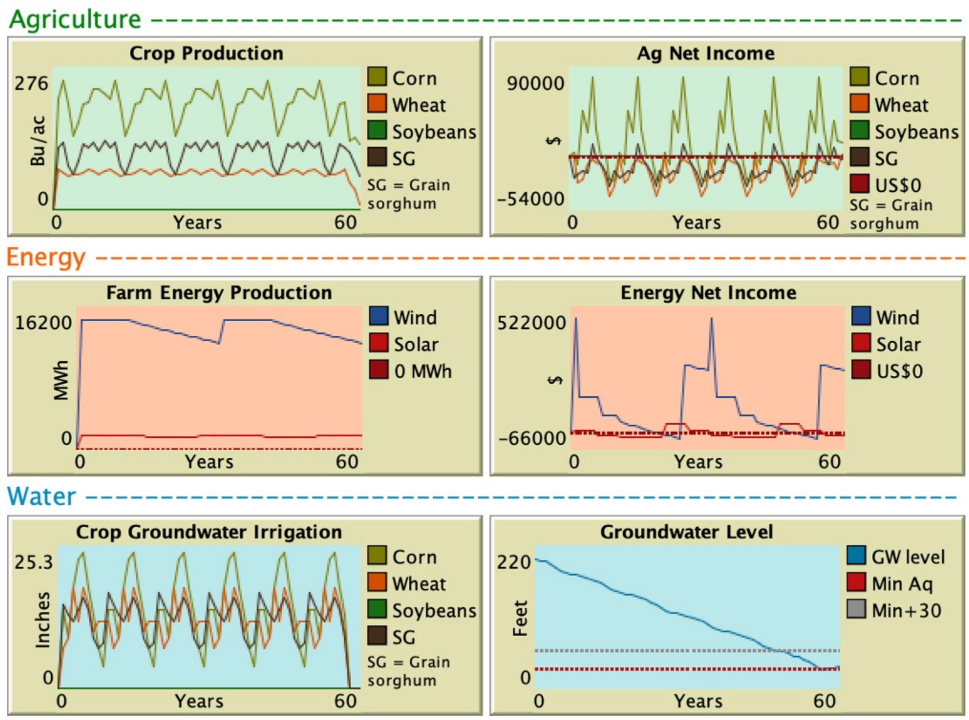

Fig. 3.9 FEWCalc annual results of Scenario 1 (Repeat Historical) showing agricultural crop production and net income, energy production and net income, and crop groundwater irrigation and groundwater level. FEWCalc simulated the 2008-2017 10-year base temperature, precipitation, and solar radiation data and repeated those conditions five times to produce results for years 11-60 (2018-2067). Dashed lines represent significant values for reference. Conversion factors: 1 bu/ac corn or grain sorghum = 62.77 kg/ha, 1 bu/ac wheat = 67.25 kg/ha, 1 in = 2.54 cm, and 1 ft = 0.3 m.

Installed solar capacity is initially set at about 9% of the total renewable energy. Higher capital costs and a shorter lifespan total cost of solar higher than wind. Wind and solar capacity slow degradation over time is evident in the energy production graph. Solar power makes money some years because of the simulated tax credit, depreciation, and loan pay off. Wind power production, on the other hand, is generally profitable because of a high wind capacity factor in the study area and the long capital lifespan can easily cover the installation costs.

3.3.3 Scenario 2: Wetter Future

For the 50 years following the base simulation, FEWCalc randomly chooses a greater percentage (70% instead of the original 30%) of wet years. Fig. 3.10 shows that crop production improves, and groundwater levels drop more slowly, though they continue to drop. FEWCalc maintains irrigation operations for the entire 60-year simulation.

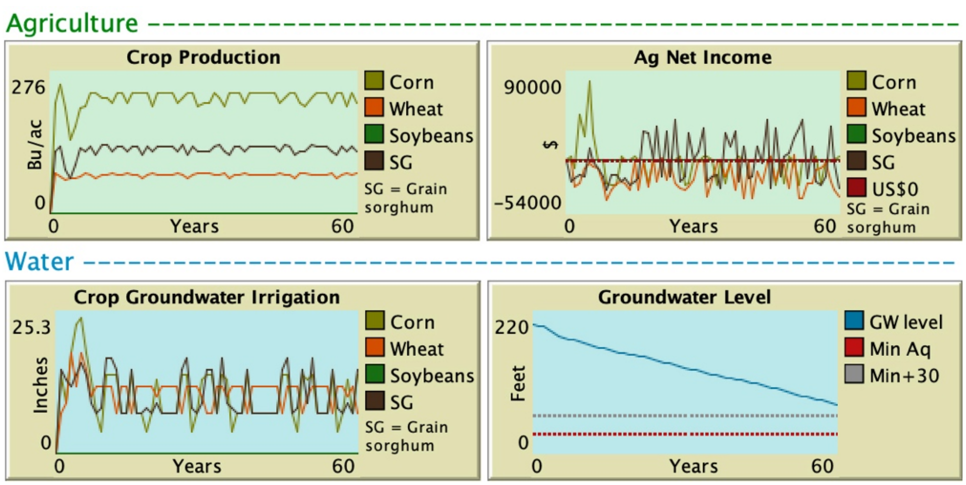

Fig. 3.10 As in Fig. 3.9, but for Scenario 2 (Wetter Future). Because the application of renewable energy remains unchanged, farm energy production and energy income results are the same as Fig. 3.9. FEWCalc simulates 2008 to 2017 10-year base simulation followed by a random 50-year sequence of wet years chosen from the 10-year base period. Conversion factors: 1 bu/ac corn or grain sorghum = 62.77 kg/ha, 1 bu/ac wheat = 67.25 kg/ha, 1 in = 2.54 cm, and 1 ft = 0.3 m.

3.3.4 Scenario 3: Drier Future

As compared to the wet scenario (Fig. 3.10), Fig. 3.11 shows that crop production simulated for a dry climate scenario drops in many simulation years. Under dry conditions, irrigated corn performed better than other crops, whereas wheat production is low and remains stable during irrigated periods. Corn net income is high because of high crop prices during dry years. The increased irrigation required in drier years accelerates the decline in groundwater levels, and FEWCalc resorts to dryland DSSAT simulations in year 46 (2053), which is 12 and ≥ 14 years ahead of Scenarios 1 and 2, respectively.

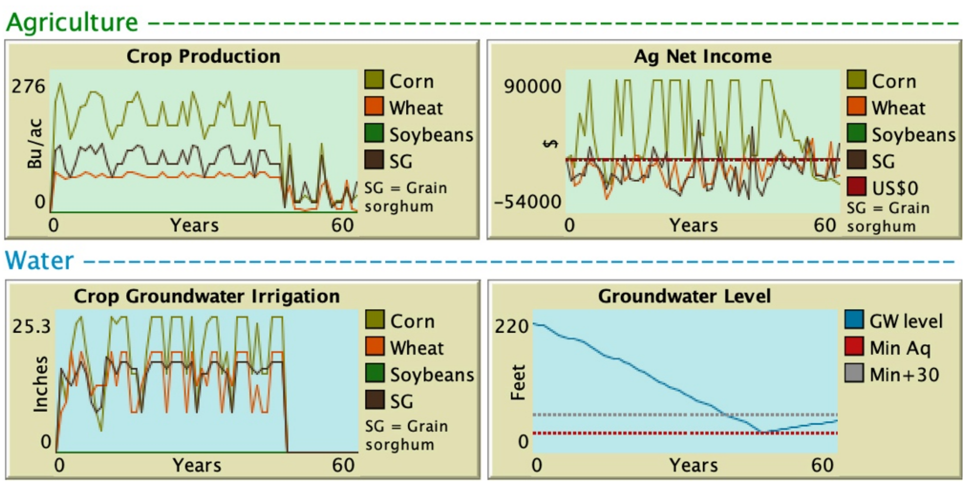

Fig. 3.11 As in Fig. 3.9, but for Scenario 3 (Drier Future). FEWCalc simulated the 10-year base simulation followed by a random 50-year sequence of dry years derived from the historical data from 2008 to 2017. Conversion factors: 1 bu/ac corn or grain sorghum = 62.77 kg/ha, 1 bu/ac wheat = 67.25 kg/ha, 1 in = 2.54 cm, and 1 ft = 0.3 m.

3.3.5 Scenario 4: RCP 8.5 Temperature, Precipitation, and Solar Radiation Changes to Create the 50-Year Future.

As depicted in Fig. 3.12, the results suggest that, overall, RCP 8.5 global climate change predictions would need to be met with effective technology changes to avoid negative crop production trends from year to year for the future period. Yet annual variability makes this trend difficult to discern in the beginning. Wheat and grain sorghum are rarely profitable. Irrigated corn's net income is projected to decrease over time and is considerably worse after simulation year 22 (2029); it improves during dryland simulation. Dryland farming is first applied in year 55 (2062), causing large crop production decline. These results show a large increase in net income for all three crops after shifting to dryland farming, however, the reduced yield would be problematic for the global food system.

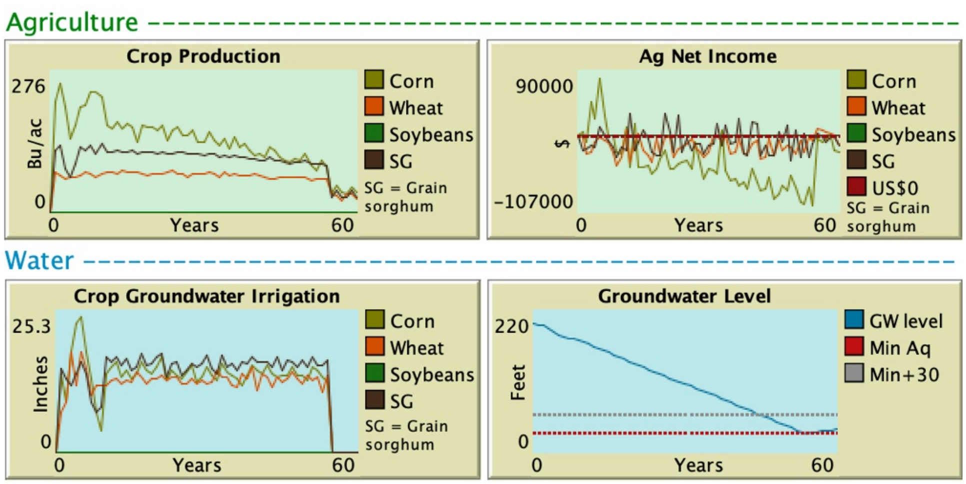

Fig. 3.12 As in Fig. 3.9, but for Scenario 4 (RCP 8.5 T, P, and S Changes). FEWCalc simulated the 10-year base simulation followed by a 50-year projection based on 20 downscaled global climate models from 2018 to 2098 under the RCP 8.5 climate scenario. Conversion factors: 1 bu/ac corn or grain sorghum = 62.77 kg/ha, 1 bu/ac wheat = 67.25 kg/ha, 1 in = 2.54 cm, and 1 ft = 0.3 m.

3.3.6 Scenario Summary

Total net farm income is shown in Fig. 3.13; income from crop insurance (the indemnity) is shown in Fig. 3.14. Metrics for the four runs are shown in Table 3.3. Time series shown for the four scenarios in Figs. 3.9 to 3.12 are also discussed in this section.

During the base period, farmers receive the same set of income for all scenarios. Income varies after that period depending on the scenario applied in the simulation (Fig. 3.13). Table 3.3 shows that dry scenario 3 yields an annual average agricultural sector profit of US$6,818, which is the only commercially successful scenario for agriculture based on the simulated crop prices and expenses. Because wind energy production is successful in western Kansas, total net income is mostly supported by the energy sector. All scenarios, in turn, have projected incomes that exceed anticipated costs, as indicated by a positive net present value for the total farm investment (NPV) (Table 3.3). For Scenario 3, farm income with energy sector profit is US$116,142, with an NPV of US$3.1M. Scenario 4, in contrast, produces the worst annual average annual total revenue of US$48,003, with an NPV of US$1.6M.

The times series in Figs. 3.9 to 3.12 show the variability in income. For example, in Scenarios 1 and 4, Figs. 3.9 and 3.12 show that corn, wheat, and grain sorghum lose less money with dryland farming than during the irrigation period because of decreased farm expenses and support from crop insurance. For Scenario 2, grain sorghum is the most profitable crop, but it loses money in some simulation years.

In FEWCalc, insurance claims (Fig. 3.14) start during any period of transition to dryland farming when the current yield drops below the actual production history. There are other common situations in which crop insurance is indemnified, such as hail storms and floods, but these are not represented in FEWCalc.

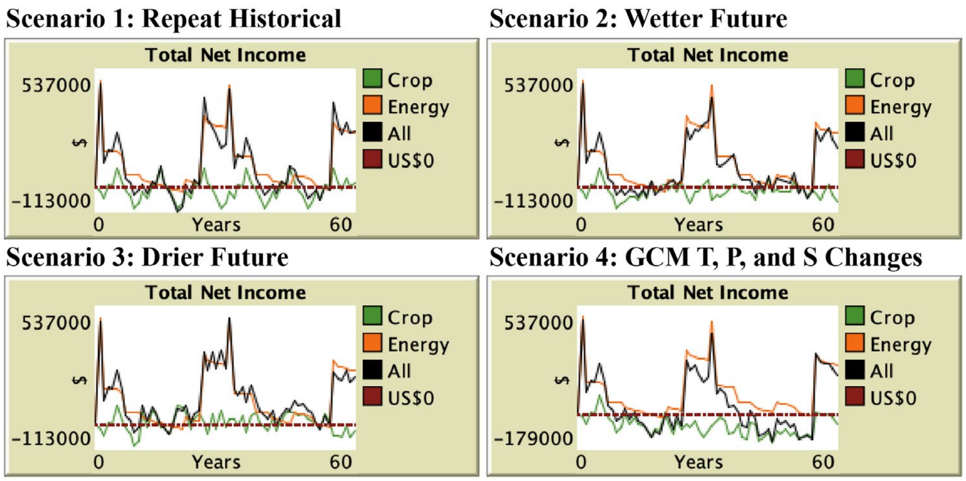

Fig. 3.13 Total net income.

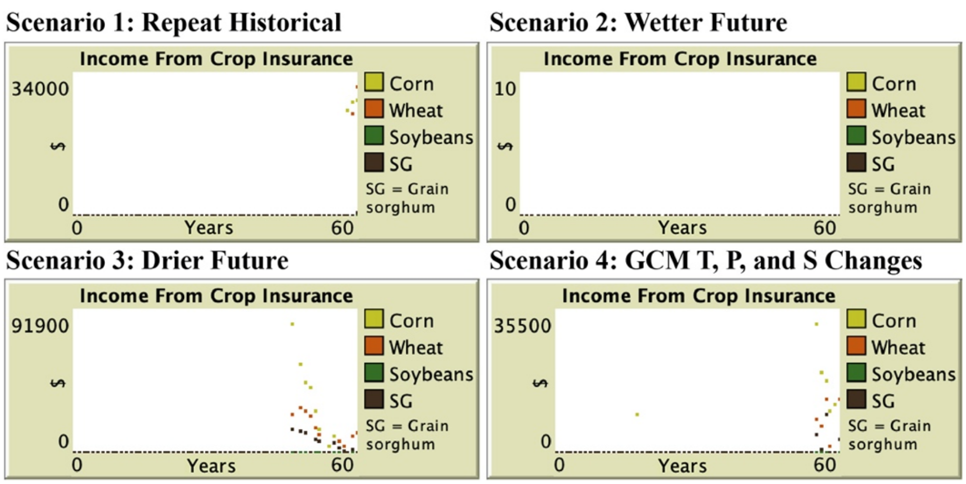

Fig. 3.14 Income from crop insurance.

Table 3.3 Metrics from the four scenarios for 60 years of FEWCalc simulation (2008-2067). All monetary amounts are in US dollars.

	Scenario 1 (Repeat Historical)			Scenario 2 (Wetter Future)			Scenario 3 (Drier Future)			Scenario 4[4] (GCMs, RCP 8.5)		
	C[1]	W[2]	SG[3]	C[1]	W[2]	SG[3]	C[1]	W[2]	SG[3]	C[1]	W[2]	SG[3]
Average annual crop yield, bushels/acre												
with irrigation	207	71	111	223	75	123	190	71	106	149 (39.8)	72 (4.7)	109 (12.1)
without irrigation	133	35	87	-	-	-	40	23	39	41 (6.3)	31 (5.2)	33 (5.9)
Insurance claims, number of years	3	2	1	0	0	0	8	10	9	7	5	4
Dryland farming starts, year	2065			-			2053			2062		
Dryland farming length, years	3			0			15			6		
Average annual net income, US dollars												
from agriculture	-US$14,197			-US$20,194			US$6,818			-US$61,321 (46,734)		
from energy	US$109,324			US$109,324			US$109,324			US$109,324 (122,970)		
total	US$95,127			US$89,130			US$116,142			US$48,003 (146,563)		
Net Present Value (NPV)[5]												
from agriculture	-US$0.4M			-US$0.5M			US$0.1M			-US$1.3M		
from energy	US$2.9M			US$2.9M			US$2.9M			US$2.9M		
total	US$2.5M			US$2.4M			US$3.1M			US$1.6M		

[1]Corn, [2]wheat, and [3]grain sorghum. [4]For Scenario 4, the standard deviation of the 20 GCM results are presented in parentheses. [5]Discount rate is 3.25% (prime rate as of June 2020); FEWCalc agriculture and energy finances are combined; for energy, capital costs are explicitly included for energy and depreciated over 10 years assuming a tax rate of 20%, for agriculture, capital costs are applied as listed in Table A.7.

Scenario 1, for which 2008-2017 weather continues into the future, results in a depleted aquifer and dryland farming. The wetter scenario 2 (typical of the 1990s) results in irrigation water lasting more than 60 years. The drier scenario 3 (typical of the 1950s) results in irrigation lasting only 45 years. The RCP 8.5 scenario 4 shows marked potential for decreased crop production: With elevated greenhouse gases and temperature conditions crop incomes are reduced. Renewable energy development is important to continued viability and, hopefully, would allow new approaches and technologies to buffer the impacts of climate change.

3.4 Conclusions

This work demonstrates the utility of FEWCalc using data from the semi-arid region in Garden City, Kansas. The conclusions from this work are presented as follows. (1) Demonstration site in Finney County, Kansas. (2) Wider consequences of FEWCalc and similar attempts to develop recognition of how complex natural-human systems function. (3) impact on identified gaps between the Integrated Assessment (IA) and Impacts, Adaptation, and Vulnerability (IAV) communities.

3.4.1 FEWCalc in the Context of the Finney County, Kansas Demonstration

FEWCalc results for Finney County, Kansas, illustrate the challenge of farming in this area. The main crops are subject to considerable price uncertainty and weather conditions can be harsh. Renewable wind energy development in this area was shown to potentially provide economic opportunities profitable enough to balance farming difficulties and enable the persistence of agricultural production in the region. In part, this is the consequence of the unusually useful wind resources available in this area.

FEWCalc results show that in this area, given current cost and electricity pricing, solar is only profitable with tax incentives and depreciation. In Kansas, the capital costs of solar energy (Fu et al., 2017) are challenging to recover given local solar radiance and electricity prices. As noted previously, an advantage of solar is that it is plentiful on hot summer days when wind velocities are low and electricity demand increases, largely due to increased use of air conditioning. In some cases, this makes solar a very useful addition to a given system despite the challenges of individual profitability. Solar is included in FEWCalc to provide this logistical advantage of solar energy and because tax incentives and even a slight reduction in the price of solar panels could make it a profitable alternative.

3.4.2 Wider Consequences of FEWCalc

FEWCalc illustrates how complicated and interacting systems, as they face new opportunities and challenges – in this case renewable energy, water scarcity, evolving technical innovations, can be assembled into a reasonably realistic, interesting to manipulate, and educational graphical interface. Agent-based modeling using the freeware NetLogo is relatively simple yet flexible enough to perform calculations related to energy, water, nitrate in soils and surface water, crop insurance, and so on, and integrate results from a separate program – in this case DSSAT for agricultural production, water demand, and fertilizer application. The FEWCalc calculations used for energy are expected to be widely applicable. The data-based approach taken for water is expected to be adaptable to other locations with sufficient data; otherwise, this work suggests that greater errors are likely if aquifer water-level response is calculated using estimates of specific yield from pumping wells, a point also noted by Butler et al. (2016) and Whittemore et al. (2016).

The crop production DSSAT model served well once combined with local agricultural expertise and comparison to historical data. The need to use a new irrigation capability designed for arid regions and the poor performance of soybeans in the region were only recognized and explained after comparison to historical data and discussions with local agricultural experts. Lack of these resources would have resulted in substantial errors.

Potential uses of the program not pursued in this work include identifying what thresholds (such as crop price, crop production, expenses, and so on) and public policies (such as tax incentives) are needed to produce profitable opportunities for landowners and agricultural communities. Also, adding technology advances and human decision-making characteristics such as avoidance of risk, maximizing profit, and evolution of policies and governmental institutions would improve the human interaction aspects of the simulation.

3.4.3 Impact on IA and IAV Gaps

The gaps between the IA and IAV communities that were summarized in Table 3.1 can be broadly categorized as gaps in the geographic and temporal scale, scenario and policy development, interdisciplinarity, and research perspective. FEWCalc addresses these gaps the following ways:

1) FEWCalc's interface (Fig. 3.7) shows the clear connection between current decisions and long-term, interdependent, and interdisciplinary consequences for both non-technical stakeholders and disciplinary specialists. This presentation of information can facilitate discussion across disciplinary boundaries and between scientists and non-technical stakeholders.
2) Metrics such as crop production, farm income, groundwater-level change, and nutrient loading of surface-water bodies, are broadly interesting to many stakeholder communities across a range of geographic scales and/or topical foci. These metrics can serve as a common point of reference for interdisciplinary discussions of their underlying discipline-specific drivers such as climate change, agricultural practices, and renewable energy policy. For example, Figs. 3.9 to 3.12, depicting the outcomes

under Scenarios 1 to 4, could serve as the basis for discussions among different stakeholder communities become an important focus of communication for topics as wide-ranging as irrigation practices, climate change impacts and adaptation strategies, renewable energy, and farm incomes.

3) Help stakeholders at all levels make better decisions, as follows.

   a) Studies of how local stakeholders use FEWCalc can help researchers gain insight into local values, which will give local stakeholders an implicit voice in scenario development and by implication the national- and global-scale public policy debates that are informed by integrated assessment, such as the Intergovernmental Panel on Climate Change (IPCC) assessment reports and the Paris Agreement.

   b) Inform local stakeholders, which could lead to better feedback and is the only way to achieve more buy-in and support for adaptive measures such as agricultural and energy tax credits and support of technological innovations in irrigation and wind turbine design. Here again, FEWCalc's outputs (Figs. 3.9 to 3.12) show the connection between global changes and local-stakeholder outcomes, while FEWCalc's intuitive interface (Fig. 3.7) allows local stakeholders to explore how their options (e.g. choices about irrigation, crop planting, and energy investment) and outcomes (e.g. farm income) are affected by climate conditions, and local and national public policy.

3.5 Summary

FEWCalc integrates information from the fields of agriculture, energy, water supply, water quality, climate change, and economics. It uses this information to enable users to explore consequences of interest to farming communities, including farm income, water supply and water quality, and potential opportunities provided by renewable energy development. It also provides a way for anyone interested in their food supply to understand the challenges and opportunities faced by farmers and farming communities.

The version of FEWCalc discussed in this work is constructed of freely available and open-source software that was chosen to facilitate future extensions of FEWCalc. In particular, the use of agent-based modeling (ABM) using NetLogo means that FEWCalc is well-positioned for expansion to simulate technology advances, behavioral and policy considerations, and the interplay between these important aspects of any natural-human system.

The input to DSSAT is region specific, but DSSAT is used globally and data from other regions can be expected to provide similar performance as long as some historical data is available for DSSAT model development. The arid-region extension to DSSAT used in this work can be turned off for areas where water is plentiful.

Programs like FEWCalc are well suited to address gaps present between current Integrated Assessment (IA) and Impacts, Adaptation, and Vulnerability (IAV) communities. Said another way, programs like FEWCalc enable users to envision both near-term impacts and long-term implications of choices made today. Thus, FEWCalc can be used by farmers considering the futures of their farms and communities, laypeople interested in how farms work, and policymakers as they consider potential consequences of regulatory and policy decisions.

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Chapter 4. Discussion and Conclusions

The advantages and limitations of the approach taken in this work are discussed, followed by a concise statement of study conclusions.

4.1 Discussion

This study aims to find a robust decision-support tool for local stakeholders. FEWCalc integrates all food, energy, and water systems, with interactive virtualization. The model, moreover, provides broad and straightforward aspects of economic activity in the farm-scale systems. Users can design and analyze their farms based on the resources they have.

Fig. 3.8 shows that DSSAT simulated yield and irrigation results for corn, wheat, and grain sorghum are relatively close to reported data from Kansas State University. However, in some years, there are minor differences in yield and water use. Since the accuracy of inputs used for calculation is essential, the inputs for DSSAT, such as soil data and farming practices, might be some sources of error for the simulation. The nearest available soil station obtained from the database is located in Haskell County, Kansas (30 miles south of Garden City, Kansas). As soils vary widely as a function of their position, it results in slightly different physical and chemical properties of soil. Changes in the composition of soil and its major nutrients would affect crop production at harvest. Soil moisture, likewise, could make a difference in water use for growing. Moreover, DSSAT is not able to simulate phosphorus and potassium at present. Therefore, simulated crop yields might be reasonably dissimilar to the actual yields.

DSSAT results simulated using downscaled global climate models show trends of crop yield and water use to the year 2098 with variability across the 20 models. The projected results used in FEWCalc averaged over 20 models. Since individual models were developed using different processes and provided with the different atmospheric resolution, they might result in a wide range of model outputs. Furthermore, the GCMs have been downscaled to a weather station as an observation point in Garden City, Kansas. The scale of spatial observation greatly affects the noise of the observations.

Available crops in the current version of FEWCalc are corn, wheat, soybeans, and grain sorghum. These crops are chosen because they are the top four most common crops grown in Kansas (KDA, 2019c). Due to the drought, pre-harvest pod shatter in soybeans has become common in arid or semi-arid regions like western Kansas. It occurs when dry pods are rehydrated under wet conditions (Ciampitti et al., 2018). Even though DSSAT can simulate soybean production and water use, this crop model does not take a pod-shattering problem into account. Soybean yield produced by DSSAT is much higher than the historical harvested yield reported by NASS as presented in Tables A.3, B.1, and B.2. Thus, soybeans are excluded from the FEWCalc demonstration runs to avoid making a substantial profit from soybeans.

FEWCalc is currently based on data from Garden City, Kansas, and policies under the United States laws. To model another area within the USA, a new DSSAT simulation using data from that area would be required (i.e., weather data, soil data, and crop practices). A basic understanding of the NetLogo programming code is vital for changing policies in areas outside the USA. FEWCalc coding provides an explanation in the source code that makes the code easy to understand.

4.2 Conclusions

Food, energy, and water are the most basic human needs. Each of them acts independently in reality, causing a complex non-linear relationship. The challenge is to explore the complex interaction since these three resources are highly dynamic, which would lead to unexpected consequences.

FEWCalc, coupled with a crop model DSSAT, is introduced for analyzing the dynamic interactions among food, energy, and water systems. A tool used for analysis is an agent-based model that is highly appropriate to simulate individuals' behavior within an environment. FEWCalc is an interactive model including detailed data for food production, wind and solar energy generation, and water calculation, as well as employing real-world policies such as crop insurance and tax credits.

A 50-year future process helps to indicate possible trends in crop production and water use in the future. The projections of Scenarios 1, 2, and 3 depend on base-period (2008-2017) climate data. These scenarios show how likely the future will occur when the model repeats years from the historical period and adds more wet or dry years. To explore climate variability, FEWCalc's Scenario 4 can perform the simulation using two distinct climate projections, including intermediate (RCP 4.5) and very high (RCP 8.5) greenhouse gas emission scenarios.

This work applies FEWCalc coupled with a crop model, DSSAT, to address research questions, as stated earlier, by the following.

1) Could local renewable energy resources provide opportunities to the farm system? Western Kansas, whose wind production factor is relatively high, has a potential for wind power

production. Thus, wind energy provides a crucial source of income, supplementing total farm income. Solar energy is also profitable when the tax incentive is applied. Even though solar energy capacity is not as beneficial as wind, solar energy generation is occasionally needed to maintain the farm's system when wind production is low.

2) What effect does climate change have on the farm economy in terms of water use and food production? Under future climate conditions, the temperature is projected to increase, and precipitation patterns will likely change over time. Crop production depends primarily on climate, and it tends to decrease with increasing air temperature. Moreover, irrigation water demand slightly increases by the end of the 21st century due to changes in precipitation patterns. Irrigated areas where irrigation primarily relies on groundwater will run out of the water quickly. A transition from irrigated to dryland agriculture causes a substantial loss of yield.

3) How do agricultural production and farm income respond to groundwater shortage? Groundwater resource is crucial for irrigation. However, it has become a critical resource due to excessive pumping for more than 50 years. Some USA states have proposed an irrigation water restriction or water conservation plan to solve groundwater decline problems. FEWCalc also allows the user to define a minimum aquifer thickness for pumping and applies dryland farming when irrigation from groundwater is insupportable. As mentioned in the previous question, crop yields decrease considerably without irrigation. Although crop yield from dryland cultivation is not as good as irrigated farming, farm income from dryland agriculture is higher because the production costs of dryland farming are much lower.

4) How and how much does nitrogen fertilizer in agricultural areas impact the environmental quality of surface water? Nitrogen fertilizer is an essential nutrient for plant

development. In this work, nitrogen particles accumulate year by year in the soil when weather conditions are dry to moderate. They are moved to surface water bodies during wet years and support the growth of algae and other aquatic organisms. The FEWCalc results show that, under the wetter future conditions, a large amount of nitrogen has presented in the surface water (rust-colored dots in the interface).

4.3 Future work

A possibility for future work would continue to provide the flexibility of FEWCalc. The current model could not include a process of switching from irrigated to dryland farming when losing money from crop production. This mechanism should help stakeholders to make a good profit since irrigated cultivation requires more money for operations. Technological improvements would also be taken into account. Crop production and water use are projected to the end of the 21st century without considering advancements in agricultural technologies. Moreover, ammonia would become another significant contributor to the generation of farm energy in FEWCalc to provide more alternative power sources for users.

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Appendix A. Data Used in this Work

Appendix A presents sources of data in Table A.1, historical data in Tables A.2 to A.13, comments on the groundwater use/water-level change relation of Fig. 3.6 in Tables A.10 and A.11, and climate model results in Fig. A.2.

Data Sources

Table A.1 Sources of data used in the article.

Host Organization	Short Name	Description	Spatial Resolution	Temporal Resolution
Agriculture and Land Use				
[1]United States Department of Agriculture	USDA	Historical crop prices	County	Annual
		Historical production	County	Annual
[2]Kansas State University, Department of Agricultural Economics	KSU	History production, Farm expenses	State's region	Annual
[3]The International Soil Reference and Information Centre	ISRIC	Soil data	Soil station	N/A
Energy				
[4]National Renewable Energy Laboratory	NREL	Solar Radiation	16 km^2	Every 30 minutes
Water				
[5]Kansas Geological Survey	KGS	Historical groundwater use	County	Annual
[6]Kansas Department of Agriculture	KDA	Historical applied irrigation	County	Annual
Weather				
[7]National Center for Environmental Information	NCEI	Temperature, precipitation	Weather station	Daily
[8]National Climatic Data Center	NCDC	PDSI data	State's region	Daily
[9]University of Idaho, Climatology Lab	UIdaho	Downscaled global climate models dataset	2.5 arc minutes	Daily

[1]NASS (2019). [2]Ibendahl et al. (2020). [3]ISRIC (2016). [4]NREL (2020). [5]KGS (2019). [6]KDA (2020). [7]NCEI (2020). [8]NCDC (2020). [9]Climatology Lab (2020).

Agriculture

Historic Crop Price and Production Data in Kansas

Table A.2 Historical crop price and production in Kansas (used in Fig. 3.5).

	Historical production, million bushels				Historical crop price, US dollars per bushel			
	Corn	Wheat	Soybeans	Grain sorghum	Corn	Wheat	Soybeans	Grain sorghum
1866	6.08	1.29						
1867	10.01	1.11						
1868	6.80	1.44						
1869	17.13	2.42						
1870	15.96	2.42						
1871	31.39	2.70						
1872	41.76	2.14						
1873	32.22	4.34						
1874	18.27	9.66						
1875	76.11	12.50						
1876	73.68	14.50						
1877	99.48	13.78						
1878	78.23	27.28						
1879	105.62	17.31						
1880	109.92	23.40						
1881	75.60	20.71						
1882	156.18	32.00						
1883	187.21	21.35						
1884	183.52	39.42						
1885	177.32	14.39						
1886	138.62	15.18						
1887	82.16	11.78						
1888	200.50	16.35						
1889	259.82	30.39						
1890	39.97	32.40						
1891	142.73	58.56						
1892	141.88	63.72						
1893	137.41	31.41						
1894	39.34	40.53						
1895	205.80	19.12						
1896	224.22	45.39						
1897	159.75	51.85						
1898	138.99	68.70						
1899	229.80	38.80						
1900	141.97	78.08						
1901	54.69	89.42						
1902	214.20	47.30						
1903	174.38	92.43						
1904	140.85	63.75						
1905	197.18	78.12						
1906	197.75	84.25						
1907	155.91	75.68						
1908	162.49	84.63			0.55			
1909	154.88	77.45			0.59			
1910	170.05	60.48			0.48			

	Historical production, million bushels				Historical crop price, US dollars per bushel			
	Corn	**Wheat**	**Soybeans**	**Grain sorghum**	**Corn**	**Wheat**	**Soybeans**	**Grain sorghum**
1911	118.28	56.80			0.67			
1912	174.23	93.70			0.53			
1913	21.96	86.79			0.76			
1914	108.23	172.75			0.69			
1915	172.05	106.48			0.63			
1916	69.50	97.98			1.09			
1917	119.03	42.79			1.51			
1918	42.91	97.71			1.59			
1919	56.98	153.31			1.49			
1920	120.70	144.93			0.47			
1921	90.93	133.96			0.43			
1922	84.76	124.81			0.68			
1923	115.51	83.80			0.72			
1924	119.22	157.02	0.02		0.96		2.32	
1925	103.73	80.54	0.04		0.67		2.52	
1926	54.73	153.99	0.04		0.75		2.19	
1927	154.87	114.22	0.04		0.72		1.98	
1928	157.58	173.19	0.04		0.74		1.94	
1929	101.68	155.56	0.04	11.20	0.73		2.12	
1930	67.49	186.28	0.05	7.98	0.52		1.66	
1931	99.27	251.89	0.11	14.67	0.28		0.67	
1932	120.02	120.18	0.08	13.49	0.27		0.77	
1933	66.58	66.93	0.09	12.33	0.44		1.14	
1934	0.89	84.32	0.04	0.56	0.97		1.39	
1935	22.89	64.06	0.05	4.38	0.73		1.10	
1936	2.98	120.23	0.02	0.93	1.19		1.57	
1937	22.35	158.05	0.03	11.03	0.56		0.96	
1938	40.82	152.16	0.06	13.06	0.50		0.99	
1939	31.84	114.86	0.09	8.12	0.58		1.05	
1940	34.28	126.55	0.31	24.13	0.58		0.96	
1941	53.22	173.33	0.54	21.89	0.73		1.58	
1942	79.35	200.10	2.44	19.59	0.91		1.59	
1943	68.70	144.24	2.32	16.83	1.10		1.80	
1944	93.07	187.70	2.53	49.26	1.02		2.03	
1945	64.79	207.94	2.35	17.70	1.23		2.06	
1946	54.32	212.98	2.18	11.49	1.54		2.53	
1947	35.75	286.70	1.96	10.93	2.21		3.18	
1948	74.13	231.37	2.64	28.79	1.29		2.26	
1949	64.15	157.07	3.73	29.93	1.19	1.89	2.07	1.18
1950	85.47	178.06	7.15	44.69	1.43	2.02	2.33	1.07
1951	52.49	126.11	5.81	57.31	1.73	2.13	2.66	1.32
1952	44.69	307.63	7.36	18.54	1.53	2.14	2.65	1.45
1953	39.03	144.66	3.39	32.14	1.48	2.11	2.45	1.27
1954	32.38	176.21	2.04	51.72	1.48	2.18	2.44	1.25
1955	24.94	128.39	3.35	33.25	1.39	2.06	2.11	1.01
1956	22.53	143.28	3.02	24.39	1.35	2.00	2.06	1.22
1957	36.18	100.11	2.46	127.49	1.13	1.96	1.97	0.97
1958	65.98	297.34	9.26	131.24	1.05	1.78	1.86	0.98
1959	72.66	211.74	9.11	137.80	1.02	1.78	1.83	0.77
1960	78.49	294.38	12.60	167.54	0.99	1.74	1.98	0.78

	Historical production, million bushels				Historical crop price, US dollars per bushel			
	Corn	Wheat	Soybeans	Grain sorghum	Corn	Wheat	Soybeans	Grain sorghum
1961	58.80	273.72	15.11	111.68	1.09	1.79	2.17	0.96
1962	66.20	211.17	16.00	128.76	1.10	2.06	2.17	0.96
1963	62.10	185.48	11.93	147.77	1.12	1.86	2.45	0.92
1964	46.80	208.78	11.56	98.51	1.19	1.37	2.51	1.04
1965	61.95	236.39	18.33	139.43	1.17	1.35	2.39	0.97
1966	59.68	200.07	20.63	139.60	1.28	1.64	2.70	1.03
1967	72.08	221.62	18.56	149.41	1.06	1.35	2.42	0.94
1968	88.45	253.53	23.93	163.33	1.06	1.22	2.30	0.91
1969	95.43	305.32	19.60	182.90	1.13	1.19	2.22	0.99
1970	82.24	299.01	13.95	145.96	1.31	1.25	2.74	1.12
1971	124.55	312.61	17.86	233.55	1.12	1.32	2.99	0.95
1972	130.00	314.90	24.50	217.00	1.52	1.68	4.10	1.39
1973	154.00	384.80	26.40	218.40	2.46	3.75	5.67	2.13
1974	131.93	319.00	19.80	132.80	3.01	3.86	6.34	2.69
1975	141.04	350.90	22.68	147.00	2.50	3.42	4.77	2.27
1976	171.84	339.00	12.98	165.00	2.12	2.59	6.52	1.86
1977	161.28	344.85	28.22	235.60	1.99	2.24	5.50	1.74
1978	153.00	300.00	26.82	196.86	2.35	2.89	6.64	1.99
1979	171.99	410.40	41.34	246.33	2.51	3.76	5.97	2.20
1980	110.92	420.00	23.93	149.64	3.32	3.85	7.58	2.92
1981	148.05	302.50	45.30	238.52	2.58	3.77	5.83	2.19
1982	139.08	458.50	46.28	207.70	2.71	3.41	5.58	2.42
1983	85.56	448.20	24.32	121.69	3.25	3.40	7.79	2.71
1984	119.38	431.20	27.83	216.75	2.77	3.32	5.78	2.24
1985	152.10	433.20	43.71	296.70	2.37	2.86	4.95	1.92
1986	181.56	336.60	58.29	311.25	1.60	2.25	4.60	1.33
1987	147.60	366.30	67.52	273.75	1.84	2.43	5.49	1.58
1988	143.75	323.00	46.00	204.60	2.60	3.58	7.26	2.21
1989	155.00	213.60	49.95	198.75	2.28	3.74	5.45	2.00
1990	188.50	472.00	46.80	184.80	2.25	2.51	5.67	2.00
1991	206.25	363.00	43.70	176.40	2.42	2.81	5.55	2.23
1992	259.50	363.80	68.45	244.00	2.15	3.13	5.42	1.80
1993	216.00	388.50	53.20	176.40	2.61	3.00	6.41	2.31
1994	300.30	433.20	73.50	231.00	2.32	3.32	5.32	2.00
1995	244.28	286.00	51.25	173.60	3.24	4.59	6.69	3.10
1996	357.20	255.20	74.00	354.20	2.83	4.63	7.17	2.28
1997	371.80	501.40	86.95	265.20	2.47	3.16	6.42	2.13
1998	418.95	494.90	75.00	264.00	1.96	2.53	4.98	1.60
1999	420.18	432.40	81.20	258.40	1.81	2.25	4.53	1.48
2000	412.10	347.80	50.00	188.80	2.00	2.65	4.50	1.79
2001	387.35	328.00	87.36	232.50	2.03	2.69	4.16	1.81
2002	301.60	270.60	58.42	135.00	2.48	3.41	5.49	2.37
2003	300.00	480.00	57.04	130.50	2.51	3.15	7.68	2.36
2004	432.00	314.50	111.11	220.40	2.12	3.25	5.39	1.65
2005	465.75	380.00	105.45	195.00	2.07	3.31	5.45	1.70
2006	345.00	291.20	98.56	145.00	3.08	4.56	6.37	3.37
2007	507.84	283.80	86.13	209.35	4.13	5.93	10.10	4.05
2008	482.79	360.00	120.25	218.40	4.12	6.94	9.39	3.14
2009	598.30	375.90	162.43	224.40	3.49	4.79	9.38	3.06
2010	576.60	360.00	140.25	171.00	4.95	5.14	11.50	5.04

	Historical production, million bushels				Historical crop price, US dollars per bushel			
	Corn	Wheat	Soybeans	Grain sorghum	Corn	Wheat	Soybeans	Grain sorghum
2011	449.40	278.25	103.40	108.00	6.28	7.03	12.10	5.99
2012	375.25	382.20	87.86	81.90	7.04	7.48	14.30	6.72
2013	504.00	321.10	130.98	168.15	4.49	6.99	12.80	4.18
2014	566.20	246.40	140.58	199.80	3.78	6.07	9.63	3.98
2015	580.16	321.90	148.61	281.60	3.69	4.74	8.56	3.12
2016	698.64	467.40	192.48	268.45	3.20	3.20	9.26	2.62
2017	686.40	333.60	191.63	200.90	3.28	4.07	9.00	3.12
2018	642.42	277.40	201.67	233.20	3.58	4.93	7.93	3.13
2019	800.66	338.00	186.34	204.00				

The Quick Stats Database published by USDA's NASS (2019). Conversion factors: 1-bushel corn or grain sorghum is 56 lb or 25.4 kg, 1-bushel wheat or soybeans is 60 lb or 27.2 kg

Historic Crop Yield Data for Finney County, Kansas

Table A.3 Historical crop yield for irrigated and non-irrigated farming in Finney County and nearby counties obtained from two data sources (a) USDA's NASS (NASS, 2019) and (b) KSU (KSU, 2019) during the simulation period, 2008-2017 (used in Fig. 3.8).

(a)	Irrigated crop yield, bushels per acre				Non-irrigated crop yield, bushels per acre			
	Corn	Wheat	Soybeans	Grain sorghum	Corn	Wheat	Soybeans	Grain sorghum
2008	170.0 (Saline)	50.5 (Finney)	34.5 (Edwards)			38.5 (Finney)		
2009	212.0 (Finney)	57.0 (Finney)	61.5 (Edwards)	127.0 (Meade)	94.0 (Finney)	48.0 (Finney)	29.0 (Edwards)	71.0 (Meade)
2010	198.9 (Finney)	54.3 (Gray)			50.1 (Finney)	51.5 (Gray)		
2011	178.9 (Scott)	52.7 (Grant)			32.7 (Hamilton)	24.3 (Gray)		
2012	196.6 (Haskell)	55.4 (Finney)			36.9 (Haskell)	18.4 (Finney)		
2013	158.3 (Wichita)	37.4 (Finney)			44.3 (Stanton)	17.8 (Finney)		
2014	178.9 (Scott)	26.7 (Gray)	51.7 (Reno)		34.5 (Hamilton)	16.7 (Gray)		
2015	194.7 (Hodgeman)	46.6 (Gray)	59.6 (Harvey)		91.5 (Hodgeman)	17.1 (Grant)		
2016	200.5 (Gray)	54.2 (Gray)	59.3 (Seward)		105.9 (Gray)	74.3 (Gray)	32.6 (Pawnee)	
2017	213.4 (Haskell)	59.4 (Gray)			94.3 (Haskell)	38.6 (Seward)		

(b)	Irrigated crop yield, bushels per acre				Non-irrigated crop yield, bushels per acre			
	Corn	Wheat	Soybeans	Grain sorghum	Corn	Wheat	Soybeans	Grain sorghum
2008	159.4 (Finney)	97.5 (Thomas)	26.7 (Finney)	122.2 (Finney)	43.8 (Finney)	51.6 (Ford)		78.6 (Finney)
2009	194.4 (Finney)	76.0 (Thomas)	42.1 (Finney)	134.4 (Finney)	94.2 (Finney)	50.5 (Finney)		46.5 (Finney)
2010	150.7 (Finney)	66.6 (Finney)	43.2 (Finney)	140.0 (Finney)	90.5 (Finney)	73.2 (Finney)		111.1 (Finney)
2011	165.9 (Finney)	62.7 (Finney)	22.4 (Finney)	108.5 (Finney)	49.9 (Thomas)	55.1 (Ford)		53.1 (Thomas)
2012	156.3 (Finney)	66.3 (Finney)	39.2 (Finney)	147.9 (Finney)	23.7 (Finney)	30.7 (Ford)		31.7 (Finney)
2013	119.1 (Finney)	40.2 (Finney)	28.9 (Finney)	106.8 (Finney)	20.5 (Finney)	16.2 (Finney)		73.6 (Finney)
2014	205.2 (Finney)	73.7 (Finney)	66.2 (Thomas)	145.8 (Finney)	82.8 (Ellis)	39.5 (Pawnee)		105.3 (Thomas)
2015	227.4 (Finney)	89.2 (Finney)	59.7 (Finney)	178.6 (Finney)	89.4 (Finney)	59.0 (Ford)		124.3 (Finney)
2016	211.9 (Thomas)	116.5 (Finney)	75.0 (Thomas)	150.4 (Thomas)	95.0 (Thomas)	94.5 (Pawnee)		96.3 (Finney)
2017	156.9 (Finney)	95.8 (Finney)	75.8 (Thomas)	113.2 (Finney)	132.7 (Finney)	77.2 (Pawnee)		95.9 (Finney)

Conversion factors: 1 bu/ac is 62.77 kg/ha for corn or grain sorghum and 67.25 kg/ha wheat or soybeans.

Crop Financial Values Used in FEWCalc

The financial values used in FEWCalc are listed in Tables A.4 and A.5, and are from farm management guides produced by Kansas State University's Department of Agricultural Economics (Ibendahl et al., 2020). More detailed lists of expenses included are provided in Table A.6. Crop insurance expenses are listed in Table A.7.

Table A.4 Crop summary budgets for irrigated crops, per acre.

		Corn	Wheat	Soybeans	Grain sorghum
Low yield	Yield (bu/ac)	< 210	< 62.5	< 58	< 150
	Income	US$780.00	US$243.79	US$453.78	US$472.85
	Expenses	US$786.23	US$498.13	US$542.07	US$618.55
	Return	US$-6.23	US$-254.34	US$-88.30	US$-145.70
Moderate yield	Yield (bu/ac)	210-237.5	62.5-67.5	58-64	150-170
	Income	US$900.00	US$264.10	US$503.28	US$540.40
	Expenses	US$861.41	US$523.43	US$572.48	US$666.17
	Return	US$38.59	US$-259.33	US$-69.20	US$-125.77
High yield	Yield (bu/ac)	> 237.5	> 67.5	> 64	> 170
	Income	US$1000.00	US$284.42	US$552.78	US$607.95
	Expenses	US$920.04	US$548.74	US$620.95	US$713.79
	Return	US$79.96	US$-264.32	US$-68.17	US$-105.84

Conversion factors: 1 bu/ac is 62.77 kg/ha for corn/grain sorghum and 67.25 kg/ha for wheat/soybeans.

Table A.5 Crop summary budgets for non-irrigated crops, per acre.

		Corn	Wheat	Soybeans	Grain sorghum
Low yield	Yield (bu/ac)	< 66	< 37.5	< 22.5	< 68
	Income	US$200.00	US$133.67	US$166.46	US$190.16
	Expenses	US$273.10	US$245.47	US$224.51	US$263.01
	Return	US$-73.10	US$-111.80	US$-58.06	US$-72.85
Moderate yield	Yield (bu/ac)	66-91	37.5-46.5	22.5-27.5	68-93
	Income	US$328.00	US$170.13	US$208.07	US$280.06
	Expenses	US$337.57	US$277.41	US$248.50	US$314.41
	Return	US$-9.57	US$-107.28	US$-40.43	US$-34.35
High yield	Yield (bu/ac)	> 91	> 46.5	> 27.5	> 93
	Income	US$400.00	US$206.58	US$249.68	US$363.04
	Expenses	US$377.54	US$309.35	US$272.48	US$361.86
	Return	US$22.46	US$-102.77	US$22.80	US$1.18

Conversion factors: 1 bu/ac is 62.77 kg/ha for corn/grain sorghum and 67.25 kg/ha for wheat/soybeans.

Table A.6 Crop expenses per acre for irrigated crops (with center pivot irrigation systems) and non-irrigated crops (Ibendahl et al., 2020).

	Irrigated				**Non-irrigated**			
	Corn[1]	**Wheat[2]**	**Soybeans[2]**	**Grain sorghum[2]**	**Corn[1]**	**Wheat[1]**	**Soybeans[1]**	**Grain sorghum[1]**
Income								
Yield (bushels/acre)	225	65	61	160	82	42	25	81
Price (US$/bushel)	4.00	4.06	8.25	3.38	4.00	4.05	8.32	3.46
Total income (US$/acre)	900.00	264.10	503.28	540.40	328.00	170.13	208.07	280.06
Farming expenses (US$/acre)								
Seed	119.43	22.28	50.49	12.98	41.98	16.09	40.39	7.31
Fertilizer less lime[3]	105.16	49.07	19.78	75.63	36.90	23.90	8.30	37.51
Herbicides								
• Burn down	8.46	0.00	3.21	8.46	20.52	12.87	10.26	20.52
• Pre-emergence	46.96	6.40	28.76	39.83	42.54	1.99	32.25	39.83
• Post-emergence	1.61	0.00	3.21	0.00	4.53	0.00	3.21	3.64
Fungicides	6.28	7.85	0.00	0.00	0.00	3.85	0.00	0.00
Insecticides	16.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Crop consulting	6.50	6.00	6.25	6.25	0.00	0.00	0.00	0.00
Custom field operations								
• Planting	18.21	17.33	18.69	18.57	18.59	14.73	18.69	18.00
• Fertilizer application	0.00	5.60	0.00	0.00	5.60	15.98	0.00	5.60
• Tillage	17.55	0.00	13.12	17.55	0.00	22.50	0.00	0.00
• Spraying	22.38	11.79	17.63	11.76	20.57	20.59	17.63	19.10
• Base harvesting	29.30	24.19	29.78	25.92	29.30	24.19	29.78	25.92
• Extra harvest charge	36.68	10.67	8.63	27.70	1.48	5.09	0.00	8.67
• Hauling	42.47	15.09	14.61	37.41	15.48	9.75	5.99	18.94
• Drying and other	10.13	0.00	0.00	9.60	0.00	0.00	0.00	0.00
Crop insurance	20.31	23.70	21.84	31.46	8.36	12.94	7.87	18.33

	Irrigated				Non-irrigated			
	Corn[1]	Wheat[2]	Soybeans[2]	Grain sorghum[2]	Corn[1]	Wheat[1]	Soybeans[1]	Grain sorghum[1]
Labor (beyond custom field operations above)	27.60	22.80	24.60	25.20	22.50	7.50	7.50	22.50
Miscellaneous	10.00	10.00	10.00	10.00	5.50	5.50	5.50	5.50
Interest on variable expenses[4]	17.93	7.76	9.19	11.92	8.22	5.92	5.62	7.54
Irrigation expenses (US$/acre)								
Natural gas	46.79	23.39	32.17	35.09				
Repair and maintenance	5.28	2.64	3.63	3.96				
Depreciation	76.67	76.67	76.67	76.67				
Interest on equipment	59.22	59.22	59.22	59.22				
Cash rent (US$/acre)	110.00	121.00	121.00	121.00	55.50	74.00	55.50	55.50
Total costs (US$/acre)	861.41	523.43	572.48	666.17	337.57	277.41	248.50	314.41
Return over total costs (US$/acre)	38.59	-259.33	-69.20	-125.77	-9.57	-107.28	-40.43	-34.35

[1]Data were obtained from southwest Kansas. [2]Data were obtained from western Kansas. [3]Expenses for fertilizer based on actual pounds as follows: Irrigated corn 182N, 80P; irrigated wheat 90N, 31P; irrigated soybeans 10N, 45P; 127N, 62; irrigated grain sorghum 127N, 62P; non-irrigated corn 63N, 29P; non-irrigated wheat 56N, 20P; non-irrigated soybeans 4N, 19P; and non-irrigated grain sorghum 62N, 32P. [4]In general, the variable expenses require a commitment of funds for six months (i.e., planting to harvest), thus the interest for these costs is half a year.

Table A.7 Crop insurance expenses per acre in southwest Kansas in 2020, and yields for three planning environments from Ibendahl et al. (2020).

Planning	Corn		Wheat		Soybeans		Grain sorghum	
Environment	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland
Low[1]	US$17.60	US$5.10	US$21.87	US$10.17	US$19.69	US$6.29	US$27.53	US$12.44
Typical[2]	US$20.31	US$8.36	US$23.70	US$12.94	US$21.84	US$7.87	US$31.46	US$18.33
High[3]	US$22.57	US$10.20	US$25.52	US$15.72	US$23.99	US$9.44	US$35.39	US$23.76

[1]**Low yield** for irrigated (dryland in parentheses) corn = 195(50) bushels (bu), wheat = 60(33) bu, soybeans = 55(20) bu, and grain sorghum = 140(55) bu. [2]**Typical yield** for irrigated (dryland in parentheses) corn = 225(82) bu, wheat = 65(42) bu, soybeans = 61(25) bu, and grain sorghum = 160(81) bu. [3]**High yield** for irrigated (dryland in parentheses) corn = 250(100) bu, wheat = 70(51) bu, soybeans = 67(30) bu, and grain sorghum = 180(105) bu. Conversion factors: 1-bushel corn or grain sorghum is 56 lb or 25.4 kg, 1-bushel wheat or soybeans is 60 lb or 27.2 kg.

Soil Profiles

Table A.8 WISE soil database collected from a soil station in Haskell County (about 30 mi [48 km] south of Garden City, Kansas) used for DSSAT simulation.

Depth, cm	Master horizon	Lower limit, cm^3/cm^3	Upper limit, drained, cm^3/cm^3	Upper limit, saturated, cm^3/cm^3	Root growth factor, soil only, 0-1	Sat. hydraulic conductivity, cm/h
13	Ap	0.114	0.277	0.52	1	2.98
36	Bt	0.203	0.333	0.506	0.61	1.01
46	Btk	0.202	0.338	0.485	0.44	0.72
66	Bck	0.202	0.339	0.469	0.33	0.57
91	Bk1	0.239	0.357	0.473	0.21	0.49
157	Bk2	0.111	0.234	0.48	0.08	4.22
191	Bk3	0.257	0.359	0.491	0.03	0.6
229	C1	0.248	0.352	0.496	0.01	0.73
262	C2	0.162	0.298	0.479	0.01	1.5

Depth, cm	Bulk density, moist, g/cm^3	Organic carbon, %	Clay, %	Silt, %	Total nitrogen, %	pH in water
13	1.18	1.05	24	53	0.1	7.3
36	1.25	0.75	35	48	0.08	7.5
46	1.31	0.53	36	52	0.05	8.1
66	1.36	0.42	34	57	0.04	8.2
91	1.32	0.33	27	61	0.03	8.3
157	1.3	0.32	24	63	0.03	8.4
191	1.28	0.25	26	59	0.03	8.4
229	1.26	0.24	27	52	0.02	8.3
262	1.31	0.23	27	47	0.02	8.1

Crop Moisture Content Used to Relate DSSAT and Historical Production

Table A.9 Average crop moisture content used to relate DSSAT-calculated and historical crop production results. Crop moisture values are used to convert DSSAT future projections to plotted values of crop production.

	Moisture content for irrigated crop, %[1]				Moisture content for non-irrigated crop, %[1]			
	Corn	Wheat	Soybeans	Grain sorghum	Corn	Wheat	Soybeans	Grain sorghum
2008	17.0	9.4		12.8	11.7	10.2		14.7
2009	18.9	12.2		13.2	19.1	8.2		13.9
2010	12.7	12.0		13.0	18.3	10.3		10.4
2011	14.6	9.0		15.1	13.2	10.4		12.4
2012	15.2	11.8		16.1	11.5	12.8		18.5

	Moisture content for irrigated crop, %[1]				Moisture content for non-irrigated crop, %[1]			
	Corn	**Wheat**	**Soybeans**	**Grain sorghum**	**Corn**	**Wheat**	**Soybeans**	**Grain sorghum**
2013	12.8	9.7		15.6	20.5	8.6		16.4
2014	16.6	11.7		14.1	12.3	10.7		17.4
2015	15.1	10.8		14.3	10.9	12.0		13.8
2016	15.7	11.5		11.9	15.1	8.7		12.9
2017	14.4	10.9		14.8	13.2	10.2		14.9
Projected[2]	15.0	18.0	13.0	13.0	15.0	18.0	13.0	13.0

[1]KSU (2019). [2]Meisner (2018) for corn, TSGC (2018) for wheat, Hurburge (2008) for soybeans, and Shedd & Walkden (1947) for grain sorghum.

Energy Costs

Installed wind turbine and solar panel capital expenditures are shown in Fig. A.1.

For wind, annual O&M costs depend on wind turbine age: the defaults used in FEWCalc are US$45/kW for years 0 to 10; US$50/kW subsequently (Ford, 2018; Wiser & Bolinger, 2019).

For solar, annual O&M costs are not user controlled. FEWCalc determines default installed capacity cost and defined O&M costs based on the user-defined solar capacity and 2018 costs from Fu et al. (2018): Cost for commercial (10 kW to 2 MW) installed capacity is US$1,750/kW (US$1.75M/MW) with annual O&M costs of US$18/kW; cost for residential (3 to less than 10 kW) installed capacity is US$2,700/kW and annual O&M is US$22/kW.

For depreciation calculations, generally only equipment components are included. For wind, a US$2,940,000 investment (one 2MW wind turbine using FEWCalc defaults) would produce a depreciable expense of 68.8% × US$2,940,000 = US$2,022,720. As of May 1, 2020, 50% of this can be deducted the year of installation (M. Gilhousen, personal communication, 2020), leading to a US$1,011,360 deduction that year. Given a 20% tax rate, this yields a net benefit to the taxpayer of US$202,272. Depreciation in the following five years is one-fifth this amount, and zero thereafter.

For solar, the modules that can be depreciated generally account for 44% of the installed cost (Goodrich et al., 2012, Fig. A.1b).

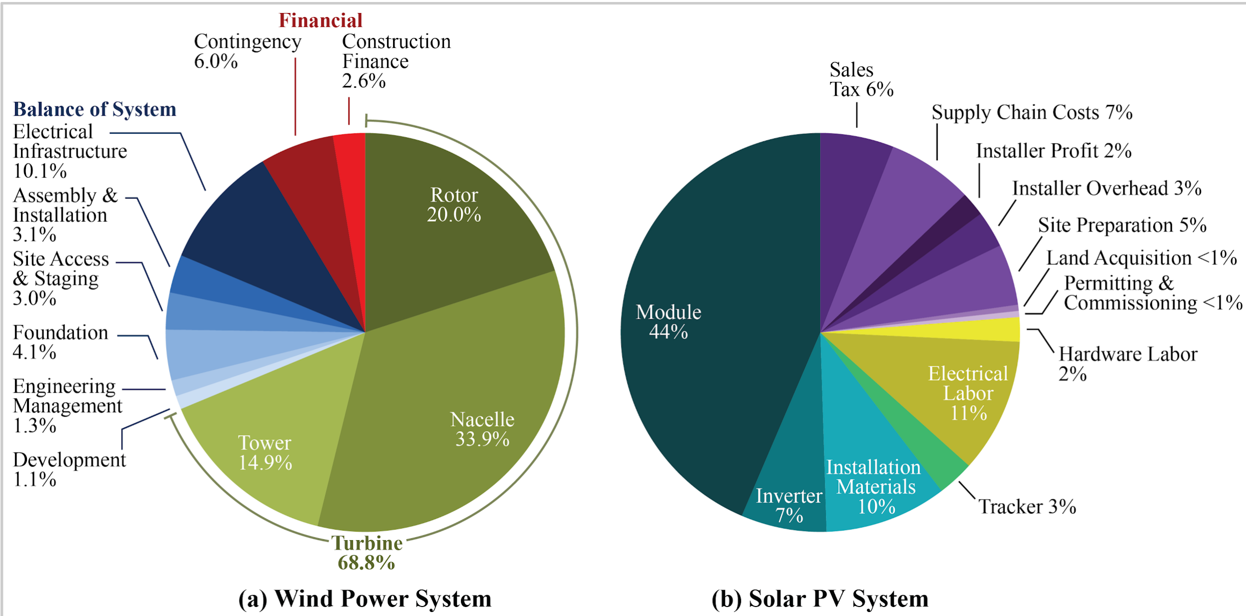

Fig. A.1 Costs of installing (a) wind and (b) solar energy production, in percent (modified from Stehly & Beiter, 2019; Goodrich et al., 2012, respectively)

<u>Water Use</u>

Table A.10 Historical water use for irrigation by crop types in Finney County during the 10-year base period, 2008-2017 (used in Fig. 3.8).

	Historical water use for irrigation, inches			
	Corn	**Wheat**	**Soybeans**	**Grain sorghum**
2008				
2009				
2010	19.68	11.40	18.84	9.00
2011	21.72	14.04	21.96	18.60
2012	21.24	15.84	21.48	14.28
2013	18.72	14.28	16.68	14.28
2014	17.4	12.72	16.20	10.92
2015				
2016				
2017	13.53	12.45	15.58	9.30

KDA (2020). Conversion factors: 1 in of water is equal to 2.54 cm.

The linear regression of water use and water-level change shown in Fig. 3.6b of the main report is $y = -32.386x + 8.001$. Of interest is whether the regression coefficients reflect reasonable field values.

The linear slope of Fig. 3.6b can be expressed as a linear relation, $y = a \times x + c$. In Table A.11, the units and description of each term are provided. For consistency, the units of the slope, a, need to be $1/L^2$, and the units of the intercept, c, need to be L/T.

Table A.11 Parsing of the linear equation for this problem, with definition of terms and units. For this work, the unit of length, L, is feet, and the unit of time, T, is years.

Term or operator	***y***	=	***-a***	×	***x***	+	***c***
Units[1]	L/T		—		L/T		L/T
Description	Change in head over a year	Equals	Slope	Times	Pumped volume over a year, divided by area	Plus	Intercept

[1]Gray shading, regressed variable so units are defined. Green shading, units derived.

Relate slope, a, to field quantities

When water is drained from or introduced to a porous media, the change in head equals the volume of water divided by the product of the area and S_y (Fitts, 2013, p. 221). Here, the volume pumped is already divided by the area of Finney County, so the slope terms equals

$$\boldsymbol{a} = 1/(S_y) \quad \Rightarrow \quad S_y = 1/(\boldsymbol{a}) \tag{A.1}$$

Using a = 32.382 gives S_y = 3%.

Relate Intercept, c, to field quantities

If $\boldsymbol{x} = 0$, $y = c$, so c is the infiltration per unit area (units L/T) that results in head change when there is no pumping. This is called groundwater recharge. If there are no surface-water body interactions (such as seepage from streams),

$$c = (\textit{infiltration rate}\ (L/T))/(S_y\ (—)) \Rightarrow \textit{infiltration rate} = c \times S_y \quad (A.2)$$

Here, the intercept is 8.001 ft/year, and the infiltration rate would equal 8.001 times 0.03 = 0.27 ft/year or 3.2 inches/year.

Comment

S_y = 3% is considered by some to be smaller than expected for the sediment considered. However, it is consistent with values obtained by Butler et al. (2016) and Whittemore et al. (2016), who provide an extensive discussion. *Infiltration rate* = 3.2 inches/year is like reasonable given that the historic average precipitation is about 20 inches and the region is arid.

Weather, Climate, and Projections

Daily weather data for air temperature, precipitation, and solar radiation used as input to DSSAT (Tsuji et al., 1994) are mentioned in Section 3.2.2. Daily data from the 10-year base period 2008 to 2017 were obtained from a weather station at Garden City Regional Airport, Finney County, Kansas (37°55'38"N, 100°43'29"W). Daily minimum and maximum air temperatures and daily precipitation data were acquired from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI). Thirty-minute solar radiation data at a 4-km horizontal resolution were acquired from the National Solar Radiation Database's (NSRDB) Data Viewer provided by the National Renewable Energy Laboratory (NREL) (Sengupta et al., 2018).

Average Historical Weather Data, 1950-2019

Table A.12 Average monthly values for precipitation and quarterly mean values for temperature in Finney County, Kansas from Jan 1950 to Oct 2019 and from Q1/1950 to Q3/2019.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average monthly precipitation (in)	0.4	0.5	1.2	1.6	2.9	3.0	2.9	2.6	1.7	1.4	0.7	0.5
Quarterly mean temperature (°C)	2.8			17.8			23.9			6.7		

Palmer Drought Severity Index, 2008-2017

Table A.13 Average annual daily[1] Palmer Drought Severity Index (PDSI) and related weather data in Garden City, Kansas during a base period, 2008 to 2017.

Year	Maximum temperature (°C)	Minimum temperature (°C)	Solar radiation (W/m^2)	Annual precipitation (in)	PDSI	PDSI category
2008	20.7	4.7	203.7	18.6	0.06	Moderate
2009	20.3	4.6	197.3	20.8	1.66	Moderate
2010	21.2	5.3	208.2	17.3	0.18	Moderate
2011	21.6	5.0	213.4	12.2	-3.24	Extremely dry
2012	23.0	6.2	217.1	14.0	-2.98	Dry
2013	20.6	4.7	212.2	17.5	-2.54	Dry
2014	20.5	4.7	210.1	18.9	-0.43	Moderate
2015	21.3	6.2	206.8	29.0	2.31	Wet
2016	22.3	5.8	213.7	20.7	3.35	Extremely wet
2017	21.7	5.6	204.6	23.4	2.06	Wet

NCDC (2020). [1]Annual average daily data applied for temperature, solar radiation, and PDSI; whereas, precipitation is reported as annual data.

Climate Model Results

RCPs dictate alternative future pathways for global greenhouse gas concentrations. RCP 4.5 is an intermediate emission scenario where emissions peak around 2040 and then decline (Thomson et al., 2011). In RCP 8.5, emissions rise throughout the projection period, and this scenario produces the most warming among the RCPs (Raihi et al., 2011).

FEWCalc users can choose either RCP 4.5 or 8.5 scenario. The GCM data used in this work has been downscaled using the method of Multivariate Adaptive Constructed Analogs (MACA) developed by Abatzoglou & Brown (2012). Data for point locations were obtained from https://climate.northwestknowledge.net/MACA/data_csv.php. Climate data are shown in Fig. A.2.

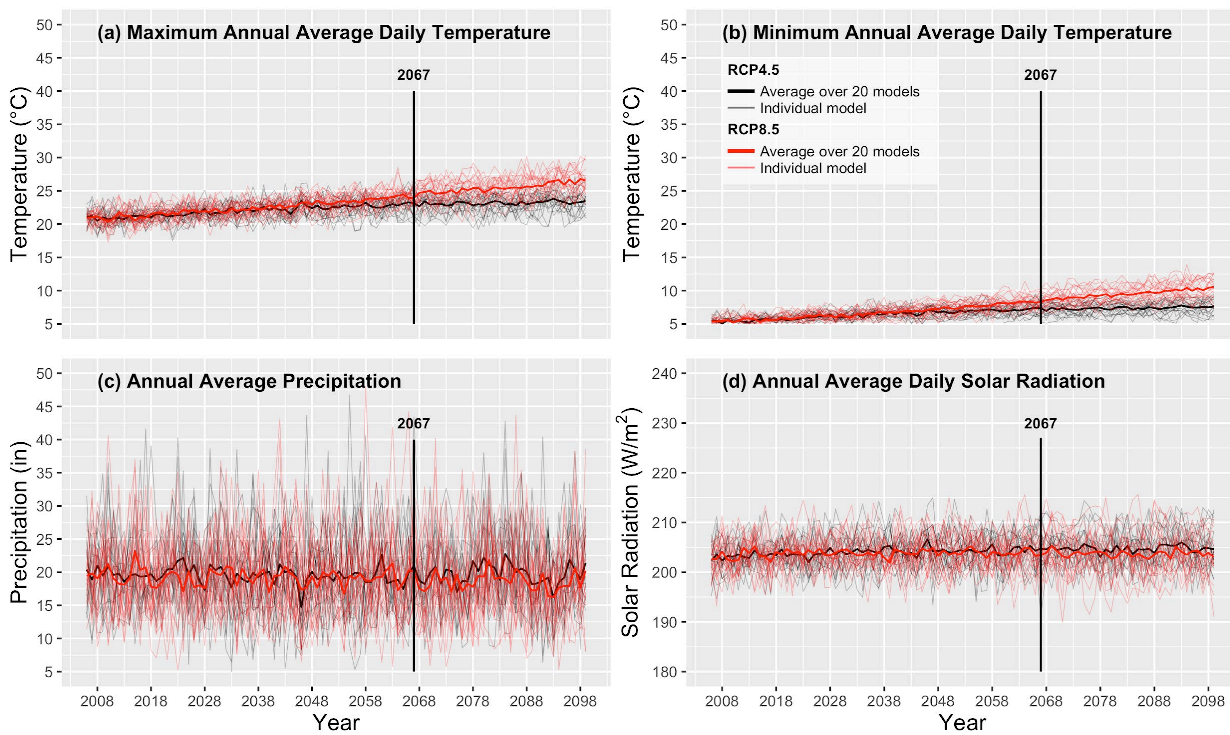

Fig. A.2 Comparison of annual average projected weather data between the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios obtained from 20 downscaled global climate models between 2006 and 2099. The end of the FEWCalc simulations in this work, 2067, is marked.

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Appendix B. Results from DSSAT and Global Climate Simulations

Appendix B provides detailed DSSAT results from the base period 2008-2017 (Tables B.1 and B.2) and the projections produced using global climate models for the period 2008-2098 (Figs. B.1 to B.3).

Results for Base Period 2008-2017

This section includes DSSAT crop-yield results produced using historical weather data for irrigated (Table B.1) and non-irrigated (Table B.2) conditions for the base period (2008-2017). The weather data involved includes solar radiation, precipitation, and temperature; Table 2.6 of the thesis summarizes the data and its sources, and Fig. 3.4 shows average monthly temperature deviations and cumulative precipitation deviations from 1950 to 2019.

Table B.1 Simulated irrigated crop yield and water use from DSSAT from 2008 to 2017. For all but soybeans, this data is plotted in Fig. 3.8 of the thesis.

	Simulated irrigated crop yield, bushels per acre				Irrigation, inches			
	Corn	Wheat	Soybean[3]	Grain sorghum	Corn	Wheat	Soybeans	Grain sorghum
2008	213	77	92	119	14	7	18	15
2009	251	70	93	130	9	9	18	13
2010	206	65	97	85	18	18	27	12
2011	144	68	90	68	23	12	33	14
2012	168	67	93	95	24	18	32	16
2013	205	71	91	127	18	15	23	14
2014	207	79	96	121	13	10	16	9
2015	233	75	95	129	7	12	12	7
2016	233	69	96	113	4	12	14	8
2017	223	74	97	134	14	12	18	17

Simulated yields (drymass yields) are adjusted to correct for moisture content reported by the Department of Agronomy, Kansas State University shown in Table A.3. Conversion factors: 1 bu/ac of corn or grain sorghum is 62.77 kg/ha, 1 bu/ac wheat or soybeans is 67.25 kg/ha, and 1 in of water is equal to 2.54 cm.

Table B.2 Simulated non-irrigated crop yield from DSSAT from 2008 to 2017. For all but soybeans, this data is plotted in Fig. 3.8 of the thesis.

	Simulated non-irrigated crop yield, bushels per acre			
	Corn	**Wheat**	**Soybeans**	**Grain sorghum**
2008	38	63	7	50
2009	107	31	14	64
2010	44	10	4	19
2011	13	25	4	11
2012	22	8	3	19
2013	34	4	21	57
2014	152	8	22	90
2015	168	53	15	109
2016	187	40	11	88
2017	128	11	13	64

Simulated yields (drymass yields) are adjusted to correct for moisture content reported by the Department of Agronomy, Kansas State University shown in Table A.3. Conversion factors: 1 bu/ac of corn or grain sorghum is 62.77 kg/ha, 1 bu/ac wheat or soybeans is 67.25 kg/ha, and 1 in of water is equal to 2.54 cm.

Results for Future Projection 2008-2098

This section includes DSSAT crop-yield results produced using climate data projected to the year 2098 under RCPs 4.5 and 8.5 (Figs. B.1 to B.3) for irrigated and non-irrigated conditions. Fig. A.2 shows annual average projected weather data obtained from 20 global climate models under different climate scenarios, RCPs 4.5 and 8.5, respectively.

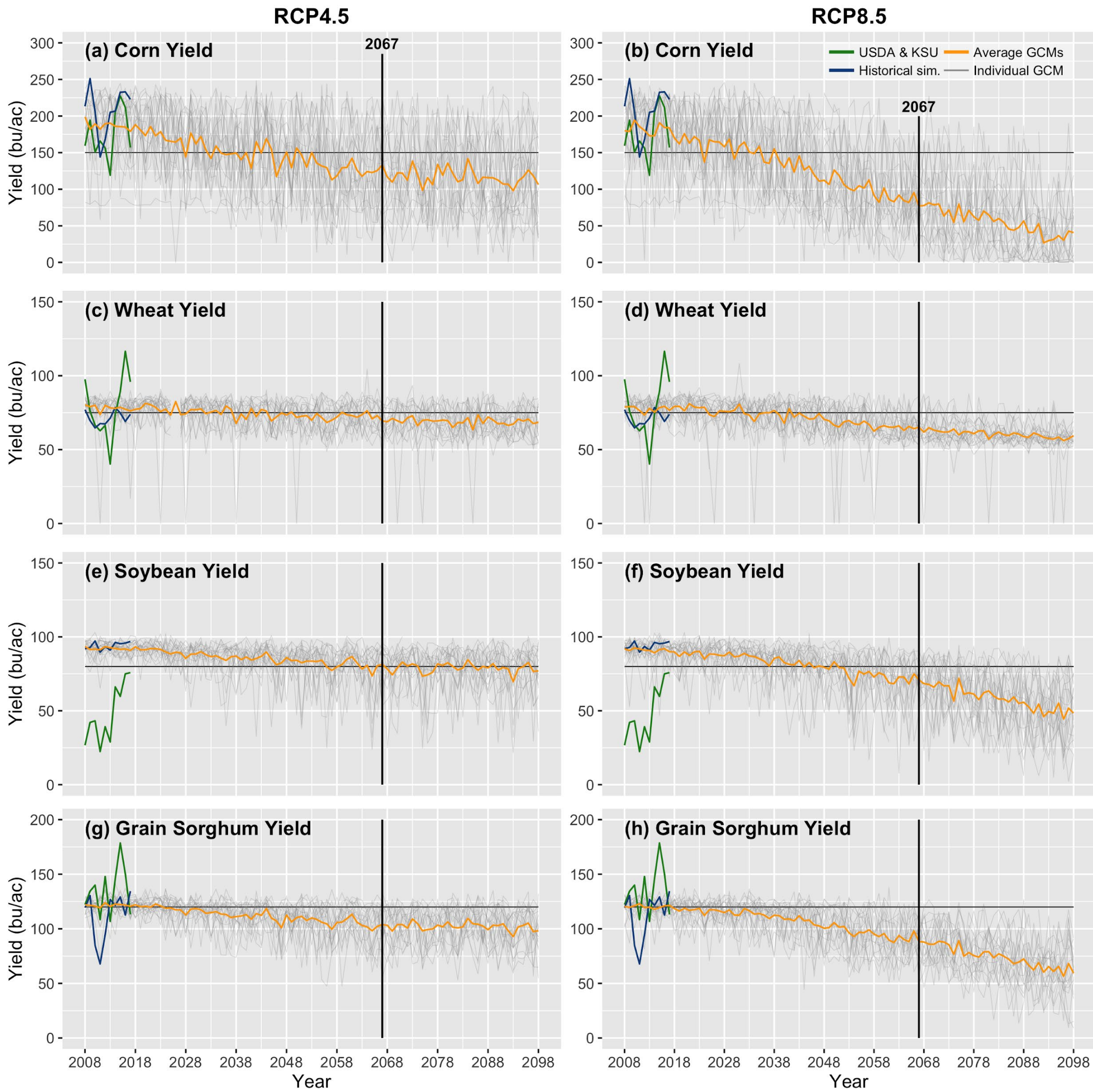


Fig. B.1 Irrigated crop yields. Historical (2008-2017) as measured by KSU and USDA for soybeans (green line) and simulated with DSSAT using historically measured climate variables (blue line). The KSU and DSSAT results are the same as those shown in Fig. 3.8 of the main article. Simulated (2008-2098) with DSSAT using climate variables from 20 individual downscaled global climate models (gray lines) and average for all climate models (gold line) under the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios. Conversion factors: 1 bu/ac of corn or grain sorghum is 62.77 kg/ha, 1 bu/ac wheat or soybeans is 67.25 kg/ha, and 1 in of water is equal to 2.54 cm.

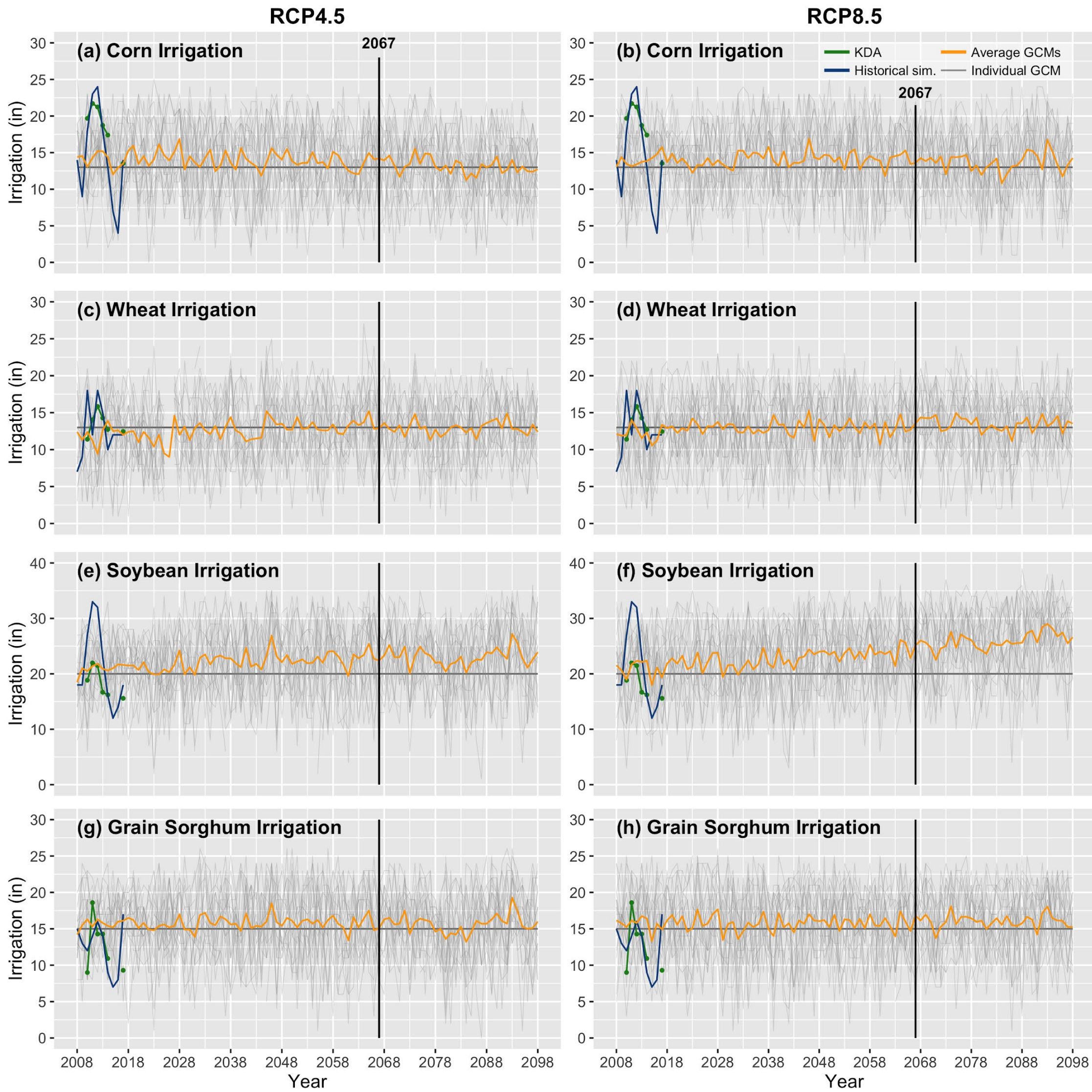


Fig. B.2 Historical irrigation measured by KDA (2008-2017), simulated with DSSAT using historically measured climate variables (2008-2017), and simulated with DSSAT using climate variables from downscaled global climate models (2008-2098) under RCP 4.5 and 8.5 scenarios. FEWCalc results shown in this article end at 2067. Conversion factors: 1 bu/ac of corn or grain sorghum is 62.77 kg/ha, 1 bu/ac wheat or soybeans is 67.25 kg/ha, and 1 in of water is equal to 2.54 cm.

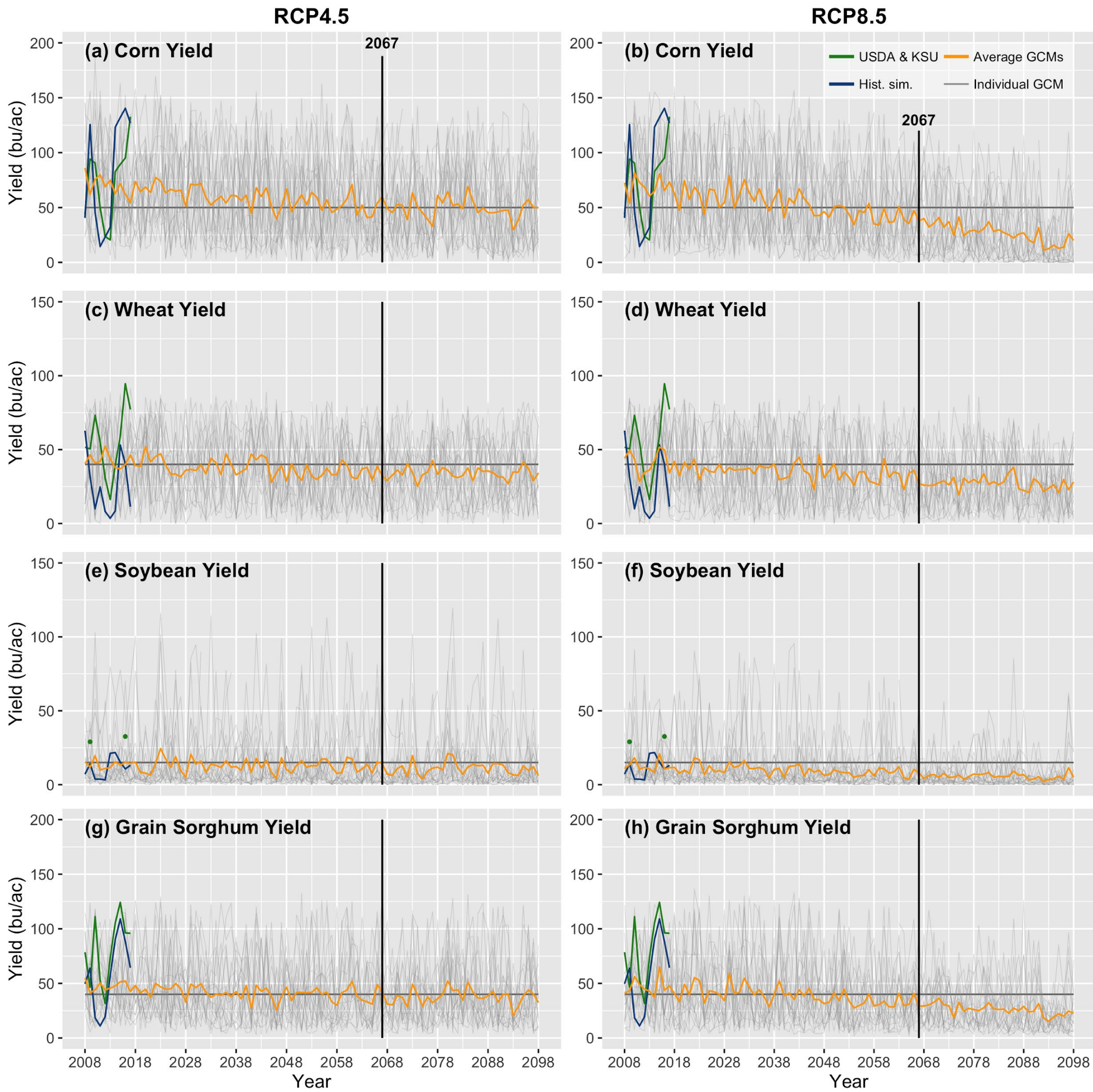


Fig. B.3 Historical dryland crop yields measured by KSU and USDA for soybeans (2008-2017), simulated with DSSAT using historically measured climate variables (2008-2017), and simulated with DSSAT using climate variables from downscaled global climate models (2008-2098) under RCP4.5 and 8.5 scenarios. FEWCalc results shown in this article end at 2067. Conversion factors: 1 bu/ac of corn or grain sorghum is 62.77 kg/ha, 1 bu/ac wheat or soybeans is 67.25 kg/ha, and 1 in of water is equal to 2.54 cm.

Appendix C. Selected FEWCalc Equations

Selected equations for calculations mentioned in Section 3.2 of the paper are provided here.

DSSAT Irrigation Calculation for Arid Regions

Irrigation is simulated to start about a month after planting or later. The soil water available for plant development is defined at management depth IMDEP (approximately 4 ft, 120 cm, for all crops). The lower and upper thresholds, ITHRL and ITHRU, were set at 50% and 90%, respectively (Waller & Yitayew, 2016; Sharda et al., 2019). At the upper-level, irrigation is delayed until the available water declines; at the lower level, irrigation starts as soon as possible.

For the irrigation simulation, a fixed amount of one inch was applied for each irrigation event. Irrigation event frequency (IFREQ) (Sharda et al., 2019) is set to 4 days for corn, and 8 days for wheat and grain sorghum. Irrigation efficiency is 80% for the center pivot system (Irmak et al., 2011).

Crop Insurance

Crop insurance indemnifies – pays – the insured based on the selected *level of coverage*. Insurance is indemnified when crop yield ($Yield_C$) is less than the yield guarantee ($Yield_{GTEE}$). The yield guarantee is calculated as the *level of coverage* times the 10-year average yield per acre for the farm, which is based on the insured's actual production history (*APH*). To determine the indemnity, the yield deficiency ($Yield_{DEFN}$) is multiplied by the futures-market crop price ($Price_{FM}$). The common "*level of coverage"* values used in FEWCalc are: corn 75%, wheat 70%, soybeans 70%, and grain sorghum 65% (K. Heger, AgFirst Crop Insurance, written communication, 2020). For FEWCalc projections, future prices are not available; the NASS 2008 market price from Finney County (for corn) and Kansas (for other crops) surrounding counties is used because 2008 is thought to be a typical year in that crop prices are within one standard deviation of the mean for the 10-year period. Values used are US$4.12 for corn, US$6.94 for wheat, US$9.39 for soybeans, and US$3.14 for grain sorghum. In FEWCalc, *APH* is derived from the previous 10 years of DSSAT-simulated production, so crop insurance is not applied for the 10-year base period.

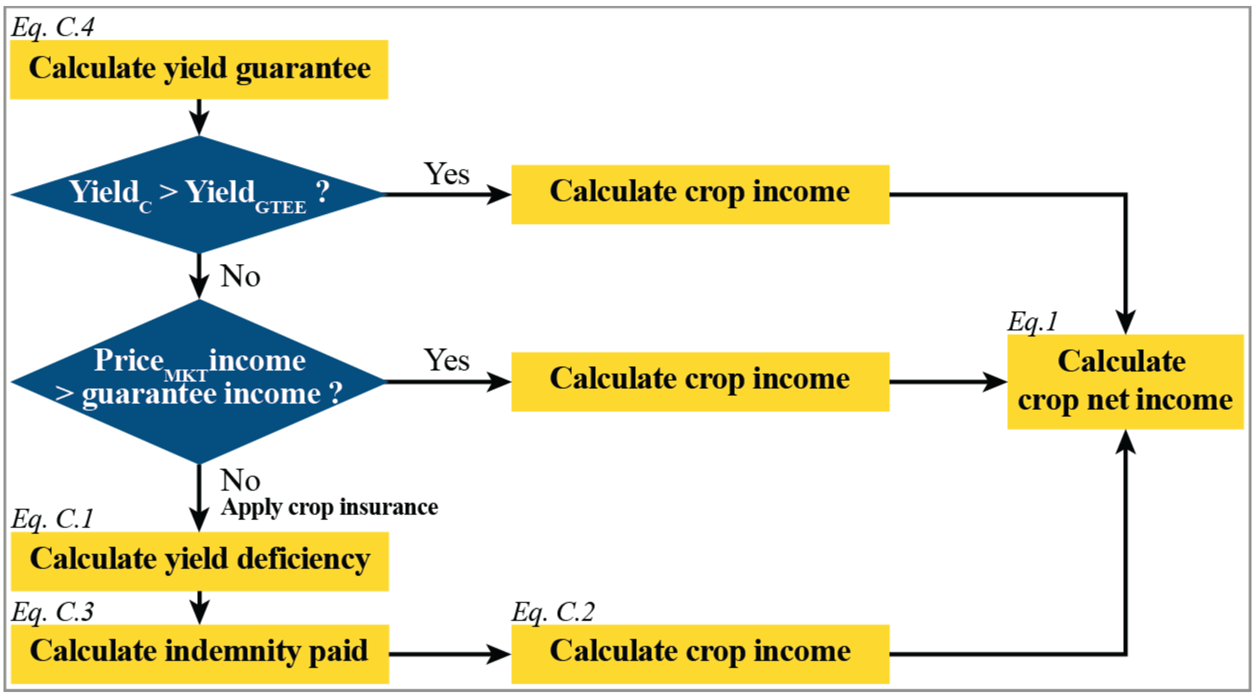


Fig. C.1 FEWCalc's crop insurance algorithm.

In FEWCalc, the insurance yield guarantee and the income per acre for years when insurance is paid are calculated as follows; the process is illustrated in Fig. C.1 and expenses per acre in western Kansas are listed in Table A.7.

If crop yield ($Yield_C$) produced less than yield guarantee ($Yield_{GTEE}$), then

$$Yield_{DEFN} = Yield_{GTEE} - Yield_C \quad (C.1)$$

$$Income_I = (Yield_C \times Price_C) + Indemnity\ paid \quad (C.2)$$

$$Indemnity\_\ paid = Yield_{DEFN} \times Price_{FM} \quad (C.3)$$

$$Yield_{GTEE} = \text{average previous 10-year } APH \times level\ of\ coverage \quad (C.4)$$

where $Income_I$ and *indemnity paid* are in US dollars per acre, all types of yield and *APH* are in bushels per acre, and prices are reported in US dollars per bushel. Subscript C identified the crop type.

Wind Energy

Annual wind energy net income, $Income_{W\_t}$, is calculated as follows. User-defined variables and their defaults are listed in Table D.1.

$$Loan\ amount_W = [N_W \times PWR_W \text{ (in MW)} \times 1{,}000] \times Cost_{Ins\_W} \text{ (per kW)} \quad (C.5)$$

$$n\_W = Loan\_term \times Nyear_W \quad (C.6)$$

$$Annual\ payment_{W\_t} = (Loan\ amount_W \times APR) / [1 - (1 + APR)^{-n\_W}] \text{ for yrs 1 to } n\_W \quad (C.7)$$

$$Interest_{W\_t} = Balance_{W\_t} \times APR \quad (C.8)$$

$$Principal_{W\_t} = Annual\ payment_W - Interest_{W\_t} \quad (C.9)$$

$$Balance_{W\_t} = \Sigma_{\text{W\_t=1 to n}} (Balance_{W\_t-1} - Principal_{W\_t}) \quad (C.10)$$

$$Prod_{W\_t} = N_W \times PWR_W \times CPTY_W \times 8{,}760 \text{ hrs/yr} \times (1.00 - Degrade_{W\_t} / 100) \quad (C.11)$$

$$Cost_{W\_t} = Annual\ payment_W + Cost_{O\&M\_t} \quad (C.12)$$

$$Sell_{W\_t} = Prod_{W\_t} \times (Energy\_value + 1{,}000 \times PTC_{W\_t}) \quad (C.13)$$

$$Income_{W\_t} = Sell_{W\_t} - Cost_{W\_t} \quad (C.14)$$

where $Loan\ amount_W$ is total installed costs of the wind power system in US dollars, N_w is the number of wind turbines installed, PWR_W is wind turbine capacity in MW, $Cost_{Ins\_W}$ is costs per kW installed of the wind energy system. n_W is the total number of interest periods, *Loan_term* is a fraction of total loan term, $Nyears_W$ is equipment usable lifetime in years. *Annual payment* is derived from the Mortgage formula (fixed periodic payment), *APR* (annual percent rate) is an annual rate of interest. $Interest_{W\_t}$ is an annual interest in year t, $Balance_{W\_t}$ is a remaining loan balance in year t. $Principal_{W\_t}$ is a principal repayment in year t. Balance in year $t = 0$ is principal loan amount. $Prod_{W\_t}$ is wind production in MWh, $CPTY_W$ is wind capacity factor in percent, and $Degrade_{W\_t}$ is annual degradation factor applied after year 10. $Cost_{W\_t}$ and $Cost_{O\&M\_t}$ are annual costs of the wind power system and annual operations and maintenance (O&M) costs per kW installed capacity (see Appendix A). $Sell_{W\_t}$ is wind energy revenue, *Energy_value* is the economic value to the owner for each MWh produced, PTC_{W_t} is the Production Tax Credit in US dollars for each kWh of energy produced in the first 10 years of operation. $Income_{W\_t}$ is net income from wind energy per year.

$Degrade_{W\_t}$ is applied annually for turbines more than 10 years old (Wiser & Bolinger, 2019). FEWCalc defaults are wind turbine installation costs of US$1,470/kW (typical of a large project) and lifespan of 30 years (20-30 years are suggested by Stehly & Beiter, 2019).

Solar Energy

Equations controlling solar and wind energy simulations are similar.

$$Loan\ amount_S = [N_S \times PWR_S \text{ (in W)} / 1{,}000 \times Cost_{Ins\_S} \text{ (per kW)}] \times (1 - \text{ITC\_S} / 100) \quad (C.15)$$

$$n\_S = Loan\_term \times Nyears_S \quad (C.16)$$

$$Annual\ payments = (Loan\ amounts \times APR) / [1 - (1 + APR)^{-n\_S}] \quad (C.17)$$

$$Interests_{\_t} = Balances_{\_t} \times APR \quad (C.18)$$

$$Principals_{\_t} = Annual\ payments - Interests_{\_t} \quad (C.19)$$

$$Balances_{\_t} = \sum_{S\_t=1 \text{ to } n} (Balances_{\_t-1} - Principals_{\_t}) \quad (C.20)$$

$$Prods_{\_t} = N_S \times PWR_S \times SunHrs \times 365 \text{ days/yr} / 1{,}000{,}000 \times (1.00 - Degrade_S / 100) \quad (C.21)$$

$$Cost_S = (Annual\ payments + Cost_{O\&M}) \quad (C.22)$$

$$Sells_{\_t} = Prods_{\_t} \times (Energy\_value + 1{,}000 \times PTC_S) \quad (C.23)$$

$$Incomes_{\_t} = Sells_{\_t} - Cost_S \quad (C.24)$$

where variables with subscript *S* are for the solar energy system and most are described in the Wind Energy Section above. ITC_S is the Investment Tax Credit expressed as a percent and applied to the total installed costs.

$Prods_{\_t}$ depends on *SunHrs*, average peak sun hours per day, which is user defined. The default value in FEWCalc is 5.6 hours per day, which is typical in western Kansas (Wholesale Solar, 2020). $Degrade_S$, $Nyears_S$, and $Cost_S$ are user controlled; default values are 0.5%, 25 years, and US$1,750/kW or US$2,700/kW (depending on $Prods_{\_t}$), respectively. More information is presented in Table D.1 and related text.

Nitrogen Concentrations in Water

$N_{field} = 10\% \times N_{applied} \times N_{acres} / 1.12$ Accumulated until moved (C.25)

$N_{stream} = \sum_{time} (N_{field})$ Moved in wet or extremely wet years (C.26)

where N_{field}, in lb, is the nitrogen applied to a field for a crop planted on N_{acres} of land. $N_{applied}$, in kg/ha, is defined as a DSSAT input variable (Table 2.6). 1.12 converts kg/ha to lb/ac. N_{stream} is the nitrogen in the stream and is accumulated over time.

Reference Cited

Irmak, S., Odhiambo, L. O., Kranz, W. L., & Eisenhauer, D. E. (2011). Irrigation Efficiency and Uniformity, and Crop Water Use Efficiency. In Biological Systems Engineering: Papers and Publications (Vol. 451, Issue EC7). https://digitalcommons.unl.edu/biosysengfacpub/451

Sharda, V., Gowda, P. H., Marek, G., Kisekka, I., Ray, C., & Adhikari, P. (2019). Simulating the Impacts of Irrigation Levels on Soybean Production in Texas High Plains to Manage Diminishing Groundwater Levels. *JAWRA Journal of the American Water Resources Association*, *55*(1), 56–69. https://doi.org/10.1111/1752-1688.12720

Stehly, T., & Beiter, P. (2019). *2018 Cost of Wind Energy Review* (NREL/TP-5000-74598; Issue December). https://www.nrel.gov/docs/fy20osti/74598.pdf

Waller, P., & Yitayew, M. (2016). *Irrigation and Drainage Engineering* (Vol. 67, Issue 803). Springer International Publishing. https://doi.org/10.1007/978-3-319-05699-9

Wholesale Solar. (2020). *Solar Insolation Map: How Many Sun Hours Do You Get?* https://www.wholesalesolar.com/solar-information/sun-hours-us-map

Wiser, R., & Bolinger, M. (2019). 2018 Wind Technologies Market Report. In *U.S. Department of Energy*. https://www.energy.gov/eere/wind/downloads/2018-wind-technologies-market-report

Appendix D. FEWCalc Instructions

Software availability

Software name:	FEWCalc
Developers:	Jirapat Phetheet and Mary C. Hill
Year first official release:	2020
Software requirement:	Netlogo version 6.1.1 or higher
Operating systems:	Windows, macOS
Program language:	NetLogo
Program size:	1.5 MB
Availability:	https://github.com/JPhetheet/FEWCalc
License:	GPL-3.0
Documentation:	This Appendix and FEWCalc's Info tab

NetLogo version 6.1.1, can run on almost all types of computers, as discussed on the NetLogo website. FEWCalc was developed using Microsoft Windows 7 and 10, and macOS Catalina (version 10.15.5). A machine with 64 MB of memory (RAM) is recommended for Windows operating systems. For macOS users, OS X Mountain Lion 10.8.3 or newer is required with 128 MB RAM (258 MB RAM recommended).

Step 1. Download NetLogo

FEWCalc is developed using a NetLogo platform as an agent-based model. NetLogo is an open source software which is available at https://ccl.northwestern.edu/netlogo. A screenshot of this site is shown in Fig. D.1. Click "Download NetLogo". **Download NetLogo version 6.1.1 or higher.** The download can be placed in any directory on your computer.

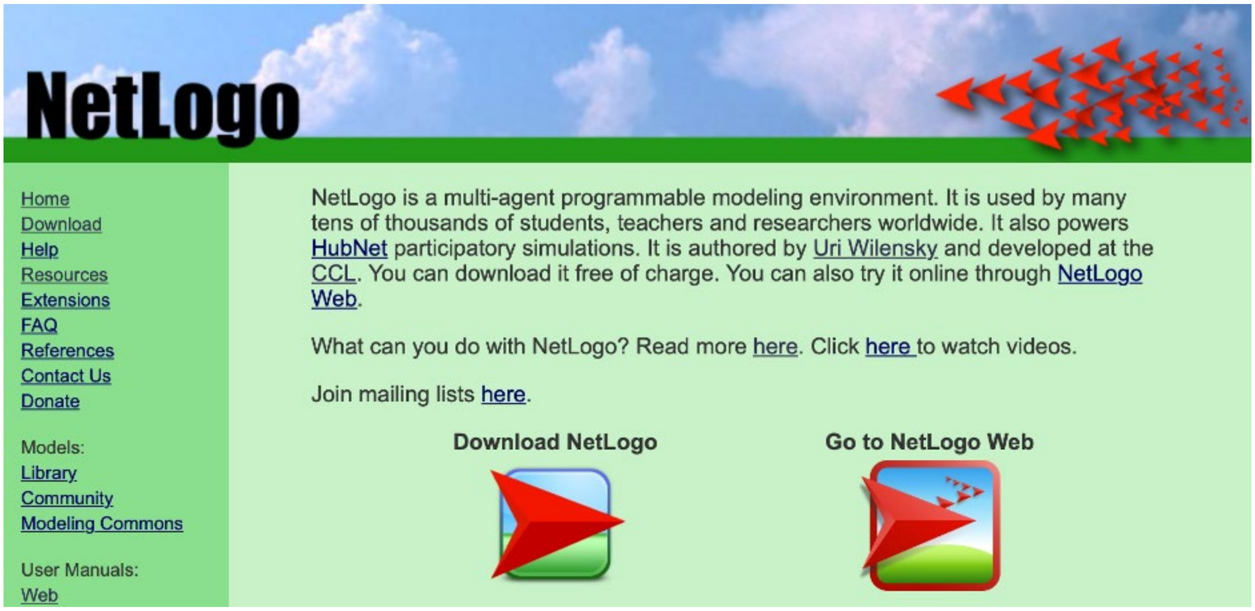


Fig. D.1 NetLogo web site.

Step 2. Get FEWCalc From GitHub Repository When You Have NO GitHub Account

[See ***Step*** *7* if you DO have a GitHub account]

Go to https://github.com/JPhetheet/FEWCalc. You will see the image in Fig. D.2. This FEWCalc repository includes a Netlogo file and its supporting documents such as input files and figures used in FEWCalc. Click **"Clone or Download"** in the top right corner to get the dropdown menu shown in Fig. D.2. Click **"Download ZIP"** to download FEWCalc. A folder **"FEWCalc-master"** is saved in a local directory that you choose. Navigate to that directory and unzip the downloaded zip file. Do this by right clicking on the zip file and selecting one of the download options. The exact options available will depend on your computer and available utilities. The FEWCalc directory is shown in Fig. D.3.

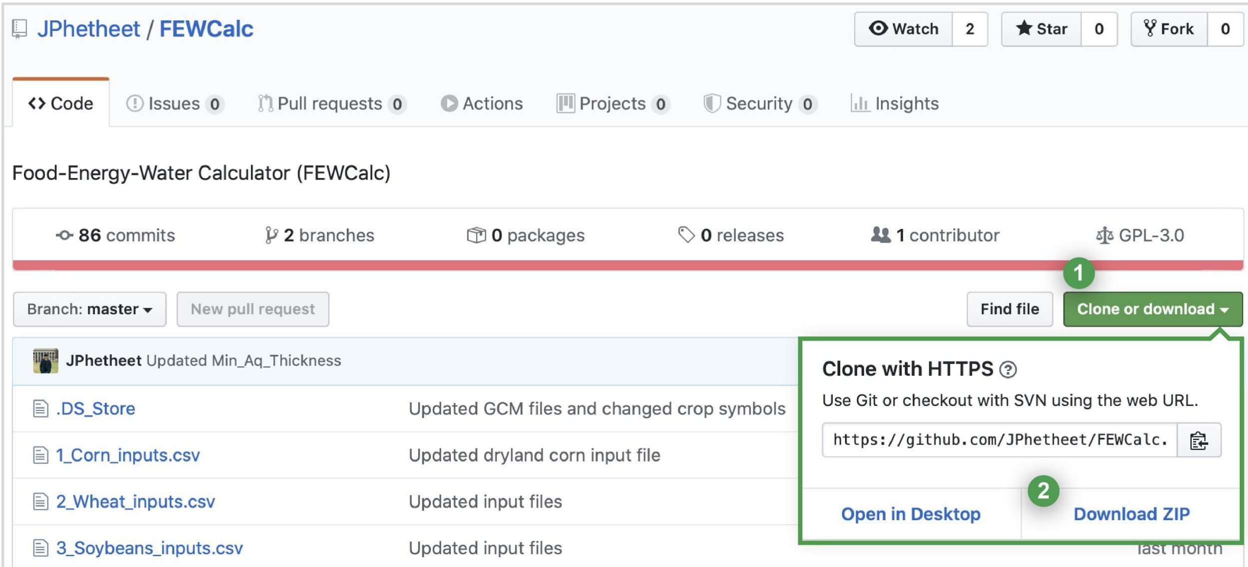


Fig. D.2 FEWCalc repository.

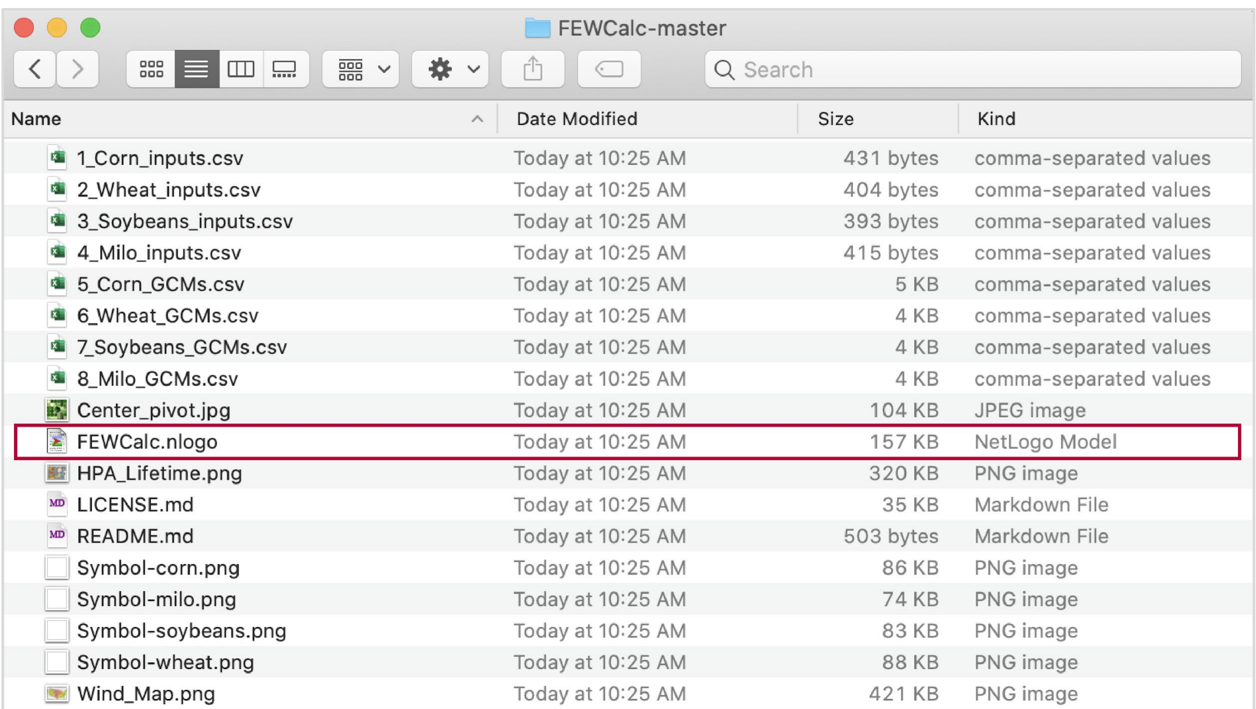


Fig. D.3 FEWCalc-master folder downloaded from FEWCalc GitHub repository.

Step 3. Launch FEWCalc

Click or double click (depending on how your computer is set up) **"FEWCalc.nlogo"** file from FEWCalc-master folder (Fig. D.3). You will see the image in Fig. D.4 with the square in the middle will be blank.

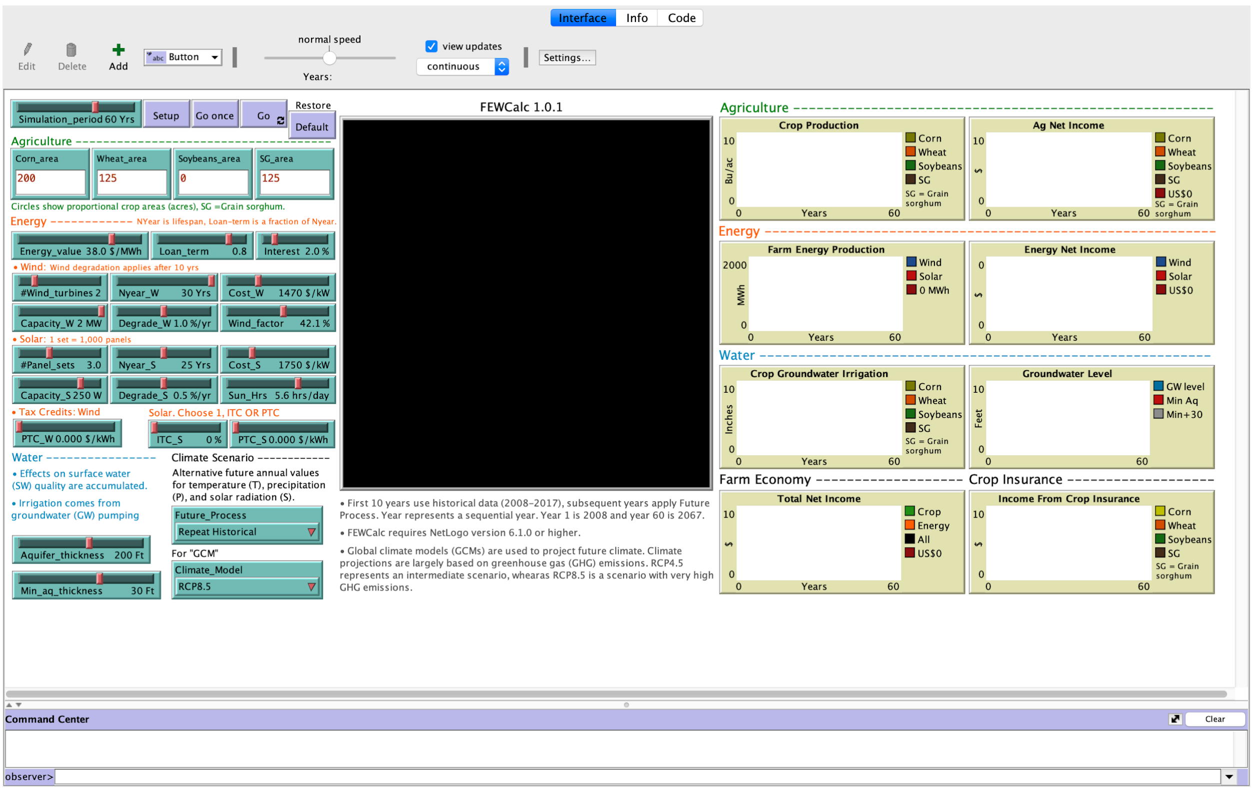


Fig. D.4 FEWCalc interface before setting model's parameters.

Step 4. SetUp FEWCalc

Click "Setup" on the top left to get the image in Fig. D.5.

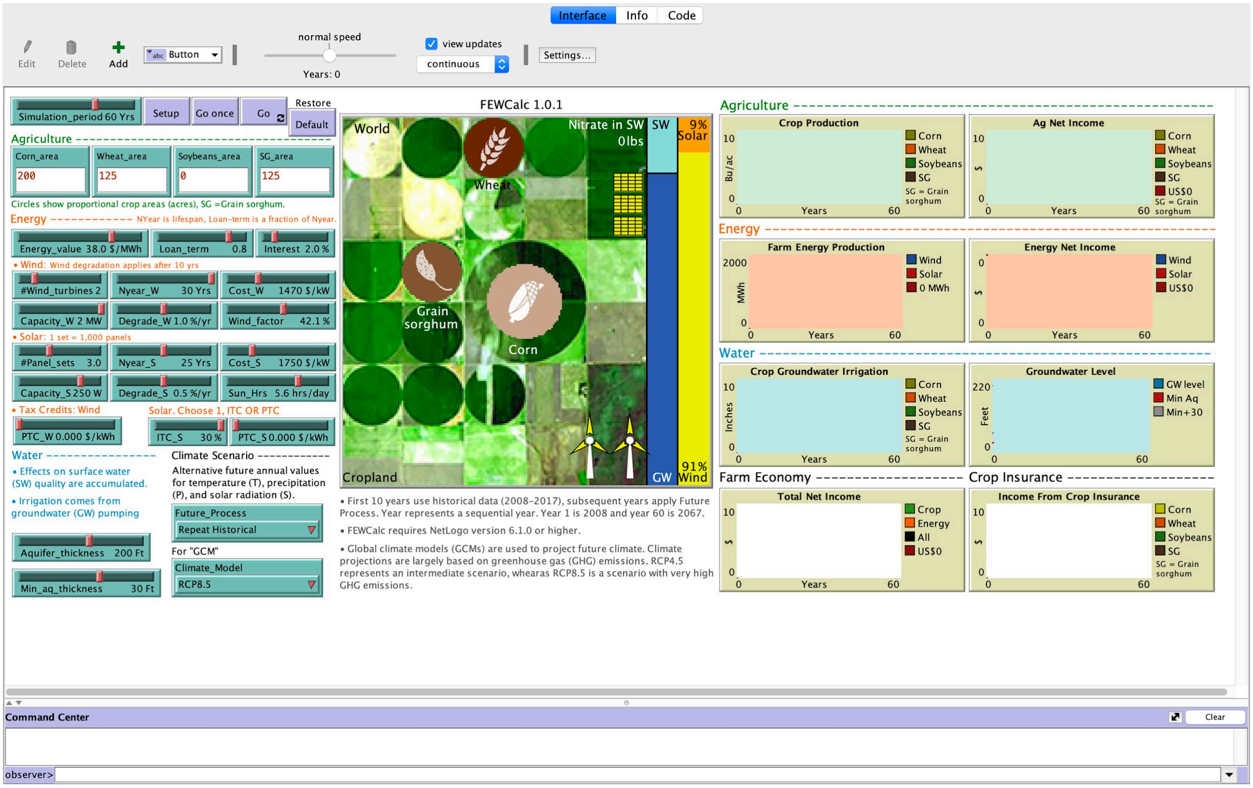


Fig. D.5 FEWCalc interface.

The user-defined inputs are controlled by the features on the left side of the image shown in Fig. D.5. This part of the image with the default values defined when FEWCalc is started using the distributed FEWCalc.nlogo file is shown in Fig. D.6. All features are defined in Table D.1.

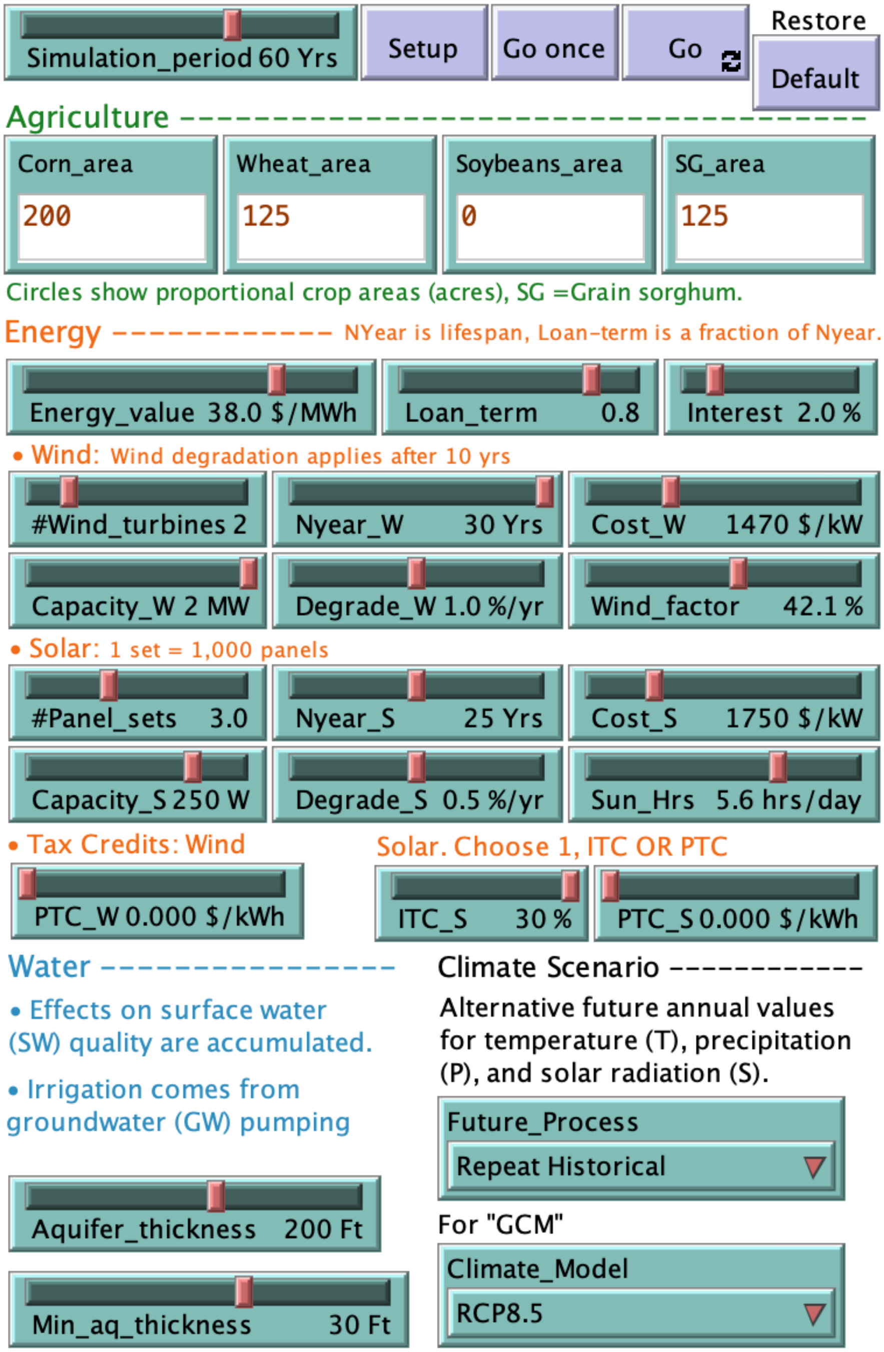


Fig. D.6 FEWCalc user inputs showing default values defined by clicking “Setup” when the unchanged distributed file FEWCalc.nlogo is used.

Table D.1 FEWCalc user-input features, descriptions, default values imposed each time FEWCalc is started, and the units of values. Default values are discussed in Appendix A and the main article.

Variable	Description	Range	Default	Unit
Simulation_period	A number of simulation years	1-90	60	Year
Setup	A setup button	-	-	-
Go once	Advance the model one-time step	-	-	-
Go	Run the model throughout the entire time period	-	-	-
Default	Restore default values	-	-	-
Agriculture				
Corn_area	Corn simulated area	-	200	Acre
Wheat_area	Wheat simulated area	-	125	Acre
Soybeans_area	Soybean simulated area	-	0	Acre
SG_area	Grain sorghum (SG) simulated area	-	125	Acre
Energy				
Energy_value	Energy buyback rate	0-50	38	$/MWh
Loan_term	Loan term, as a fraction of Nyear_S and Nyear_W	0-1	0.8	-
Interest	Interest rate applied to the loan	0.1-1	2.0	%/year
Wind Energy				
#Wind_turbines	A number of wind turbines	1-6	2	Turbine
Capacity_W	Installed capacity of each wind turbine	1-2	2	Megawatt
Nyear_W	Wind turbine lifespan	20-30	30	Year
Degrade_W	Annual degradation rate, after 10-yr operation	0-2	1	%/year
Cost_W	Wind turbine capital costs	1,000-2,500	1,470	$/kW
Wind_factor	Wind capacity factor	20-60	42.1	%
PTC_W	Production Tax Credit	0-0.030	0	$/kWh
Solar Energy				
#Panel_sets	Set of solar panels, one set is 1,000 panels	0-8	3	1k panels
Capacity_S	Installed photovoltaic capacity, for each panel	100-300	250	Watt
Nyear_S	Solar panel lifespan	20-30	25	Year
Degrade_S	Annual degradation rate	0-1	0.5	%/year
Cost_S	Solar panel capital costs	1,000-4,000	1,750	$/kW
Sun_hrs	Average peak sun hours	0-8	5.6	Hour/day
ITC_S	**Choose one**: Investment Tax Credit	0-40	0	%
PTC_S	**Choose one**: Production Tax Credit	0-0.030	0	$/kWh
Water				
Aquifer_thickness	Saturated thickness of the aquifer	70-300	200	Foot
Min_aq_thickness	Minimum available aquifer thickness	0-50	30	Foot
Climate Scenario				
Future_Process	Future process applied after base period	-	Repeat Historical	-
Climate_Model	This option is only for the "GCM" scenario. Simulation under climate projection data, RCP 4.5 and RCP 8.5.	-	-	-

Step 5. Run FEWCalc

If any inputs are changed, click **“Setup”** again before running the program.

Run the program by doing one of the following.

- Click **“Go once”** to advance the simulation one time step. User inputs can be changed each step of the simulation.
- Or click **“Go”** to run the entire simulation period. The same user inputs are used throughout the simulation

When the simulation is completed using the default values, FEWCalc will look like Fig. D.7. The defaults provide results for creating the last 50 years of the simulation by repeating the first 10 historical years five times. Additional future scenarios can be simulated using the “Future Process” drop down menu under “Climate Scenario” section of the input panel.

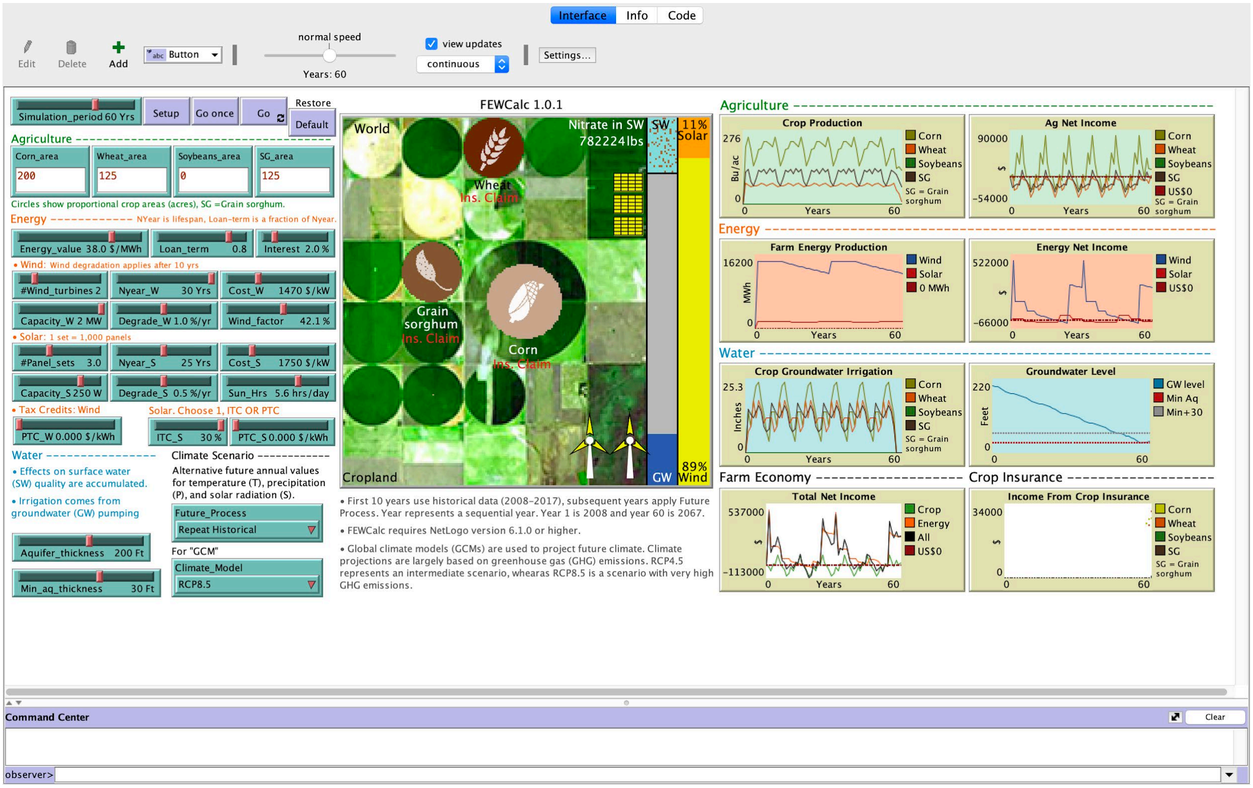
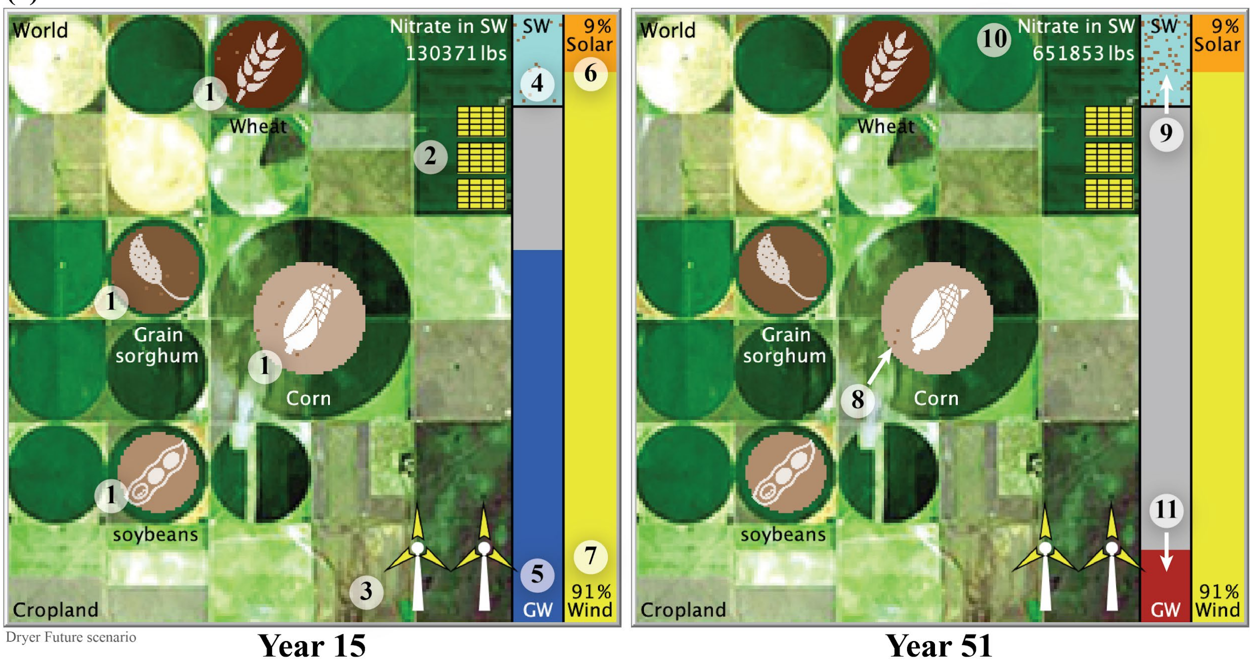


Fig. D.7 FEWCalc interface after running the entire defined simulation time of 60 years (top left). This can be accomplished by clicking on "Go Once" 60 times, or "Go" once (top left).

Annotated images of the central area, which is called the World are shown in Fig. D.8.

(a)



(b) Number	
1	A circle with different radius represents a proportion of crop area applied for simulation.
2	A number of solar panels. Each solar panel indicates 1,000 solar panels.
3	A number of wind turbines
4	Surface water showing the quality of water
5	Groundwater showing the quantity of water
6	A proportion of solar energy applied during the simulation
7	A proportion of wind energy applied during the simulation
8	Nitrogen accumulation (rust-colored dots) on the fields during dry and moderate years
9	Nitrogen particles are washed into surface water bodies during wet years
10	Amount of mobile nitrogen transferred to surface water
11	Groundwater turns red when water level drops below 30 feet

Fig. D.8 (a) FEWCalc interface and (b) a list of graphical components within the World.

To obtain the results shown in the article for which this section in an appendix, add a Production Tax Credit (PTC) of 30% and rerun FEWCalc.

To save the input file for the altered run, click File at the top left of the NetLogo window, and click Save As. Save the file as, for example. FEWCalc-PTC.30.nlogo. If this file is clicked to start FEWCalc next time, this change will be implemented.

Step 6. Advanced Features of FEWCalc

6.1 More Information About FEWCalc

For more information, you can click an **Info** tab at the top of the program (Fig. D.9).

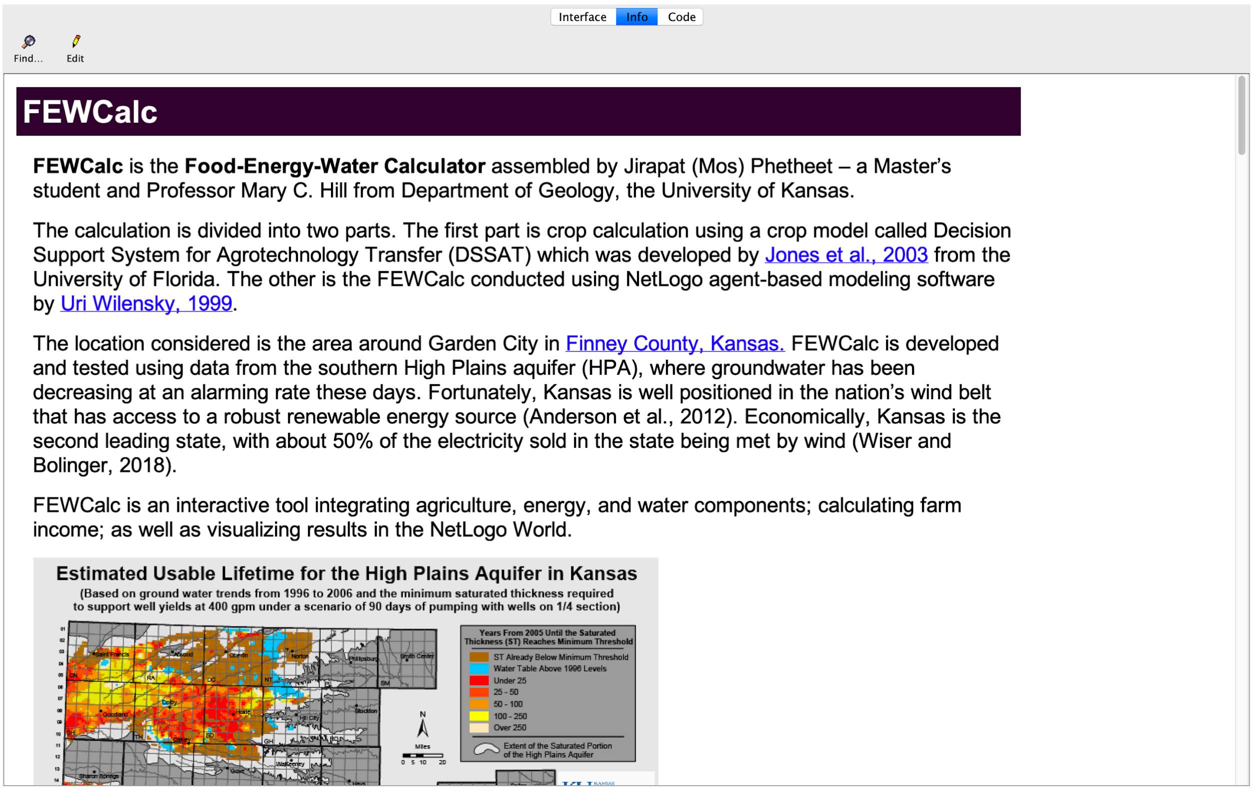


Fig. D.9 Info tab.

6.2 Additional Parameters That Can Be Changed.

Selected parameters are listed at the top of the program under a Code tab, as shown in Fig. D.10. Here, users are able to adjust model inputs such as level of crop insurance coverage, and futures market crop price. These changes will be saved if the project is saved as described at the end of Step 5.

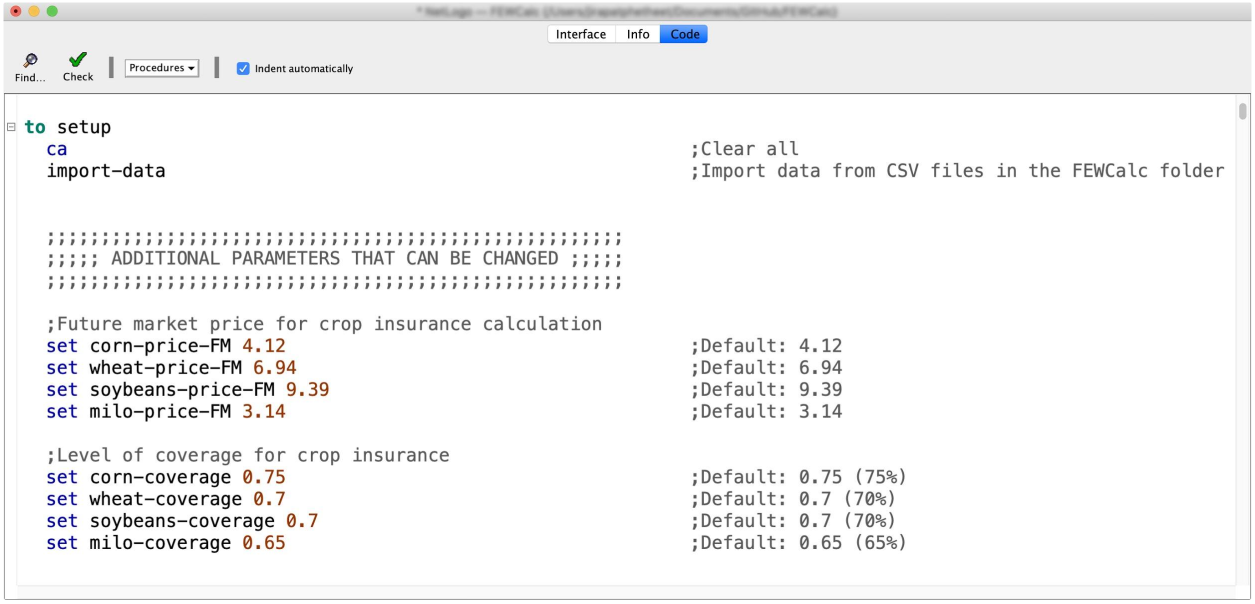


Fig. D.10 Parameter values for which value can be changed at the top of the Code.

Additional input can be controlled by the user through CSV files. The file "*9a_Farm_Expenses_For_Users.csv*" can be used to control crop expenses. The file "*10_capital _depreciation.csv*" can be used to control depreciation rates for each year. These files include labels that define the values listed.

6.3 Restoring Default Values

A default button is provided in the interface to restore variables defined in the FEWCalc interface to their original values.

For the additional parameters mentioned in Step 6.2, default values can be restored by copying csv files *"9b_Farm_Expenses_Reference.xlsx"* to *"9a_Farm_Expenses_For_Users.csv,"* and *"10b_Capital_depreciation_Reference.xlsx"* to *"10a_Capital_depreciation.csv."*

For the values listed at the top under the Code tab, any changes from or back to the originally distributed value are controlled by the user.

6.4 Saving the nlogo File and Files of Results

Clicking File on the top right of the interface window provides the opportunity to save the Nlogo file for future runs and export a range of output files.

CSV files for results from any graph also can be exported by left clicking on a graph and choosing "Export". Default files names are assigned and can be changed by the user.

Step 7. Getting FEWCalc From GitHub Repository When <u>You DO Have a GitHub Account</u>

Go to https://github.com/JPhetheet/FEWCalc. This FEWCalc repository includes a Netlogo file and its supporting documents such as input files and figures used in FEWCalc.

Click **"Fork"** in the top-right corner of the page (Fig. D.11). Forking provides an alternative option for users to freely experiment without affecting the original "FEWCacl" project. The screen will look like that in Fig. D.12.

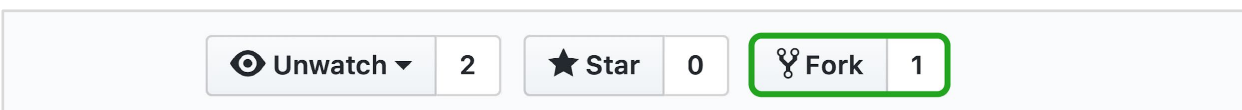


Fig. D.11 Fork a repository.

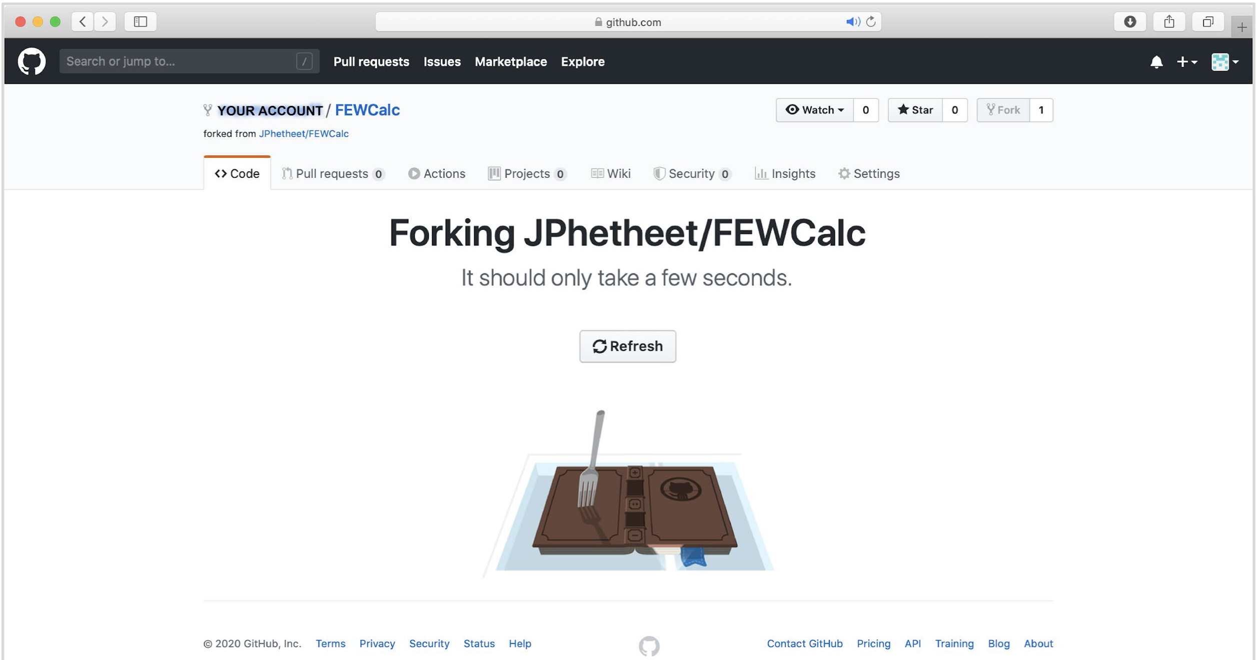


Fig. D.12 FEWCalc repository is forked (copied) from the JPhetheet account to your account.

GitHub now navigates to your user account. See that there is the FEWCalc repository under your account with a note "**forked from JPhetheet/FEWCalc**", as in Fig. D.13.

Click the green button **"Clone or download"** and choose **"Open in Desktop"** to download the files so they can be used and modified in your account.

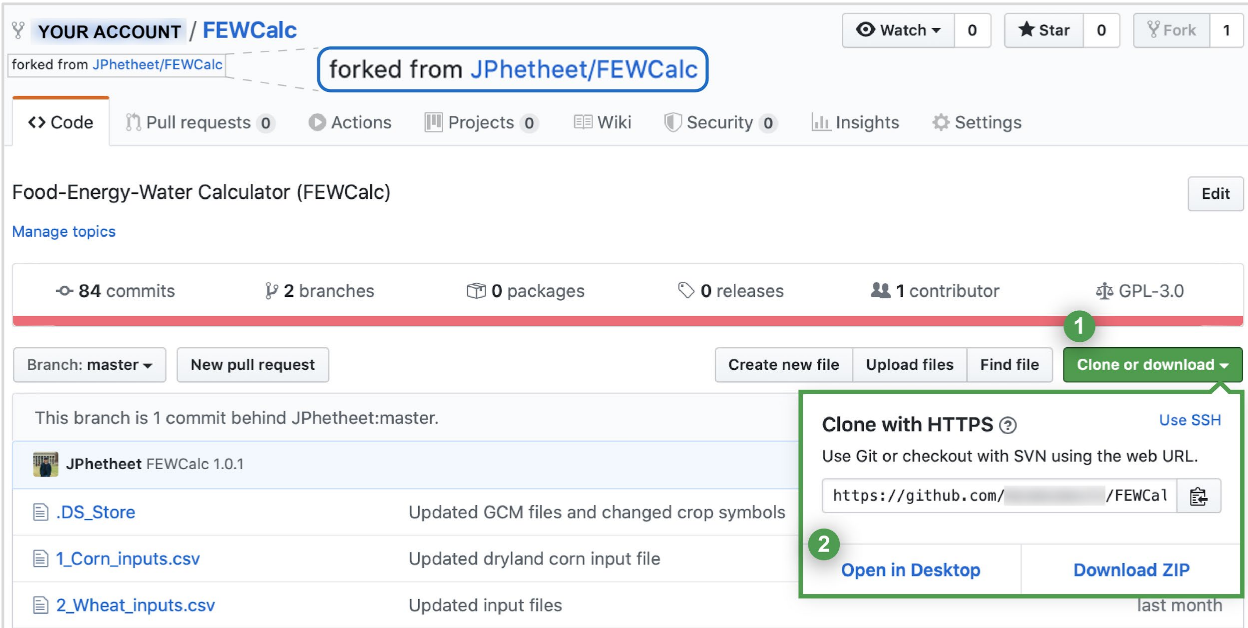


Fig. D.13 Clone your FEWCalc repository to your machine.

GitHub navigates to your GitHub Desktop. Then, **"Clone a Repository"** window appears automatically as shown in Fig. D.14.

Define your local directory to store a FEWCalc folder in your machine.

Repository URL or GitHub and repository

https://github.com/***YOUR-USERNAME***/FEWCalc

Local Path

Choose a local directory in your machine to store FEWCalc

Then, click **"Clone"**. The FEWCalc folder is saved in a local path you choose above.

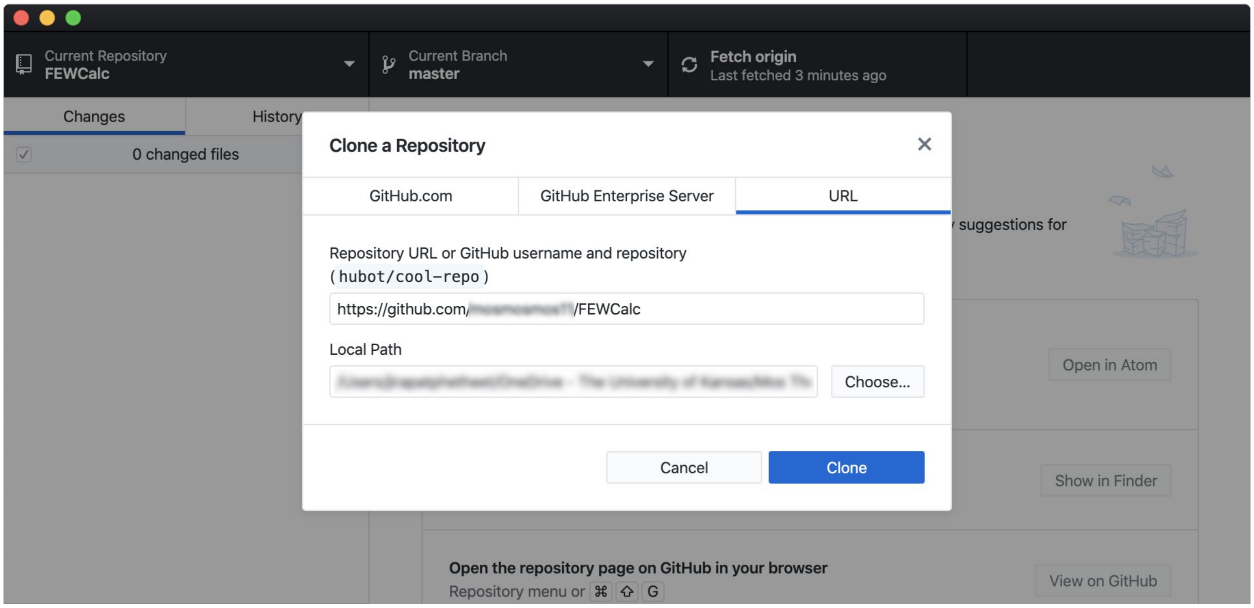


Fig. D.14 Clone a Repository.