

## 1    **Relating Agriculture, Energy, and Water Decisions to Farm Incomes and 2    Climate Projections using Two Freeware Programs, FEWCalc and DSSAT**

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### 18    **Abstract**

19    CONTEXT: The larger scale perspective of Integrated Assessment (IA) and smaller scale  
20    perspective of Impacts, Adaptation, and Vulnerability (IAV) need to be bridged to design long-  
21    term solutions to agricultural problems that threaten agricultural production, rural economic  
22    viability, and global food supplies. FEWCalc (Food-Energy-Water Calculator) is a new freeware,  
23    agent-based model with the novel ability to project farm incomes based on crop selection,  
24    irrigation practices, groundwater availability, renewable energy investment, and historical and  
25    projected environmental conditions. FEWCalc is used to analyze the interrelated food, energy,  
26    water, and climate systems of Finney County, Kansas to evaluate consequences of choices  
27    currently available to farmers and resource managers.

28    OBJECTIVE: This article aims to evaluate local farmer choices of crops and renewable energy  
29    investment in the face of water resource limitations and global climate change. Metrics of the  
30    analysis include agricultural and renewable-energy production, farm income, and water

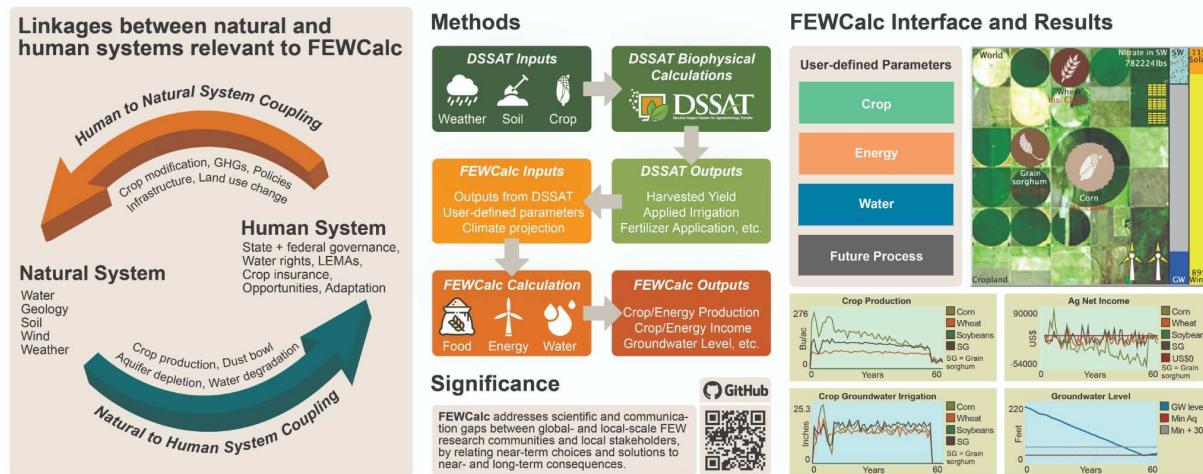
31 availability and quality. The intended audience includes farmers, resource managers, and scientists  
32 focusing on food, energy, and water systems.

33 METHODS: Data derived from publicly available sources are used to support user-specified  
34 FEWCalc input values. DSSAT (Decision Support System for Agrotechnology Transfer) with  
35 added arid-region dynamics is used to obtain simulated crop production and irrigation water  
36 demand for FEWCalc. Here, FEWCalc is used to simulate agricultural and energy production and  
37 farm income based on continuation of recent ranges of crop prices, farm expenses, and crop  
38 insurance; continuation of recent renewable-energy economics and government incentives; one of  
39 four climate scenarios, including General Circulation Model projections for Representative  
40 Concentration Pathway 8.5; and groundwater-supported irrigation and its limitations.

41 RESULTS AND CONCLUSIONS: A 50-year (2018-2067) climate and groundwater availability  
42 projection process indicates possible trends of future crop yield, water utility, and farm income.  
43 The simulation during more wet years produces high crop production and slower depletion of  
44 groundwater, as expected. However, surprisingly, the simulations suggest that only the Drier  
45 Future scenario is commercially profitable, and this is because of reduced expenses for dryland  
46 farming. Although simulated income losses due to low crop production are ameliorated by the  
47 energy sector income and crop insurance, the simulation under climate change still produces the  
48 worst annual total income.

49 SIGNIFICANCE: FEWCalc addresses scientific, communication, and educational gaps between  
50 global- and local-scale FEW research communities and local stakeholders, affected by food,  
51 energy, water systems and their interactions by relating near-term choices to near- and long-term  
52 consequences. This analysis is needed to craft a more advantageous future.

## 53 Graphical Abstract



54

## 55 Keywords

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

## 58 Highlights

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

## 64 1. Introduction

65 Small towns and rural (STAR) agricultural communities produce much of the food for an  
66 increasingly urban world. Yet they face serious problems such as declining populations, increasing  
67 challenges resulting from disadvantageous changes in farm economic conditions, and exacerbating  
68 climatic conditions. Many STAR communities in the USA have been diversifying their economies  
69 over the past 50 years in efforts to sustain their viability (Bureau of Economic Analysis, 2020).  
70 Increasingly, they are taking advantage of their wide open, low density areas to diversify into  
71 renewable energy production. Yet the expertise needed to consider such alternatives is largely  
72 unavailable to many stakeholders.

73            FEWCalc (Food-Energy-Water Calculator) makes expertise accessible to local  
74 stakeholders whose decisions will lead their communities into more viable futures by enabling  
75 clearer understanding of tradeoffs and possibilities. This introduction briefly reviews other  
76 attempts to create similar models and the systems included in FEWCalc, including climate change,  
77 water resource degradation and depletion, renewable energy opportunities, and public policy  
78 priorities. It then briefly outlines how FEWCalc fits into two broad approaches to research on food,  
79 energy, and water system decision-support capabilities.

80            The linkage of the FEW system has been studied and conducted mostly at the academic  
81 level using different approaches and aspects (Endo et al., 2017). For example, some FEW studies  
82 previously focused on land use optimization (Nie et al., 2019), nutrient flow (Yao et al., 2018),  
83 environmental security for livelihood (Biggs et al., 2015), food-energy tradeoff (Cuberos Balda &  
84 Kawajiri, 2020), and water-energy-food production and consumption (Guijun et al., 2017) using  
85 distinct analytical tools such as MATLAB Simulink, crop models, and agent-based models. Most  
86 previous works have not connected all three FEW components together with other variable factors  
87 (e.g., climate projection and economics). Some of the more developed efforts at simulating all or  
88 part of food-energy-water systems are CLEWS (Climate, Land, Energy, Water and Soil) (IAEA,  
89 2009; Villamayor-Tomas, 2015; Welsch, 2014), WEAP (Water and Energy Assessment Program)  
90 (Stockholm Environmental Institute, 2020), and ITEEM (Li, 2021). FEWCalc represents a broader  
91 set of options than these alternatives and is open-source freeware, readily available on GitHub to  
92 serve as a foundation for future development.

93            Climate change is apparent through surface rising temperatures and historically extreme  
94 weather conditions that are becoming more frequent (Campbell, 2020; Lesk et al., 2016). Climate-  
95 change driven increases in water and food insecurity pose emerging and long-term challenges.  
96 Increasing temperatures are already increasing crop water requirements and shifting precipitation  
97 patterns and may directly affect global food supply quantity and quality going forward (Dore,  
98 2005; Li et al., 2019; Wheeler & von Braun, 2013; Zhang et al., 2019). Moreover, shifting  
99 regulations and restrictions on carbon emissions may alter the menu of available adaptation  
100 options. FEWCalc enables users to evaluate the impact on agricultural production of climate  
101 change by choosing future General Circulation Model (GCM) projections and other future climate  
102 scenarios.

103        Water scarcity is an immediate and enduring challenge in many regions, which can in part  
104    be addressed with groundwater reserves. Irrigated areas currently produce 30-40% of the world's  
105    food, and 70% of global water withdrawals are for agriculture (FAO, 2014; Kovda, 1977; WWAP,  
106    2012). Farmers and policy makers in some regions are recognizing the need to collaborate to  
107    extend the usable lifetime of their local water resources by reducing irrigation rates (Hardin, 1968;  
108    Kansas Department of Agriculture, 2021; California Water Boards, 2021). Groundwater is  
109    important: for example, in China's dry northern region, groundwater accounts for as much as 70%  
110    of irrigation in some locations (Calow et al., 2009). In India, it accounts for 70-80% of the value  
111    of irrigated production and supports 90 million rural households (World Bank, 1998; Zaveri et al.,  
112    2016). Groundwater from the Central Valley aquifer of California and the High Plains aquifer  
113    (HPA) supply as much as 16% and 30% of irrigation water in the entire USA (Dieter et al., 2018;  
114    Maupin, 2018; Maupin & Barber, 2005). FEWCalc includes irrigation derived from groundwater  
115    and the generally hidden and delayed effect of declining groundwater on agricultural production.

116        Producing wind and solar energy could contribute to the diversification and viability of  
117    STAR communities' economy in three principal ways. (1) Renewable energy exported to existing  
118    load centers has been profitable for farmers participating in land-lease programs with power  
119    producers (Weise, 2020). (2) FEWCalc is designed to investigate how the direct investment by  
120    rural landowners in renewable energy production changes their economic situation (Epley, 2016;  
121    Hill et al., 2017; Phetheet et al., 2019). Although in the area used to demonstrate FEWCalc wind  
122    turbines tend to be more profitable than solar panels (Fu et al., 2017), both technologies are  
123    included in FEWCalc to generalize its utility. (3) More affordable local renewable energy could  
124    be used to attract and retain businesses to create and grow jobs (Hill et al., 2019). FEWCalc  
125    addresses option 2 and provides a foundation for option 3.

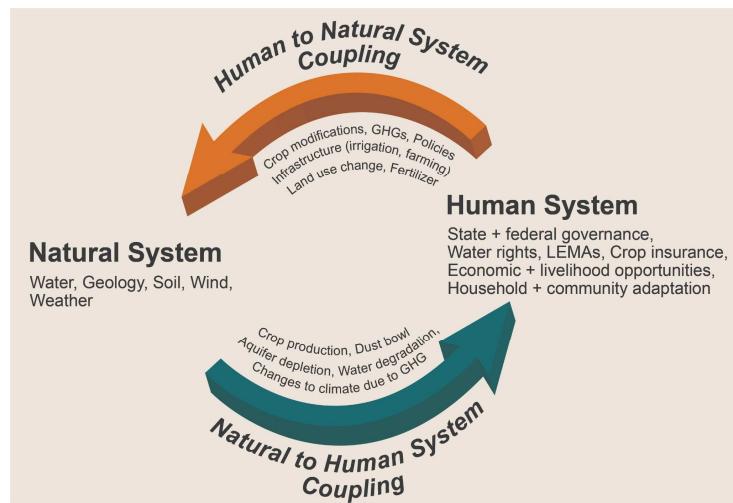
126        Effective policies supporting current and evolving local, regional, national initiatives in the  
127    food, energy, and water nexus are imperative to ensure the sustainable viability of STAR  
128    communities. These will be influenced by institutional, economic and socio-cultural attitudes, and  
129    subjective perceptions (Cash et al., 2006). Farm income, as a major income in STAR communities,  
130    can be affected by these policies. To this end, FEWCalc simulates the effects of crop insurance  
131    and selected renewable energy incentive programs on farm incomes.

132 As a tool focused on how decision-makers perceive the viability of their communities or  
 133 businesses, FEWCalc bridges the gap between two dominant research themes — Integrated  
 134 Assessment (IA), and Impacts, Adaptation, and Vulnerability (IAV) (Table 1). The themes have  
 135 been converging as the value of integrated, multi-scale approaches to climate research has become  
 136 apparent (Absar & Preston, 2015; de Bremond et al., 2014; Huber et al., 2014; Kraucunas et al.,  
 137 2015; Rosenzweig et al., 2014). The standardized, multi-scale Shared Socioeconomic Pathways  
 138 (SSPs) scenario framework (O'Neill et al., 2014) relates economic and technological choices to  
 139 carbon emissions, and is thus closely related to Representative Concentration Pathways (RCPs)  
 140 levels used in FEWCalc. FEWCalc supports carbon emission mitigation through developing  
 141 greater local familiarity with renewable energy production and greater research-level familiarity  
 142 with the challenges of local stakeholders. Fig. 1 shows how the major components of the FEW  
 143 system form a natural and human system of concern to IA and IAV, showing how they can be  
 144 thought of as a collection of heterogeneous and autonomous individuals interacting cooperatively  
 145 and competitively with one another and the environment (Bert et al., 2015; Hu et al., 2018).

146 **Table 1.** Summary IA and IAV approaches to technology and policy analysis.

Description	IA (Integrated Assessment)	IAV (Impacts, Adaptation, and Vulnerability)
<b>Typical topic</b>	<b>Climate policy impacts<sup>1</sup></b>	<b>Climate change effects and responses<sup>2</sup></b>
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.

147 <sup>1</sup>Weyant, (2017). <sup>2</sup>Absar & Preston, (2015) and van Ruijven et al., (2014).



148

149 **Fig. 1.** The linkages between natural and human systems relevant to FEWCalc (modified from K.  
 150 Rogers, East Carolina University, written communication, 2017; NSF [National Science  
 151 Foundation], 2018). LEMA (Local Enhanced Management Area) is a governance structure used  
 152 in the state of Kansas, USA, to limit water use from a depleted aquifer.

153 Unresolved scale and human connection issues still limit the utility and relevance of IA  
 154 and IAV models (Ericksen, 2008; Ericksen et al., 2009; Vervoort et al., 2014). For example,  
 155 national policies could be rendered ineffective for want of local-level adaptation and mitigation  
 156 options, and local-level efforts could be stymied by national policy or global market conditions.  
 157 Climate, weather, hydrology, politics, energy, and economics are all important and interact across  
 158 multiple societal scales, including jurisdictional, institutional, and managerial ones (Cash et al.,  
 159 2006; Allan et al., 2015; Endo et al., 2017), so that FEWCalc exists within the context of national-  
 160 and global-scale dynamics (Ericksen et al., 2009). Proper support and coordinated action are  
 161 required for successful outcomes such as those achieved by Sustainable Groundwater Management  
 162 Act (SGMA) in California and the LEMAs in Kansas. The FEWCalc model can be thought of as  
 163 addressing three key needs identified by Vervoort et al. (2014): (1) engage diverse stakeholders  
 164 across multiple levels; (2) move beyond analysis of single interventions towards system-wide  
 165 measures that act across multiple spatial, temporal, and geographic scales; and (3) develop long-  
 166 term capacity for collaborative decision making.

167 FEWCalc is an agent-based model (ABM) constructed using NetLogo (Hu et al., 2018;  
 168 Tisue & Wilensky, 2004; Wilensky, 1999), designed to integrate complex real-world systems and

169 evaluate future policy decisions (Anderson & Dragićević, 2018; Guijun et al., 2017). ABMs have  
170 been used in business (Forrester, 1971; Morecroft, 2015), urban problems (Sterman, 2000), and  
171 environmental evaluations (Meadows, 2008) and recently for the FEW nexus (Al-Saidi & Elagib,  
172 2017; Memarzadeh et al., 2019; Schulterbrandt Gragg et al., 2018). Most of this recent research  
173 has been conceptual or focused on regional applications. Focus on individual stakeholders is rare  
174 (Ravar et al., 2020; Shannak et al., 2018) and mostly limited to urban systems (Bieber et al., 2018;  
175 Guijun et al., 2017). FEWCalc is novel and contributes to the emerging ABM literature using the  
176 NetLogo platform.

177 The purpose of this study is to develop a scientific tool able to represent a real-world  
178 complex system composed of agriculture, energy production, and water use under complicated  
179 climate and economic conditions, and use it to reveal unexpected interactions within this system  
180 of systems that are important to stakeholders. The rest of this article, along with online appendices  
181 A-D, describes the methods and data using in FEWCalc and its utility in a scientific investigation  
182 of the roles played by water scarcity and climate change in the productivity and economics future  
183 of a typical STAR community

184 **2. Methods**

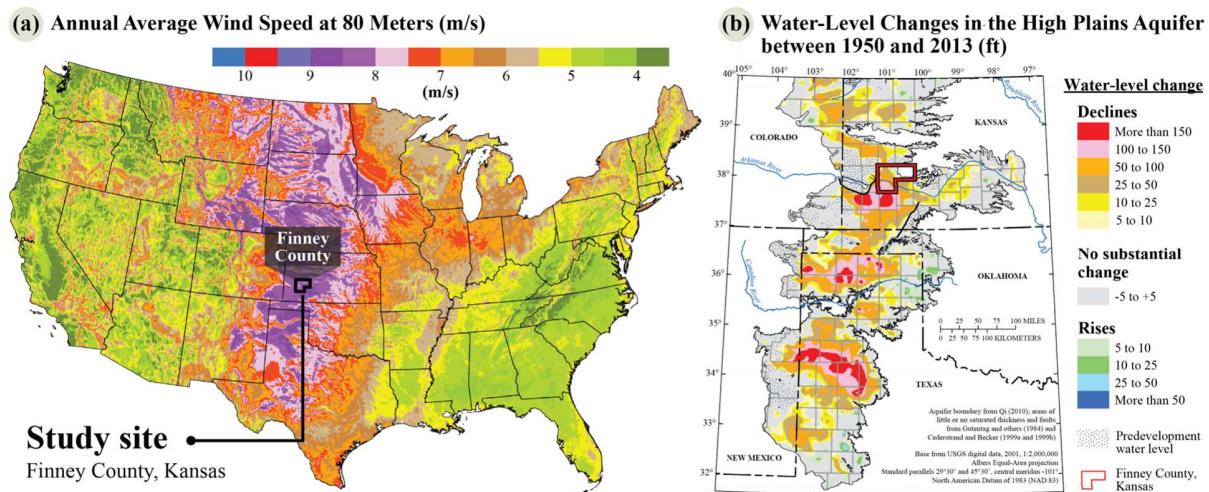
185 In this section, the FEWCalc workflow is briefly introduced, and FEWCalc components  
186 and related equations are described using a Finney County, Kansas test case to provide motivation  
187 and examples. The Decision Support System for Agrotechnology Transfer (DSSAT) model (Araya  
188 et al., 2019; Jones et al., 2003; Jones et al., 2017a, 2017b; Sharda et al., 2019) was chosen for the  
189 agrosystems simulations based on its capabilities, availability, and feasibility. Selected DSSAT  
190 and FEWCalc inputs, outputs, and equations are listed here; more detail is provided in appendices  
191 A, B, and C. Default values for user-controlled FEWCalc variables are provided in Table D.1. As  
192 programmed, all costs are in US dollars.

193 **2.1 Workflow and Case Study from the High Plains Aquifer, USA**

194 The workflow of FEWCalc with inputs from DSSAT is shown in Fig. A.1, including  
195 components representing agriculture, energy, and water. Climate data and crop choices are entered  
196 using the weather data DSSAT input or WeatherMan (Pickering et al., 1994). DSSAT is then  
197 executed to provide input needed for FEWCalc via files in a comma-separated values format (CSV

198 files). The final results are presented in graphs as shown in Fig. A.1. Selected graphs are presented  
 199 in the Results section of this article. The time discretization of DSSAT is one day. FEWCalc time  
 200 is incremented annually and simulation length is defined by the user, with simulations of 60 to 90  
 201 years being common.

202        FEWCalc is developed and tested using data from Finney County, Kansas, USA (Fig. 2).  
 203 The High Plains aquifer (HPA) consists of the Ogallala aquifer and its overlying aquifer units. The  
 204 area's water problems are typical of arid agricultural regions around the world: Large-scale  
 205 irrigation over many decades has depleted groundwater resources and produced now dry irrigation  
 206 wells (Buchanan et al., 2015). The region's potential to develop renewable energy, its declining  
 207 water resources, and its rich, 70-year-long time series of historical data makes it an ideal candidate  
 208 for exploring opportunities to sustain farmers' economic well-being under alternative agricultural  
 209 and energy production choices using FEWCalc.



210        **Fig. 2.** (a) Average annual wind speed map for the Continental USA (modified from NREL, 2011).  
 211 Finney County has very high average wind speeds (shown here) and moderate solar energy  
 212 supplies (not shown). (b) High Plains aquifer water-level changes (modified from McGuire, 2014).

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

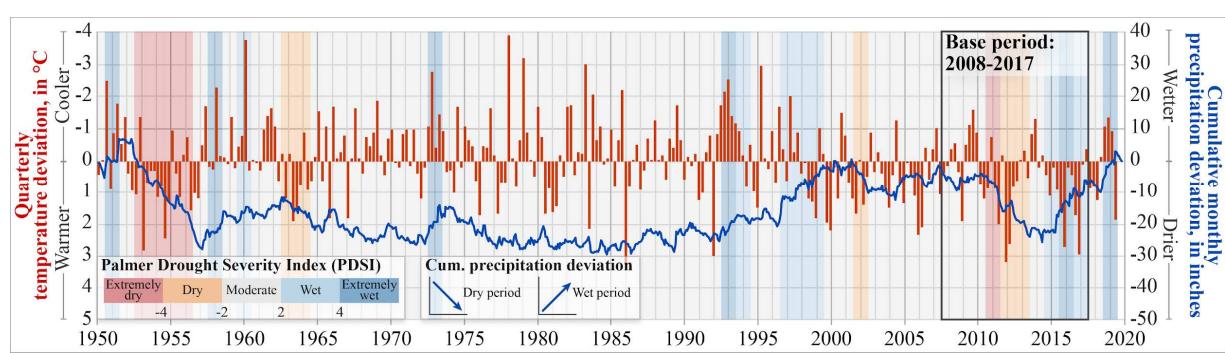
219 **2.2 Weather, Climate, and Projections**

220 Daily weather data for air temperature, precipitation, and solar radiation are used as input  
 221 to DSSAT (Tsuji et al., 1994) and acquired as described in Appendix A.

222 A 10-year period from 2008 to 2017 is used as the historical base period for this work. This  
 223 10-year period is presented in the context of data since 1950 in Fig. 3, in which wet and dry periods  
 224 are identified using the Palmer Drought Severity Index (PDSI) (Palmer, 1965). The base period  
 225 was chosen because a generally complete set of weather and agricultural data is available, and  
 226 because wet, moderate, and dry years are included in that period of time (see Fig. 3). This  
 227 variability is used to create future climate scenarios.

228 The four 60-year long scenarios used to demonstrate FEWCalc are listed in Table 2. All  
 229 scenarios have the same 10-year (2008 to 2017) temperature, precipitation, solar radiation, and  
 230 agricultural price conditions, and differ for the following 50 years. **Scenario 1**, Repeat Historical  
 231 tests the time progression in FEWCalc, and allows users to focus on the impact of groundwater  
 232 declines and energy production. **Scenarios 2 and 3** are dominated by wetter or drier years to create  
 233 wetter and drier “futures”. The weather data are chosen from the 10-year base set of years. So, for  
 234 example, if those 10 years are numbered 1, 2, ..., 10, years 8, 9, and 10 are wet (Fig. 3). Going  
 235 forward, 7 of each 10 years will be selected from the three wet years. The other 3 of each 10 years  
 236 are chosen from the 4 moderate base years (years 1, 2, 3, and 7). The random sequence of moderate  
 237 to wet years results in increased crop production with no significant loss of yield. **Scenario 4** is  
 238 based on 20 General Circulation Model projections out to 2098 (Fig. A.5), though only the values  
 239 through 2067 are used in the FEWCalc demonstration provided in this work. Projected crop prices  
 240 are described in Section 2.3.2.

241



242 **Fig. 3.** Annual average PDSI, monthly cumulative precipitation deviation, and quarterly  
243 temperature deviation data from January 1950 to September 2019. Monthly and quarterly base  
244 values are listed in Table A.13. The 2008-2017 base period used in this work is highlighted. The  
245 axes for precipitation and temperature deviation are scaled so that conditions producing drought  
246 (high temperature and low precipitation) produce downward pointing bars of temperature  
247 deviation and downward sloping trend of cumulative precipitation deviation.

248 **Table 2.** Simulation scenarios used to represent climate conditions in DSSAT for the 50-year  
249 projection period (2018-2067) that follows the 2008-2017 historical base period in the FEWCalc  
250 simulations.

Name	DSSAT Temporal Progression of T, P, and S <sup>1</sup>
<b>Scenario 1. Repeat Historical</b>	Repeat conditions from 2008 to 2017 for all 50 years of the projection period.
<b>Scenarios 2 &amp; 3. Wetter/Drier Future</b>	Use more wet or dry years from 2008 to 2017, respectively to create a correlated random 50-year projection. The Wetter Future is similar to this area in the 1990s; the Drier Future is similar to this area in the 1950s.
<b>Scenario 4. GCM-simulated RCP8.5 T, P, and S Changes<sup>2</sup></b>	Apply GCM-simulated climate for the 50-year projection period

251 <sup>1</sup>T, temperature, in degrees Celsius; P, precipitation, in inches per year; S, solar radiation, in watts per square meter.

252 <sup>2</sup>GCM, General Circulation Model.

253 Scenario 4 uses DSSAT results in which runs use projected air temperature, precipitation,  
254 and solar radiation from 20 downscaled GCMs to represent years 2008 to 2067 (Taylor et al., 2009,  
255 2012). Results from the 20 DSSAT runs are averaged and used in FEWCalc. RCP 4.5 and 8.5  
256 results are available in FEWCalc — see Appendix B for a discussion of RCP. FEWCalc results  
257 using the RCP 4.5 and 8.5 scenarios are compared in Phetheet et al. (2021). Results from the more  
258 severe RCP 8.5 are presented in this article.

## 259 **2.3 Calculations for Agriculture**

260 FEWCalc starts with the assumption that the decision maker is already in business as a  
261 farmer and, for the demonstration provided here, produces crops in the Garden City area of Finney  
262 County, Kansas. FEWCalc envisions a farmer considering investments in renewable energy as a  
263 diversification strategy to improve farm incomes, which have been extremely variable in the last  
264 decade. The environmental conditions and resources are as described in Sections 2.2 and 2.5.  
265 Therefore, FEWCalc's focus is on farm operations and renewable-energy investment decisions.  
266 Methods for simulating crop production, crop net income, and crop insurance are presented below.

267 To communicate results to stakeholders, this article presents both English and metric units. DSSAT  
268 uses metric units. In this section, metric units or appropriate conversion factors are listed to  
269 facilitate cross-referencing to DSSAT results.

270 **2.3.1 Crop Production**

271 The crops commonly produced in Kansas are corn, winter wheat, soybeans, and grain  
272 sorghum, all of which FEWCalc incorporates into the simulations (Table A.2). Fig. A.3 shows  
273 Kansas crop production, planted acres, crop prices, and, to represent expenses, gasoline prices in  
274 the USA from 1866 to 2019. The increase in productivity per acre is apparent by comparing Figs.  
275 4a and 4b. Although soybeans are generally not produced in Finney County due to unfavorable  
276 soil and heat conditions, they are retained in the software because it is a common crop throughout  
277 the USA Midwest, and hence allow for other locations to use FEWCalc without major changes.

278 DSSAT simulations are conducted using a one-day time step. Results are accumulated to  
279 produce annual results for FEWCalc. Datasets are prepared using DSSAT built-in software  
280 programs XBuild and SBuild (Fig. A.1). XBuild allows users to specify management options such  
281 as cultivars, planting date, and plant population. SBuild assembles physical and chemical soil data.  
282 The soil database available in DSSAT was developed by the International Soil Reference and  
283 Information Centre for the project “World Inventory of Soil Emission Potentials (WISE)”. The  
284 WISE database is one of the most comprehensive soil databases, with samples well distributed  
285 globally (Gijsman et al., 2007).

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

292 The long periods of interest in this work were simulated using the DSSAT Biophysical  
293 Analysis part of the Seasonal Analysis option. Outputs such as harvest yield, applied irrigation,  
294 and applied fertilizer are calculated based on parameters defined in Table A.2; the values were  
295 chosen based on the cited references.

296                   **2.3.2 Crop Income After Variable Costs**

297           Revenue from crop production is the product of crop output and price per acre, and acres  
298           planted. Because farmers often produce more than one crop per year, production costs may be  
299           shared across more than one crop. Therefore, net farm income from crop production is the  
300           difference between gross revenue from crop production less total variable costs. Future crop yield,  
301           crop prices, and input costs are all uncertain (Figs. 4a and 4c). While production variability may  
302           be attributed to weather and other production vicissitudes, price variability is driven by global  
303           market conditions and trade and other policies (USDA, 2020). No attempt to project this process  
304           is made in FEWCalc since no individual farmer or group of farmers influence prices. However,  
305           the Midwest USA is a large enough producer of global corn and sorghum to affect global prices  
306           (USDA, 2020). This means higher supplies during good weather years often depress prices and  
307           vice versa. Although western Kansas is a major wheat production area in the USA, it is not large  
308           enough to influence global prices. These conditions define how prices are treated in FEWCalc.

309           The FEWCalc base period (2008-2017), has three wet, three dry, and four average years,  
310           and is used to create projected climate conditions as described in Section 2.2. For corn and grain  
311           sorghum, the following procedure is used. In Scenario 1, the base period prices along with the  
312           climate data (temperature and precipitation) are repeated in sequence five times to create the 50-  
313           year projections. For Scenarios 2 and 3, the base period is used to define 10 sets of annual climate  
314           and crop-price data and selections are made from this 10-member set (with replacement) to create  
315           wetter and drier futures. For Scenario 4, prices are assigned based on precipitation: Less than 17  
316           inches of precipitation is considered a dry year and price is selected randomly from one of the  
317           three dry years; 20 inches or more is treated as a wet year and price is selected randomly from one  
318           of the three wet years.

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

322           Total annual crop income after variable expenses is computed as:

$$Income_{C\_t} = \sum_i [(p_{i\_t} \times q_{i\_t}) - w_{i\_t}] \quad i = 1, 2, \dots, N \quad (1)$$

324 Where  $Income_{C\_t}$  is crop income after variable expenses earned for each year t in US dollars per  
325 acre, and i identifies an acre;  $p_{i\_t}$  is the market price per bushel,  $q_{i\_t}$  is the yield (bushels/acre from  
326 DSSAT) and  $w_{i\_t}$  is the variable production costs per acre for the crop planted on acre i. The items  
327 making up the variable production costs are irrigation, fertilizer, herbicide, pesticide, labor, rent,  
328 and crop insurance; details are listed in Tables A.5 to A.8. As noted in Table A.7, six of the  
329 included costs are not strictly variable costs. They are included to reflect what is thought to be a  
330 fair representation of operating costs for irrigated and unirrigated farming.

331 **2.3.3 Crop Insurance**

332 Agricultural farm income support takes many forms which may or may not improve  
333 financial stability (Mishra & Cooper, 2017). FEWCalc includes the option of insurance for crop  
334 yield. General characteristics of crop-yield insurance are described by Edwards (2011) and RMA  
335 (2020). Crop-yield insurance is purchased to protect against potential losses of crop yield from  
336 natural disasters, and especially droughts. In practice, insurance companies will increase premiums  
337 if indemnities are high, so over the long term, farm incomes will not be increased by crop  
338 insurance. However, the insurance does mitigate income declines in exceptionally bad years. In  
339 FEWCalc, the crop prices and premiums from the 2008-2017 base period are maintained, and years  
340 and values of indemnities are noted. How crop insurance is represented in FEWCalc is described  
341 in Appendix C, Eqs C.1 to C.4.

342 **2.4 Calculations for Renewable Energy**

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

346 The version of FEWCalc presented here considers farmer-owned energy production  
347 facilities that serve both local electric loads and electricity sale to the grid. These are not  
348 represented explicitly, the FEWCalc input is simply the resulting average value obtained from the  
349 electricity produced. Section 2.4.1 describes this process.

350                   **2.4.1 Energy Net Income**

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

$$353 \quad Income_{E\_t} = Income_{W\_t} + Income_{S\_t} = Energy\_value_t \times (M_{w\_t} + M_{s\_t}) \quad (2)$$

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

366                   The effects of equipment depreciation on net income are simulated using a CSV file that is  
367                   read by FEWCalc and defines the percent of installed cost to be depreciated, the depreciation taken  
368                   each year, and the tax rate of 20% to be applied (see Appendix A). This deduction may require a  
369                   third-party financial partner. This tax savings can be used to increase farmer income or reduce the  
370                   loan to cover the renewable energy costs.

371                   In Eqs. C.5 and C.15, installed costs for energy production are financed over a period  
372                   defined by the user as a fraction of the life of the equipment ( $N_{yearsW}$  or  $N_{yearsS}$ ) and an interest  
373                   rate (APR) that is also defined by the user.

374                   **2.4.2 An Overview of Energy Production and Regulatory Environment**

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

378           Regulation of solar production can depend on capacity, and policy is not well established.  
379           Commercial size installed solar capacity is about 1 MW in Kansas (KCC, 2019); capacities under  
380           3MW are commonly classified as small (Green Coast, 2019). States with less total solar capacity  
381           tend to have smaller installations: in the three lowest ranked states (including Kansas) solar  
382           installations for agricultural use average around 0.0004 MW (Xiarchos & Vick, 2011). In 2019,  
383           Kansas had 47 MW of installed solar (SEIA, 2020a). In contrast, neighboring Missouri, with less  
384           solar potential but more solar-friendly policies, had 258 MW of installed solar capacity (SEIA,  
385           2020b).

386           FEWCalc supports the installation of up to 2.4 MW of solar installed capacity, which  
387           would require 8,000 solar panels with a combined area of 16.6 acres (6.7 hectares) (Ong et al.,  
388           2013). In southwest Kansas, where an average peak sun hour (*PSH*) is 5.6 hours per day, Eq. C.21  
389           suggests that these solar panels would produce about 4,906 MWh of electricity per year. Eq. C.11  
390           indicates that it would require about 0.7 2-MW wind towers and 0.9 acres of land (0.4 hectares) to  
391           produce the same output per year (Denholm et al., 2009). The net revenue gained by this land use  
392           would need to be compared with crop revenues as part of deciding whether to make the renewable  
393           energy investment. FEWCalc provides the results needed for the user to produce such a  
394           comparison.

395           **2.4.3 Financial Assumptions — Energy Equipment Tax Incentives and Depreciation**

396           Tax incentives and equipment depreciation can produce large tax deductions that exceed  
397           what some owners can deduct from their taxes. It can thus be advantageous to contract with a third-  
398           party financial partner, called a Tax Equity Investor, who can claim the credit and return much of  
399           the value to the owner, depending on the agreement made; typical cost is 6-7% (M. Gilhouse, 400  
written communication, 2020). In FEWCalc, use of the tax incentives (ITC or PTC; see Eqs. C.13,  
401           C.15 and C.23) and depreciation often imply that such third-party arrangements are involved. The  
402           transaction fee is not included, and the entire value of any tax credit and deduction is applied to  
403           the owner as income in the year it is incurred. It could be accumulated to defray the cost of updating  
404           equipment, but FEWCalc does not provide for this.

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

408        **2.5 Calculations for Water**

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

416        **2.5.1 DSSAT Irrigation Calculation for Arid Regions**

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

423        **2.5.2 Calculating Groundwater Levels Based on Water Use**

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

431 For FEWCalc, a two-step process was developed using two linear regressions and reported  
432 Finney County data from B. Wilson (Kansas Geological Survey, written communication, 2019).  
433 The process is described in Appendix A using Fig. A.5.

434 **2.5.3 Nitrogen Concentrations in Surface Water**

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

442 **2.6 FEWCalc Interface**

443 FEWCalc's NetLogo interface (Fig. D.5) is divided into three main areas. From left to  
444 right, the areas include (1) sliders, input boxes, and dropdown menus that allow users to vary  
445 model parameters and control the simulation (see Fig. D.6). All inputs are at default values (Table  
446 D.1) except ITC<sub>S</sub> is set to 30%. (2) In the center, a NetLogo World area shows circular cultivated  
447 areas, solar panel and wind turbine installations, and groundwater (GW) quantity and surface-  
448 water (SW) quality impacts, and a fraction of energy produced from solar and wind (see Fig. D.8).  
449 (3) Eight output plots on the right show FEWCalc results evolving over time.

450 In years that production conditions trigger an insurance claim, the text "Ins. Claim"  
451 appears next to the related crop in the World. The indemnity is shown in the lower right graph.  
452 The rust-colored dots are used to represent nitrogen accumulation on fields and its concentrations  
453 in surface water (see Section 2.5.3). Each particle represents 10,000 lb (4,500 kg) of nitrogen.  
454 Groundwater levels vary as irrigation is applied each year as described in Section 2.5.

455 **3. Results**

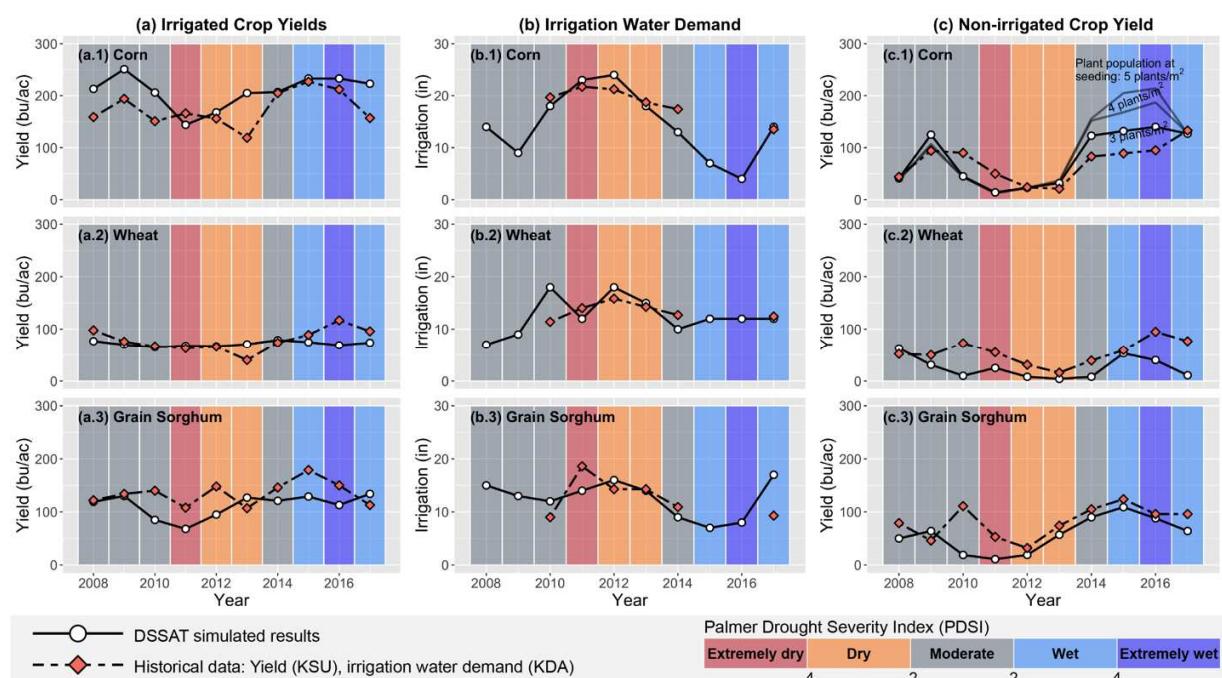
456 For the results presented here, the input values are those shown in Fig. D.5, except that the  
457 future process is modified for Scenarios 2 through 4. The solar panels occupy about 5.2 acres (2.1  
458 hectares), and a similar area is occupied by the wind turbines (Denholm et al., 2009).

459 Results comparing the DSSAT simulation with historical results are presented in Section  
 460 3.1. The four subsequent sections show results from the four climate scenarios listed in Table 2  
 461 and support an analysis of climate impacts on crop income in the context of potential farm energy  
 462 capacity development. Finally, Section 3.6 focuses on financial results from all simulations.

463 **3.1 Comparison with Historical Data**

464 Crop production and irrigation water use simulated by DSSAT for 2008 to 2017 are  
 465 compared to historical data in Fig. 4. As in Fig. 3, colors based on PDSI are used to identify dry  
 466 and wet years. Fig. 4 suggests crop yields and water use are reasonably well represented using  
 467 DSSAT, though in some years the differences are substantial (for example, non-irrigated grain  
 468 sorghum yield in 2010).

469 For non-irrigated corn, the simulated yield was unrealistically large during some wet years,  
 470 and it was suspected that the plant population per acre was too high. Fig. 4c (top figure) shows the  
 471 effects of accounting for the plant population at seeding for corn under dryland farming. In this  
 472 work, a plant population of 13,000 plants/acre (3 plants/m<sup>2</sup>) was used.



473  
 474 **Fig. 4.** Comparison of the DSSAT results (solid lines) and historical data (dashed lines) between  
 475 2008 and 2017 for corn, wheat, and grain sorghum. (a) Irrigated crop yields, (b) Irrigation water

476 demand, (c) Non-irrigated crop yields. (Crop yield data from the Department of Agronomy,  
477 Kansas State University, irrigation data from KDA, and simulated results are in Tables A.4, A.11,  
478 B.1 and B.2). Conversion: 1 bu/ac corn or grain sorghum = 62.77 kg/ha, 1 bu/ac wheat = 67.25  
479 kg/ha, and 1 in = 2.54 cm. Moisture adjustments have been applied (see Table A.10).

480 **3.2 Scenario 1: Repeat 10 historical years to create the 60-year simulation**

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

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

490 **3.3 Scenario 2: Wetter Future**

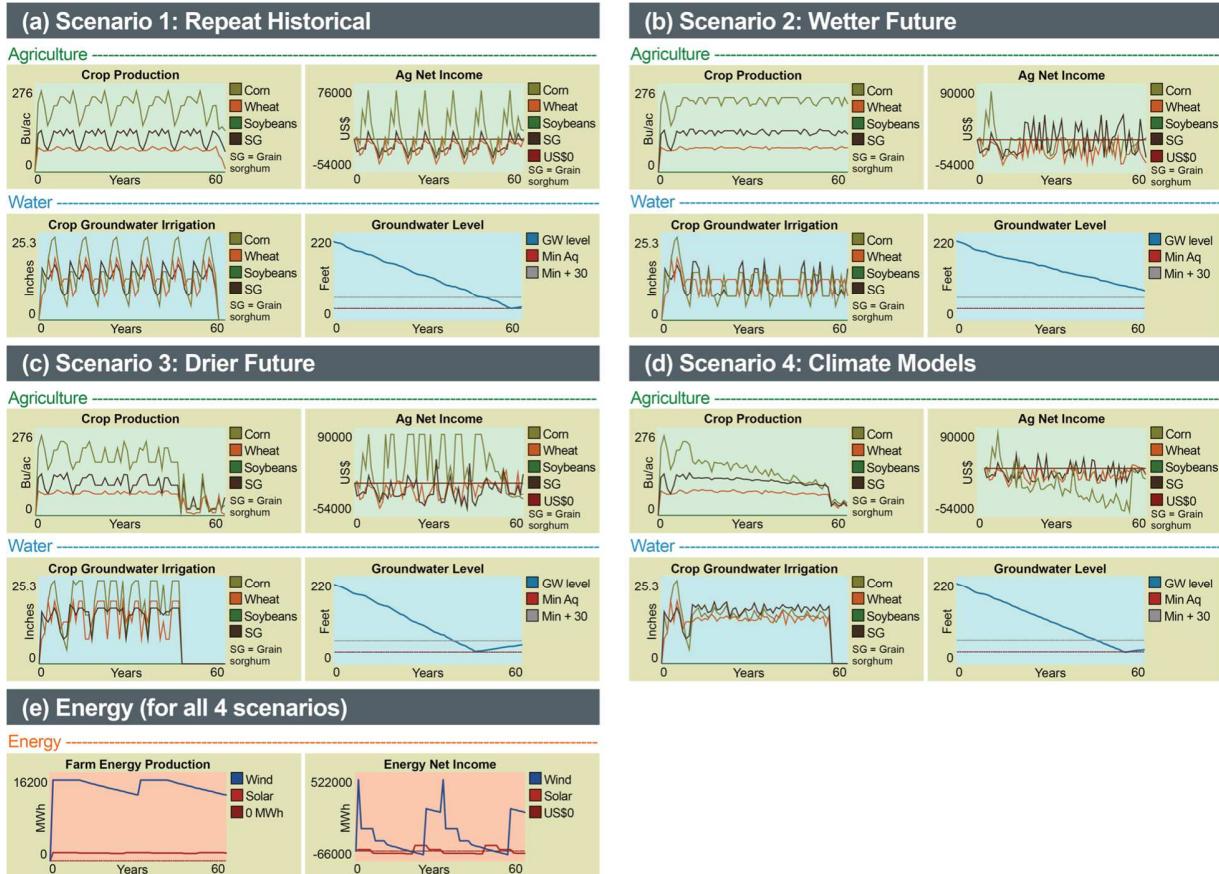
491 For the wetter future, FEWCalc randomly chooses a greater percentage (70% instead of  
492 the original 30%) of wet years.

493 **3.4 Scenario 3: Drier Future**

494 For the drier future, FEWCalc randomly chooses a higher percentage of dry years (70%  
495 instead of the original 30%). As compared to the wet scenario (Fig. 5b), Fig. 5c shows that crop  
496 production simulated for a dry climate scenario drops in many simulation years.

497 **3.5 Scenario 4: RCP 8.5 Temperature, Precipitation, and Solar Radiation Changes to Create  
498 the 50-Year Future.**

499 In Fig. 5d, the first 10 years of crop production reflect historical (2008-2017) climate  
500 variability, while years 11 to 60 (2018 to 2067) show GCM results that tend to be smoother because  
501 results from 20 GCMs are averaged (Figs. B.1 and B.3).

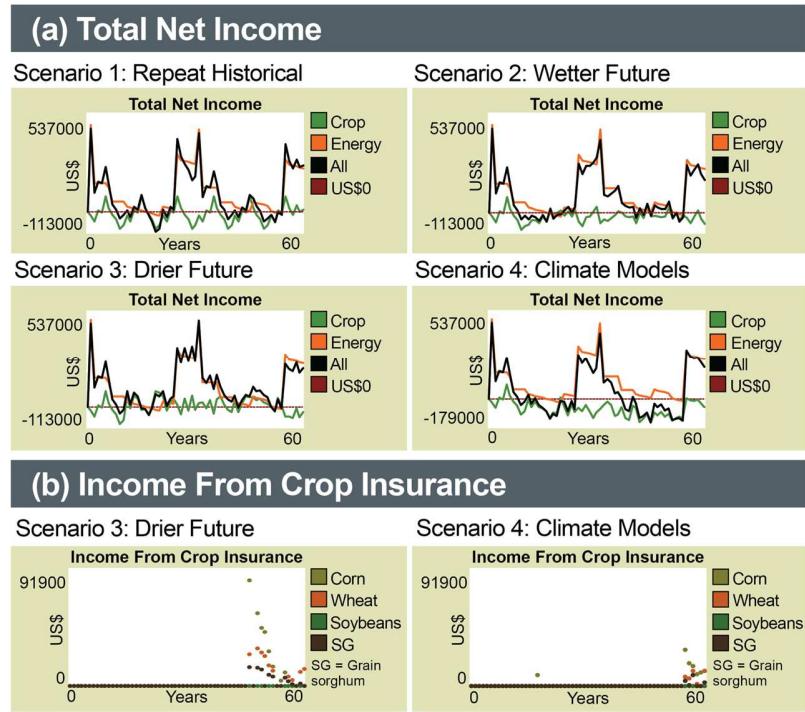


502

503 **Fig. 5.** FEWCALC annual results showing agricultural crop production and net income, energy  
 504 production and net income, and crop groundwater irrigation and groundwater level for all four  
 505 climate scenarios. Dashed lines in the charts represent significant values for reference.  
 506 Abbreviation: bu = bushel, ac = acre, SG = grain sorghum, US\$ = US dollar, MWh = megawatt-  
 507 hour, GW level = groundwater level, Min Aq = minimum available aquifer thickness, and Min +  
 508 30 = a level of 30 feet above minimum thickness. Conversion: 1 bu/ac corn or grain sorghum =  
 509 62.77 kg/ha, 1 bu/ac wheat = 67.25 kg/ha, 1 in = 2.54 cm, and 1 ft = 0.3 m.

510 **3.6 Total Net Income and Crop Insurance for All Four Scenarios**

511 Total farm net annual income is shown in Fig. 6a; income from crop insurance (the  
 512 indemnity) is shown in Fig. 6b. Selected metrics for the four runs are shown in Table 3. Time  
 513 series shown for the four scenarios in Fig. 5 are discussed in Section 4 of this article.



515 **Fig. 6.** (a) Total net income and (b) income from crop insurance. The yield-based crop insurance  
 516 tends are indemnified mostly when farming converts from irrigated to non-irrigated (e.g., year 58  
 517 in Scenario 3). Plots for Scenarios 1 and 2 are not shown because annual crop insurance  
 518 indemnifications were less than \$31,000 for Scenario 1 and not indemnified for Scenario 2

519 **Table 3.** Metrics from the four scenarios for 60 years of FEWCalc simulation (2008-2067). All  
 520 monetary amounts are in US dollars.

	Scenario 1 (Repeat Historical)			Scenario 2 (Wetter Future)			Scenario 3 (Drier Future)			Scenario 4 (GCMs, RCP 8.5)		
	C <sup>1</sup>	W <sup>2</sup>	SG <sup>3</sup>	C <sup>1</sup>	W <sup>2</sup>	SG <sup>3</sup>	C <sup>1</sup>	W <sup>2</sup>	SG <sup>3</sup>	C <sup>1</sup>	W <sup>2</sup>	SG <sup>3</sup>
Average annual crop yield, bushels/acre <sup>4</sup>												
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	<span style="color: red;">-US\$14,197</span>			<span style="color: red;">-US\$20,194</span>			<span style="color: green;">US\$6,818</span>			<span style="color: red;">-US\$61,321 (46,734)</span>		
from energy	<span style="color: green;">US\$109,324</span>			<span style="color: green;">US\$109,324</span>			<span style="color: green;">US\$109,324</span>			<span style="color: green;">US\$109,324 (122,970)</span>		
total	<span style="color: green;">US\$95,127</span>			<span style="color: green;">US\$89,130</span>			<span style="color: green;">US\$116,142</span>			<span style="color: green;">US\$48,003 (146,563)</span>		
Net Present Value (NPV) <sup>5</sup>												
from agriculture	<span style="color: red;">-US\$0.4M</span>			<span style="color: red;">-US\$0.5M</span>			<span style="color: green;">US\$0.1M</span>			<span style="color: red;">-US\$1.3M</span>		
from energy	<span style="color: green;">US\$2.9M</span>			<span style="color: green;">US\$2.9M</span>			<span style="color: green;">US\$2.9M</span>			<span style="color: green;">US\$2.9M</span>		
total	<span style="color: green;">US\$2.5M</span>			<span style="color: green;">US\$2.4M</span>			<span style="color: green;">US\$3.1M</span>			<span style="color: green;">US\$1.6M</span>		

521 <sup>1</sup>Corn, <sup>2</sup>Wheat, and <sup>3</sup>Grain sorghum. <sup>4</sup>For scenario 4, the standard deviation of the 20 GCM results are presented in parentheses. <sup>5</sup>Discount rate is  
 522 3.25% (prime rate as of June 2020); FEWCalc agriculture and energy finances are combined; for energy, capital costs are explicitly included for  
 523 energy and depreciated over 10 years assuming a tax rate of 20%, for agriculture, capital costs are applied as listed in Table A.7.

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

#### 531 4. Discussion

532 FEWCalc is designed to produce the same net income for all scenarios in the base period.  
 533 Income differences determined by scenario conditions and parameters begin after the base period  
 534 (Fig. 6a).

535           In Scenario 1, simulated crop yields for corn and sorghum decline during dry periods (Fig.  
536 4). However, wheat yield remains stable for most simulation years. Wheat and grain sorghum are  
537 rarely profitable, and corn is the most profitable crop under the Repeat Historical scenario (Fig.  
538 5a). Repeated historical irrigation water use results in continuous groundwater level decline. This  
539 continues well known current trends and in the simulation dryland farming in this area starts in  
540 2065 or, year 58 of the simulation. Crop yields decline after switching from irrigated to dryland  
541 cultivation. However, average non-irrigated crop net incomes are higher than irrigated net incomes  
542 because dryland farming expenses for all three crops are low enough to make up for lost crop sales.  
543 For corn and grain sorghum, the tendency of prices to increase globally when the local yields  
544 decline (see Section 2.3.2) could prove even more advantageous than indicated.

545           For Scenario 2, the 50 years following the base simulation, Fig. 5b shows that crop  
546 production improves and groundwater levels drop more slowly, though they continue to drop.  
547 Dryland farming is not reached, and FEWCalc maintains irrigation operations for the entire 60-  
548 year simulation. However, the downward trend makes it clear that a time will come when dryland  
549 farming will be necessary in some years, even with this wetter future simulation.

550           In Scenario 3, the Drier Future, irrigated corn performed better than other crops, whereas  
551 wheat production is low and remains stable during irrigated periods. Corn net income is high  
552 because of high crop prices during dry years. The increased irrigation required in drier years  
553 accelerates the decline in groundwater levels, and FEWCalc resorts to dryland DSSAT simulations  
554 in year 46 (2053), which is 12 and  $\geq$  14 years ahead of Scenarios 1 and 2, respectively.

555           Table 3 shows that dry scenario 3 yields an annual average agricultural sector profit of  
556 US\$6,818, which is the only commercially successful scenario for agriculture from the  
557 simulations. Potential crop price increases caused by reduced production in a drier future are not  
558 simulated, and could affect farm profitability and food availability. Because wind energy  
559 production is successful in western Kansas, total net income is mostly supported by the energy  
560 sector. All scenarios, in turn, have projected positive net incomes and post positive net present  
561 value (NPV) using a discount rate of 3.25% for the total farm investment (Table 3). For Scenario  
562 3, farm income with energy sector profit is US\$116,142, with an NPV of US\$3.1M. Scenario 4, in

563 contrast, produces the worst average annual total revenue of US\$48,003, with an NPV of  
564 US\$1.6M.

565 In Scenario 4, what is thought to be the most likely future scenario results in wheat and  
566 grain sorghum are rarely profitable. Irrigated corn's net income is projected to decrease over time  
567 and is considerably worse after simulation year 22 (2029). Dryland farming first occurs in year 55  
568 (2062), causing large crop production decline. These results show a large increase in net income  
569 for all three crops after shifting to dryland farming as costs decline more than income. The reduced  
570 yield would be problematic for the global food system.

571 The time series in Fig. 5 show the variability in income. For example, in Scenarios 1 and  
572 4, Figs 5a and 5d show that corn, wheat, and grain sorghum lose less money with dryland farming  
573 than during the irrigation period because of decreased farm expenses and support from crop  
574 insurance. For Scenario 2, grain sorghum is the most profitable crop, but it loses money in some  
575 simulation years.

576 In FEWCalc, insurance claims (Fig. 6b) start during any period of transition to dryland  
577 farming when the current yield drops below the actual production history. There are other common  
578 situations in which crop insurance is indemnified, such as hailstorms and floods, but these are not  
579 represented in FEWCalc.

580 Figs. 8d, B.1, and B.3 results suggest that, overall, RCP 8.5 global climate change  
581 predictions would need to be met with effective technology changes to address crop production  
582 trends that slowly decline for the future period. It appears that annual variability would make this  
583 trend difficult to discern until reductions are substantial, and history indicates that such obscured  
584 consequences tend to make early remedies difficult to implement. While global analyses suggest  
585 that delaying action exacerbates both the cost and feasibility of mitigation, how these tradeoffs  
586 play out locally requires careful evaluation of how projected changes and uncertainty impact  
587 individual FEW systems, a challenge that FEWCalc enables users to address directly for  
588 agricultural systems.

589 For all scenarios, installed solar capacity is initially set at about 9% of the total renewable  
590 energy. Higher capital costs and a shorter lifespan make the total cost of solar higher than wind.

591 The slow degradation of wind and solar capacity over time is evident in the energy production  
592 graph. Solar power makes money some years because of the simulated tax credit, depreciation,  
593 and loan pay off. Wind power production, on the other hand, is generally profitable, in part because  
594 of a high wind capacity factor in the study area and the simulated 30-year capital lifespan that  
595 makes it easy to cover installation costs.

596 Overall, the DSSAT results are expected to be adequate for the analysis of renewable  
597 energy development and agricultural performance given potential future climate scenarios for  
598 which FEWCalc was developed.

599 The scenarios do not include technological, crop management, crop price, or energy  
600 production changes that would be expected to occur. Thus, these results reflect the climate- and  
601 market-related pressures to which such changes would need to respond to maintain crop production  
602 and farm incomes.

## 603 **5. Conclusions**

604 This work shows how FEWCalc can provide scientific, engineering, and economic  
605 analyses required by stakeholders and policy makers using data from the semi-arid region around  
606 Garden City, Kansas. Here we discuss the two points about FEWCalc and provide some final  
607 comments.

### 608 **5.1 FEWCalc Utility for Individual, Community, and Policy Maker Decision Support**

609 The FEWCalc results for Finney County, Kansas, illustrate many of the general challenges  
610 of farming. The main crops are subject to considerable price uncertainty, weather conditions can  
611 be harsh and unpredictable, and selected resources have limited availability. As presented here,  
612 FEWCalc is applicable directly to farmers in arid regions of the middle part of the USA interested  
613 in alternative income sources. The design of FEWCalc has broad applicability for agricultural-  
614 energy-water system decision support research and education. Applicability to other regions  
615 requires local data, development of a DSSAT model, and adjustment of the FEWCalc input  
616 variable values. Little or no programming would be required.

617 Distributed energy production requires considerable land and rural areas can provide  
618 important opportunities, depending on local attitudes and local to national policies. FEWCalc

619 illustrates major input variables relevant to renewable energy development and how local  
620 economic impact can be evaluated and projected.

621 Renewable wind energy development in this area was shown to potentially provide  
622 economic opportunities profitable enough to balance farming difficulties and enable the  
623 persistence of agricultural production in the region. In part, this is the consequence of the unusually  
624 useful wind resources available in this area; other areas will have different advantages and  
625 disadvantages that can be evaluated using the framework provided by FEWCalc.

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

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

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

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

658        **5.2 FEWCalc Impact on IA and IAV Gaps**

659        The gaps between the IA and IAV communities that were summarized in Table 1 can be  
660 broadly categorized as gaps in the geographic and temporal scale, scenario and policy  
661 development, interdisciplinarity, and research perspective. FEWCalc addresses these gaps the  
662 following ways:

- 663        1) FEWCalc's interface shows the clear connection between current decisions and long-  
664 term, interdependent, and interdisciplinary consequences for both non-technical  
665 stakeholders and disciplinary specialists. This presentation of information can facilitate  
666 discussion across disciplinary boundaries and between scientists and non-technical  
667 stakeholders.
- 668        2) Metrics such as crop production, farm income, groundwater-level change, and nutrient  
669 loading of surface-water bodies, are broadly interesting to many stakeholder  
670 communities across a range of geographic scales and/or topical foci. These metrics can  
671 serve as a common point of reference for interdisciplinary discussions of their  
672 underlying discipline-specific drivers such as climate change, agricultural practices,  
673 and renewable energy policy. For example, Fig. 5, depicting the outcomes under  
674 Scenarios 1 to 4, could serve as the basis for discussions among different stakeholder  
675 communities and become an important focus of communication for topics as wide-

676 ranging as irrigation practices, climate change impacts and adaptation strategies,  
677 renewable energy, and farm incomes.

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

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

684 b) Inform local stakeholders, which could lead to better feedback and is the only way  
685 to achieve more buy-in and support for adaptive measures such as agricultural and  
686 energy tax credits and support of technological innovations in irrigation and wind  
687 turbine design. Here again, FEWCalc's outputs (Fig. 5) show the connection  
688 between global changes and local-stakeholder outcomes, while FEWCalc's  
689 intuitive interface allows local stakeholders to explore how their options (e.g.,  
690 choices about irrigation, crop planting, and energy investment) and outcomes (e.g.,  
691 farm income) are affected by climate conditions, and local and national public  
692 policy.

### 693 **5.3 Final Comments**

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

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

705        The input to DSSAT is region specific, but DSSAT is used globally and data from other  
706 regions would likely provide similar performance as long as some historical data is available for  
707 DSSAT model development.

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

714        **Acknowledgements**

715        With gratitude, we note that this work was funded by the University of Kansas, Department  
716 of Geology startup [account 05192015] and the National Science Foundation [grant number  
717 1856084] FEWtures project. Mr. Jirapat Phetheet was funded by the Royal Thai Government  
718 Scholarship.

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