Environmental Defense Fund

KANSAS IN 2050

A pathway for climate-resilient crop production

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Acknowledgements

We thank Two Degrees Adapt for their invaluable contributions to this report on climate-proofing Kansas food production. We also thank the farmers, scientists and leaders whose insights and expertise have helped to shape this study. This report underscores their collaborative efforts and unwavering commitment to a more sustainable future for agriculture. Additionally, we would like to express our appreciation to the generous funders of this study, whose support made this research possible.

EXECUTIVE SUMMARY

Over the past century, advancements in farming technologies and practices have helped U.S. farmers increase crop yields. Climate change, which brings higher temperatures and changes in rainfall, is starting to hinder this progress, even as farmers work ever harder to stay ahead.

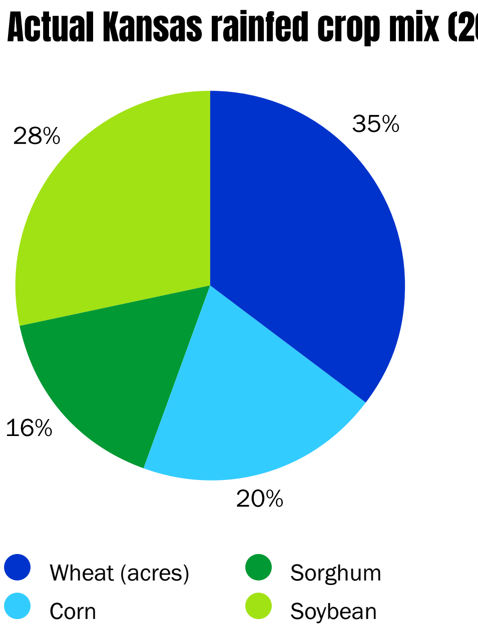
In a previous study, we found that climate change will slow yield growth for Iowa corn, Kansas winter wheat and Minnesota soybeans as soon as 2030.[1] That concerning trend held true even when climate and yield models included likely innovation and technology gains. Given the important role these crops and regions play in national and global food production, these expected impacts present significant consequences for agricultural economies and food supplies locally and globally. Kansas, a critical breadbasket for the U.S. and the world, serves as an important case study for this follow up research, which illuminates a path forward that will help ensure agriculture continues to thrive in a changing climate.

This report explores alternative crops that Kansas farmers could grow to respond to decreased water availability and hotter temperatures, while still growing nutrient-rich food for an expanding global population. In particular, we evaluated the potential resilience benefits at a county level of growing sorghum instead of corn, winter rye instead of winter wheat, winter oats instead of winter wheat, and millet instead of soybeans. Interviews with Kansas farmers helped identify these as feasible crop switching options.

Our findings for a "reimagined" Kansas crop mix for 2050 are presented in **Figures E1** and **E2**. Individual counties are aggregated into their associated agricultural region, a grouping used by the Kansas Department of Agriculture.

FIGURE E1.

Pie charts showing actual 2021 and projected 2050 rainfed row crop mix for Kansas



**Values may not add up to 100% due to rounding*

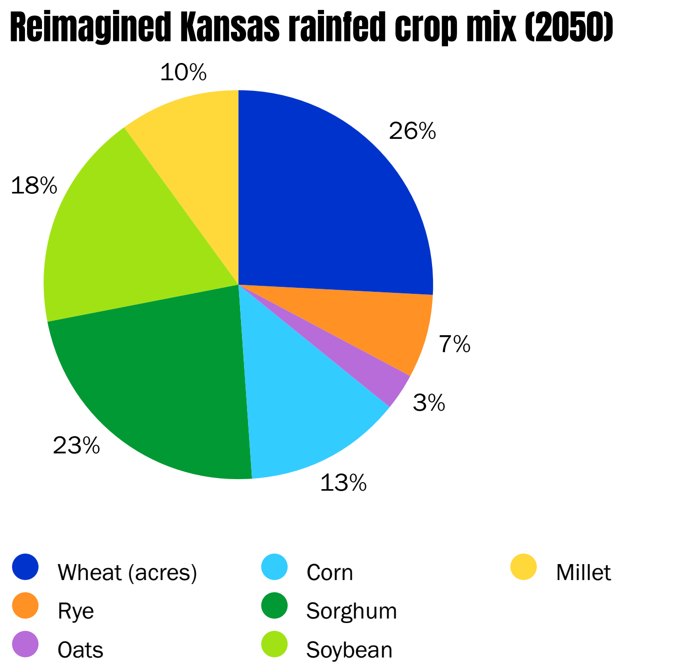
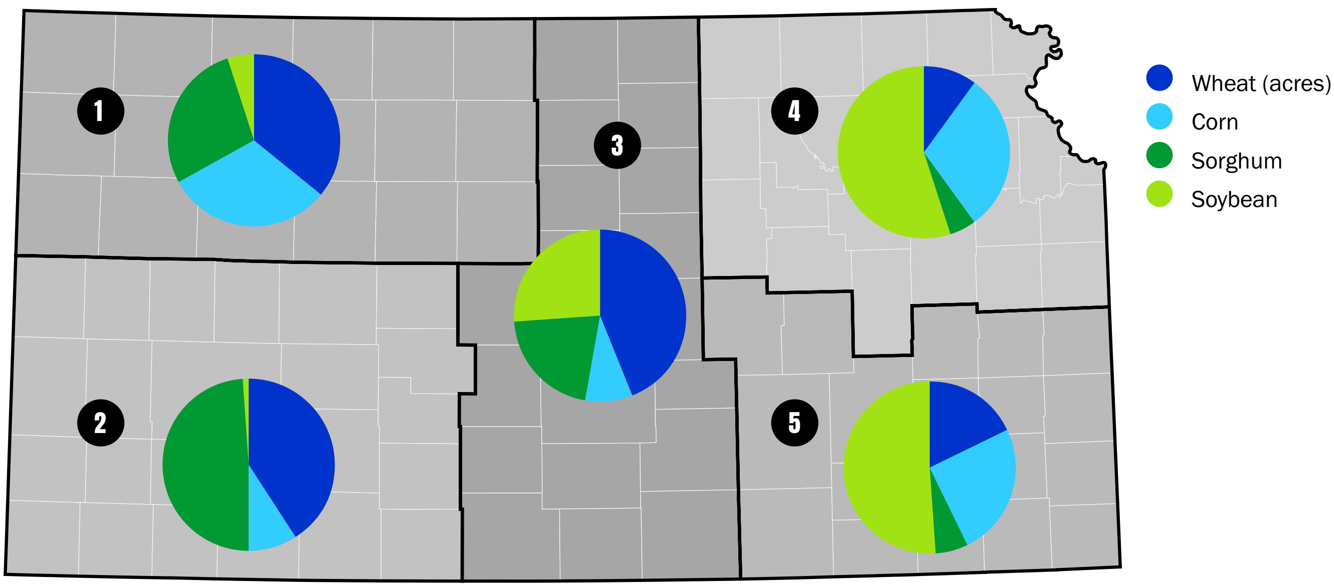


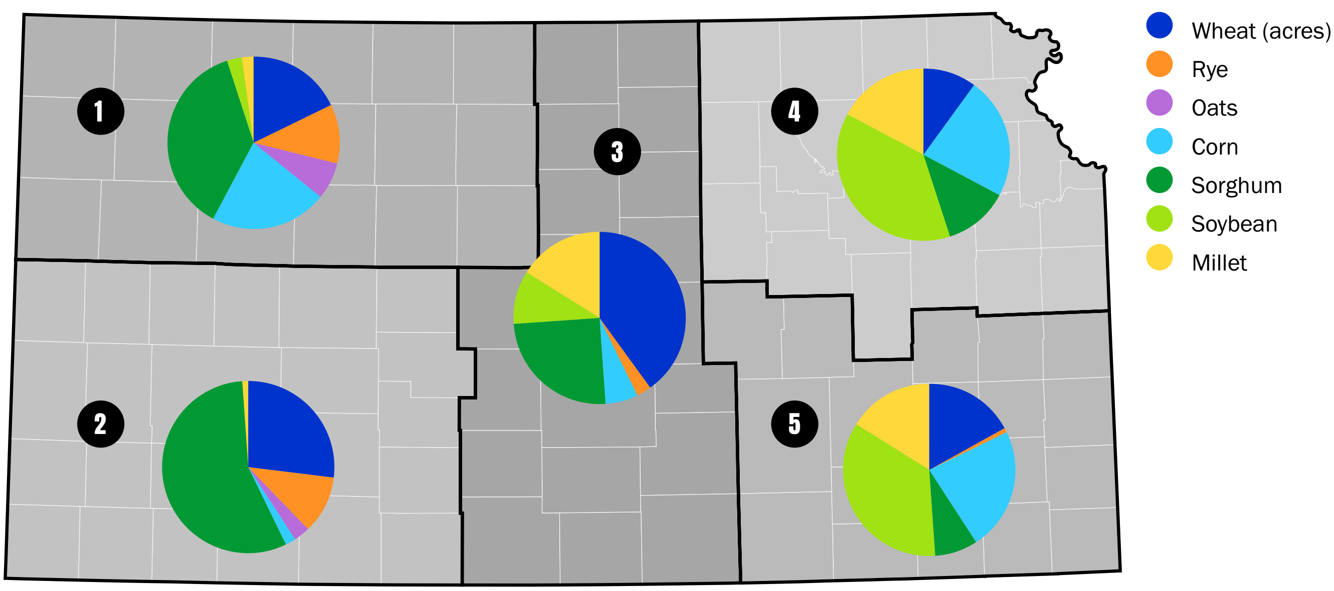
FIGURE E2.

Pie charts showing actual 2021 and projected 2050 rainfed row crop mix for each of the five agricultural regions in Kansas

Actual Kansas rainfed crop mix by region (2021)



Remimagined Kansas rainfed crop mix by region (2050)

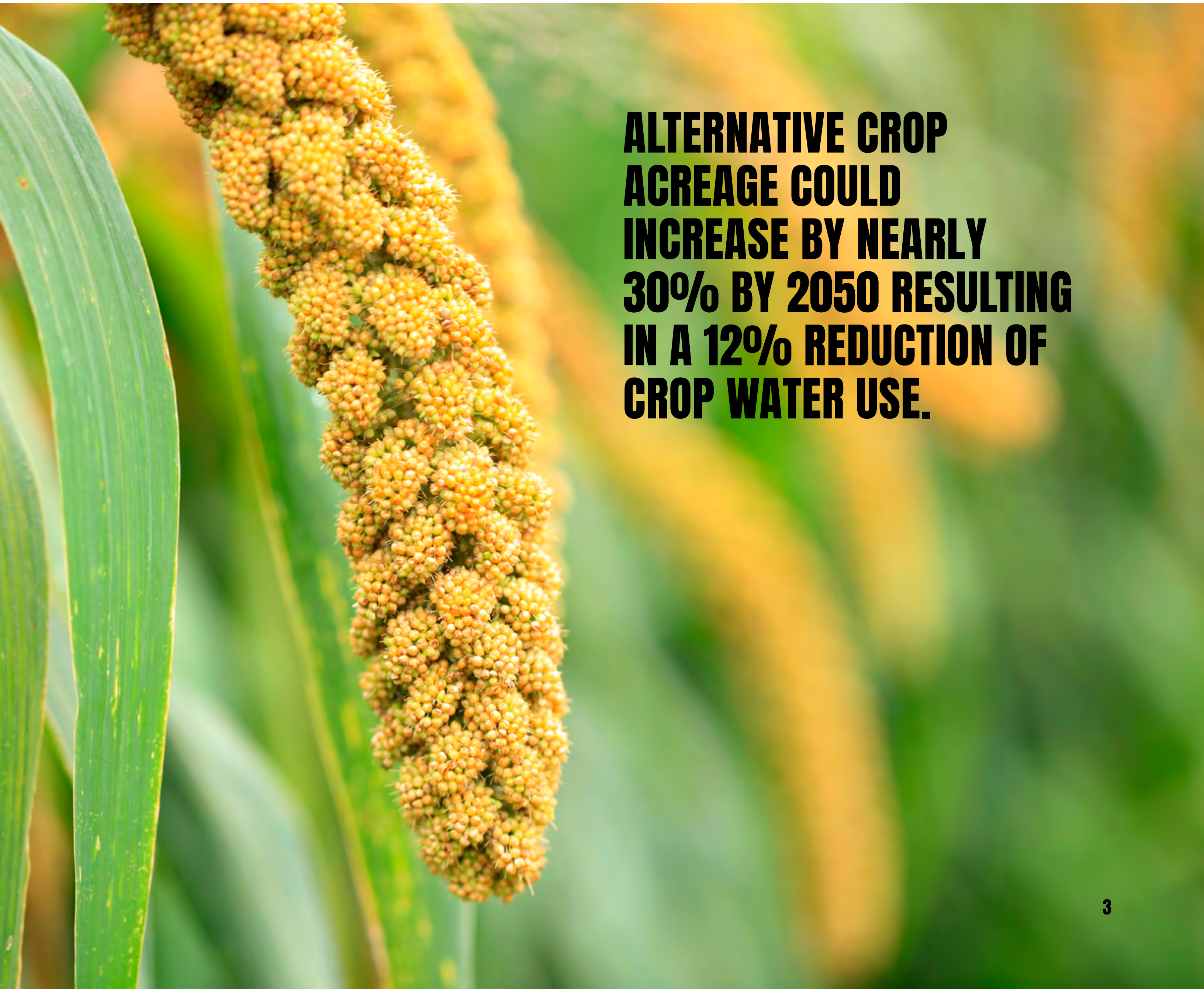


Our analysis suggests that by 2050:

- A sizeable proportion of current rainfed crop acres would need to shift to alternative crops in order to meet constraints related to nutritional value and water use.
- Alternative crops could increase from 16% of acreage in 2021 to 43% of acreage in 2050 (see **Figure E1**) resulting in a crop water use reduction of 12%. This crop water use reduction would be concentrated in parts of the state that will experience the greatest change in water needs between today and mid-century.

Some of the crop switching envisioned in our future scenario (e.g., corn to sorghum) is already underway and could be accelerated. However, other types of crop switching represented in our scenario—for example, winter wheat to winter rye—are not yet underway.

Our analysis has shown that it is biophysically possible for future crop production in Kansas to be sustainable and resilient. Achieving this vision on the ground, however, will require major shifts in the broader agricultural system and market. Food companies, agricultural lenders and policymakers will need to play a key role in enabling farmers to make this large-scale shift. With changing climate conditions already upon us, the time to begin this transition is now.



Definitions

Climate boost:

Climate boost is an increase in yields resulting from climate change. If the yields predicted for a future date with climate change are larger than the yields predicted for that date without climate change, the difference between these yields is the climate boost. It occurs when the positive impacts of climate change exceed the negative impacts of climate change, for example when warming leads to more growing-degree days. In general, this boost is more likely to accrue at higher, colder latitudes.

Climate burden:

Climate burden is a decrease in crop yield resulting from climate change. If the yields predicted for a future date with climate change are smaller than the yields predicted for that date without climate change, the difference between these yields is the climate burden. It occurs when the negative impacts of climate change exceed the positive impacts of climate change. For example, a burden on crop yields can happen when extreme heat decreases crop yields by more than warmer temperatures or technological advancement can boost crop yields.

Growing-degree days:

Growing-degree days are heat units used as a metric to estimate the growth of crops during the growing season. These are calculated based on the high and low temperatures during a day. They measure the accumulated average daily temperatures that are above a minimum temperature for plant growth to occur. Corn and soybeans need a minimum temperature of 50°F (10.0°C) for growth, and winter wheat needs a minimum of 40°F (4.4°C). They are not reported as traditional 24-hour days. As an example, corn requires 1,600 to more than 2,500 accumulated growing-degree days.

Failing-degree days:

Failing-degree days are a similar metric as growing-degree days, but they measure heat units in a detrimental temperature range. The accumulated temperatures in this range are, at best, too hot for crops to grow and, at worst, damage or kill the crop. For corn, soybeans and winter wheat, maximum temperatures are those above 84°F (28.9°C), 85°F (29.4°C) and 82°F (27.8°C), respectively.

Representative concentration pathways, or RCPs:

RCPs are a shorthand way to reference different scenarios for how severe climate change will be by the year 2100. They are based on assumptions about how factors like population growth, technology development and land use will influence future levels of new GHG emissions, cumulative concentrations from past emissions and levels of expected warming. For example, RCP4.5, which is what we use in this report, assumes new climate pollution will peak before 2050 and slowly decline thereafter, resulting in a climate that is, on average, 4.3°F (2.4°C) warmer by mid-century.

INTRODUCTION

Within the past two decades, there has been growing momentum for international and national policies to stabilize the climate, as well as important progress deploying climate-smart practices on the ground. Despite this, the world is behind where it needs to be to limit the worst effects of climate change.

The United States is projected to warm even more than the global average by 2050, leaving communities more vulnerable to devastating storms, droughts, fires and other serious climate impacts. But climate change impacts aren't only a future-facing concern—extreme and variable weather, including hotter temperatures and heavier precipitation, are already being felt today across the country.[2]

As weather extremes become more frequent, it will become increasingly difficult for farmers to grow their crops, and annual swings in yields will be more likely. Climate-driven changes in temperature and precipitation are likely to negatively impact crop yields across the U.S. and globally.[3] As witnessed in 2012, drought extending from the Corn Belt to the west resulted in $30 billion in agricultural losses.[4] More recently, the 2019 Midwest floods led to a $4.5 billion loss in agricultural sales.[5] These are but two examples of extreme heat and precipitation that foreshadow harmful impacts of climate change on crop production. Future climate impacts on crop yields will not only impact farmer livelihoods and rural communities, but also carry alarming implications for domestic and international food security.

The majority of assessments of climate change impacts on crop yields have been conducted at the global, national and subnational level.[6–8] While broadly informative, assessments of this scale lack the level of detail needed for agricultural operations. In this report, we provide such an assessment at the county and regional level to assist farmers, the agricultural community, food companies and policymakers in their planning and decision-making as they prepare for a changing climate.

In a previous study, we found that climate change will significantly lower yield gains for Iowa corn, Minnesota soybeans and Kansas winter wheat by 2030 compared to gains that would be expected without climate change.[1] The number of counties within each state experiencing negative climate impacts—along with the magnitude of those impacts on these important commodity crops—will only increase through mid-century.

Key Findings of 2022 Climate Change Impact on Midwest Crop Yield Study

By 2030

- 100% of Iowa counties will see climate burdens of more than 5%, and more than half will see climate burdens of more than 10%.
- 56% of Minnesota counties will see climate burdens of more than 5%, and 17% of counties will see climate burdens of more than 10%.
- While no Kansas counties will see climate burdens of more than 10% by 2030, one comes close at a 9.3% burden.

ONE PROMISING STRATEGY INVOLVES SWITCHING TO LESS WATER-INTENSIVE CROP ALTERNATIVES, EFFECTIVELY REDUCING CROP WATER USE AND HELPING TO CLIMATE-PROOF KANSAS AGRICULTURE FOR A DRIER FUTURE.

In this study, we have focused on Kansas, the top wheat-producing state and a top 10 producer of soybeans and corn in the U.S.[9,10] Kansas agriculture makes a global impact with all three crops comprising the state's leading agricultural exports.[11] The impact of climate change on wheat is of particular concern as it is one of the world's most important crops both in terms of production and nutrition.[12] Similarly, we sought to understand climate impacts on corn and soybean production. In total, industries for all three crops directly contribute more than $6 billion to the state's economy and support more than 13,000 jobs.[13,14]

Kansas farmers are exploring several adaptation strategies to address the challenge of climate impacts on key crop yields. One promising strategy involves switching to less water-intensive crop alternatives, effectively reducing crop water use and helping to climate-proof Kansas agriculture for a drier future.

For this study, we developed a crop switching decision tool to imagine a more resilient crop mix for Kansas in 2050. The goal was to identify a new crop mix that doesn't exceed current crop water requirements while maintaining nutritional value. Conversations with Kansas farmers about their needs, concerns and considerations pertaining to crop switching informed development of the tool.

There is an urgent need to understand what the crop production picture will look like in Kansas in the future, and how that landscape might need to change to ensure the security of farmer livelihoods and global nutrition.[12] What will projected future climate conditions mean for Kansas crop production? What crop mix could provide the same level of nutrition under future climate conditions and environmental constraints, without expanding crop production acreage? With these questions in mind, we provide one possible future scenario of resilient crop production for Kansas. Despite the climate challenges Kansas agriculture faces and will face in the coming decades, our study offers hope that pathways exist for Kansas farmers to continue to cultivate crops and support global nutrition into the future.

Previous work on climate change impacts and crop production

Previous scientific studies have looked at the impact of historic climate trends, future climate scenarios and water scarcity on crop yields. However, very few of these studies have focused on Kansas. Our analysis provides data specific to the Wheat State. In doing so, we hope to stimulate additional research that is urgently needed for Kansas agriculture to successfully adapt to climate change.

Globally, wheat production is predicted to decrease by 6% for each degree Celsius of warming.

Based on previous studies in the U.S., future corn and wheat yield decreases are expected due to a shorter growing season, fall freezing temperatures and extreme heat in the spring.[15,16,17] More specifically, modelling studies predict that Kansas corn yields will fall by up to a third with winter wheat yields decreasing by 17% under RCP4.5—a "middle-of-the-road" scenario in which GHG emissions peak before mid-century and then slowly decline.[16] Higher yield reductions are expected for both crops under high emissions scenario RCP8.5 where emissions continue to rise throughout the 21st century.[15,16] Globally, wheat production is predicted to decrease by 6% for each degree Celsius of warming.[18]

Existing research has also examined historical climate data and its impact on crop yields. Using data from 1950-2016, researchers found that winter wheat yields in Kansas were reduced when May precipitation was lower than average.[19] Other observations from within this timeframe demonstrate that warming temperature trends were harmful for sorghum and soybean yields, but beneficial for corn in the Great Plains region. The increasing and decreasing precipitation trends throughout the region over this same period were favorable for all three crops.[20]

In contrast to beneficial precipitation trends in the historical record, predictions about future precipitation and groundwater trends are less favorable. Studies show that irrigated crops in the Southern Plains are highly vulnerable to climate change with researchers projecting that groundwater pumping costs will begin to limit irrigated agriculture by 2030.[21] Furthermore, modeling suggests a forced shift to farming without irrigation, or dryland farming, in the Central High Plains by end of century.[22] Irrigated corn acreage would be reduced by 60% and irrigated wheat acreage by half. Another study points out how catastrophic a forced transition to dryland agriculture would be for the 12 million acres of irrigated cropland dependent on the High Plains Aquifer.[23]

In addition to these findings, in our previous study we reported a gradient in Kansas winter wheat climate impacts from the east to the west.[1] An increasing climate burden (a climate change-induced drag on yields) is anticipated in the northwest while a small climate boost (a climate change-induced uplift on yields) is anticipated elsewhere. We also projected a meaningful decrease in the protein content for winter wheat that could affect the price and decrease an important part of nutrient density. Despite the possibility of a boost in some locations, such a benefit may not be large enough to counteract the long-term yield declines in irrigation-dependent western Kansas.

Overview of Kansas agriculture

Kansas agriculture varies significantly across the state's geography. Biophysically, agriculture is influenced by a gradual increase in temperature from the north to the south and precipitation from the west to the eastern part of the state. The intensity of crop production also varies by region across the state. For our study, we used publicly available climate model data that had been "downscaled" to a 4km x 4km scale using peer-reviewed methods. This scale is equivalent to about 4,000 acres. When Kansas is segmented by this scale, only half of the sections in eastern Kansas are under cultivation whereas nearly all sections are under cultivation in western Kansas.[24] Cultivated land in eastern Kansas is also under continuous crop production without fallow periods, whereas some cropland in western Kansas is allowed to fallow each year. Cropping intensity and fallowing impact soil nutrient retention and water storage with fallow periods increasing soil moisture and nutrient availability for the following growing season. These important implications will be increasingly important as climate change impacts temperatures, water availability and yields in the coming years.[25]

Kansas has significant regional differences in the extent of irrigation used as well as the irrigation source. As seen in **Figures 1** and **2**, western Kansas uses much more irrigation compared to eastern Kansas. Western Kansas largely pulls from groundwater whereas the east and north-central regions primarily irrigate with surface water from the residing 16 reservoirs (see **Figure 3**).

FIGURE 1.

Crop irrigation in Kansas by county in units of acre-feet

Over 50,000 acre-feet | Between 5,000-49,999 acre-feet | Less than 5,000 acre-feet

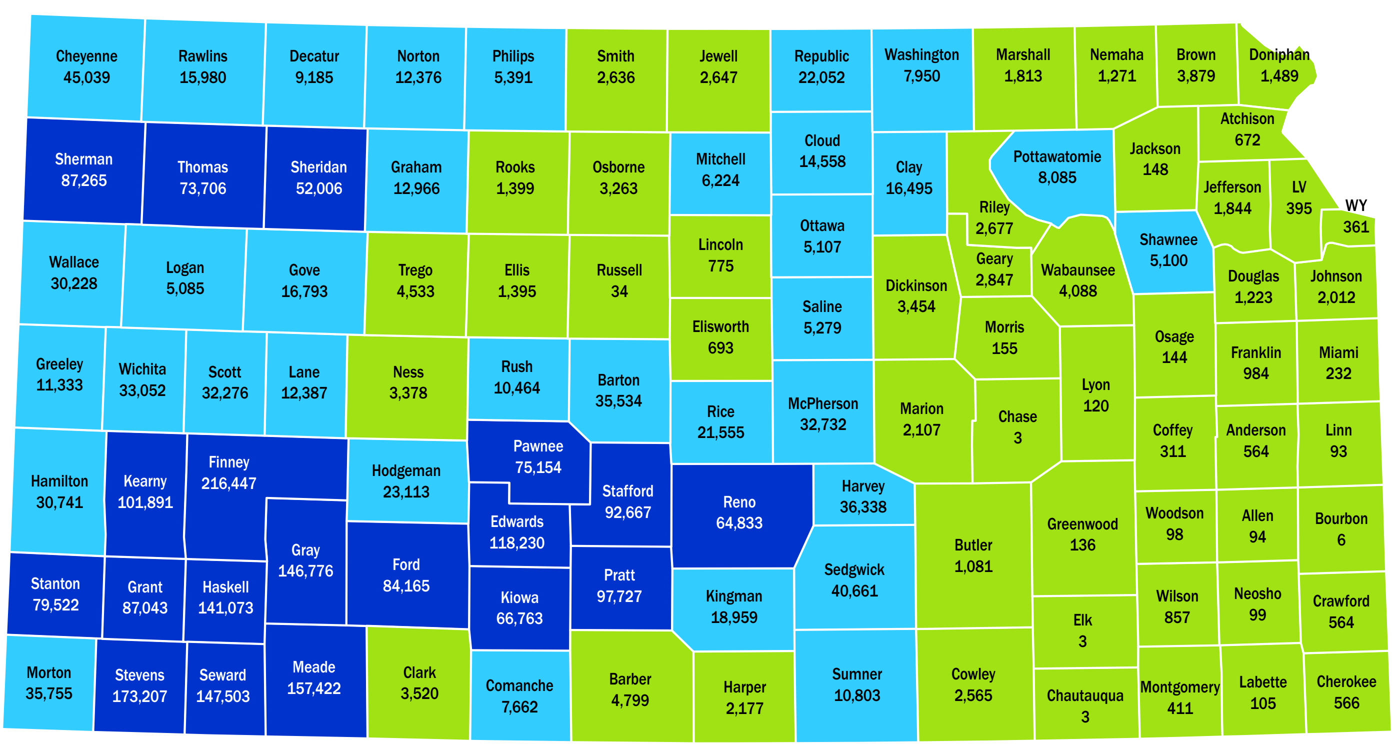
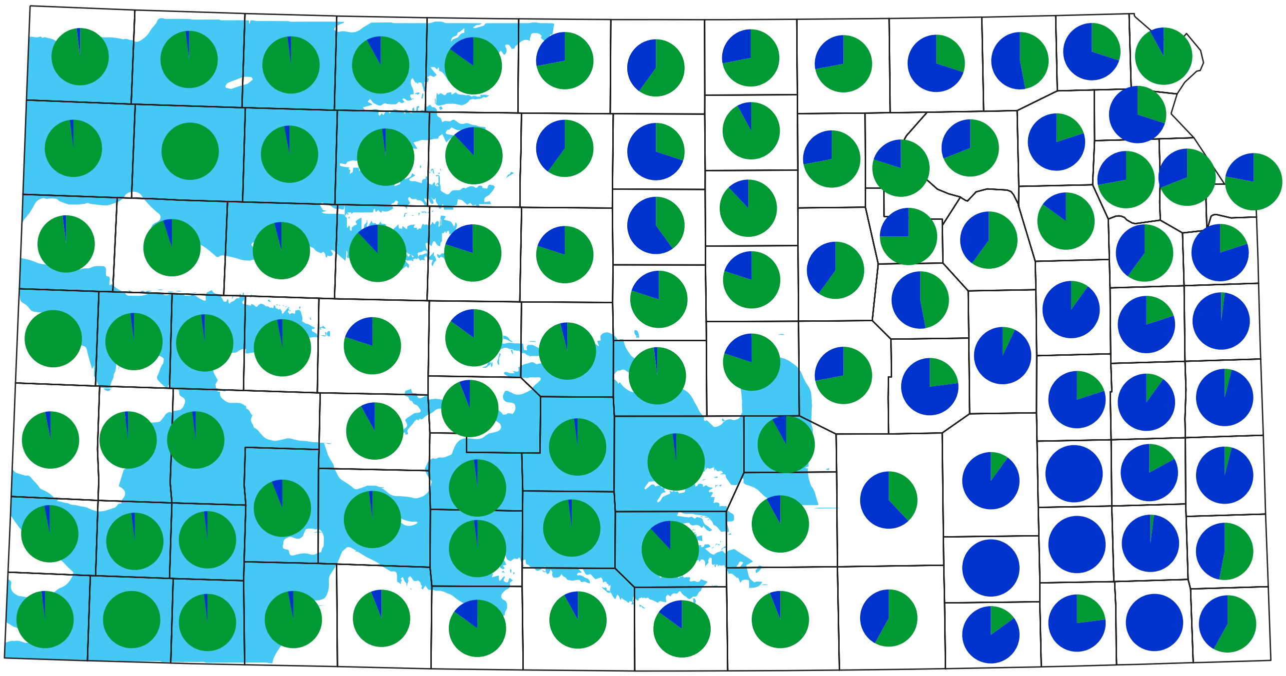


Figure reproduced from a 2017 report by the Kansas Department of Agriculture

FIGURE 2.

Sources of irrigation in Kansas by county

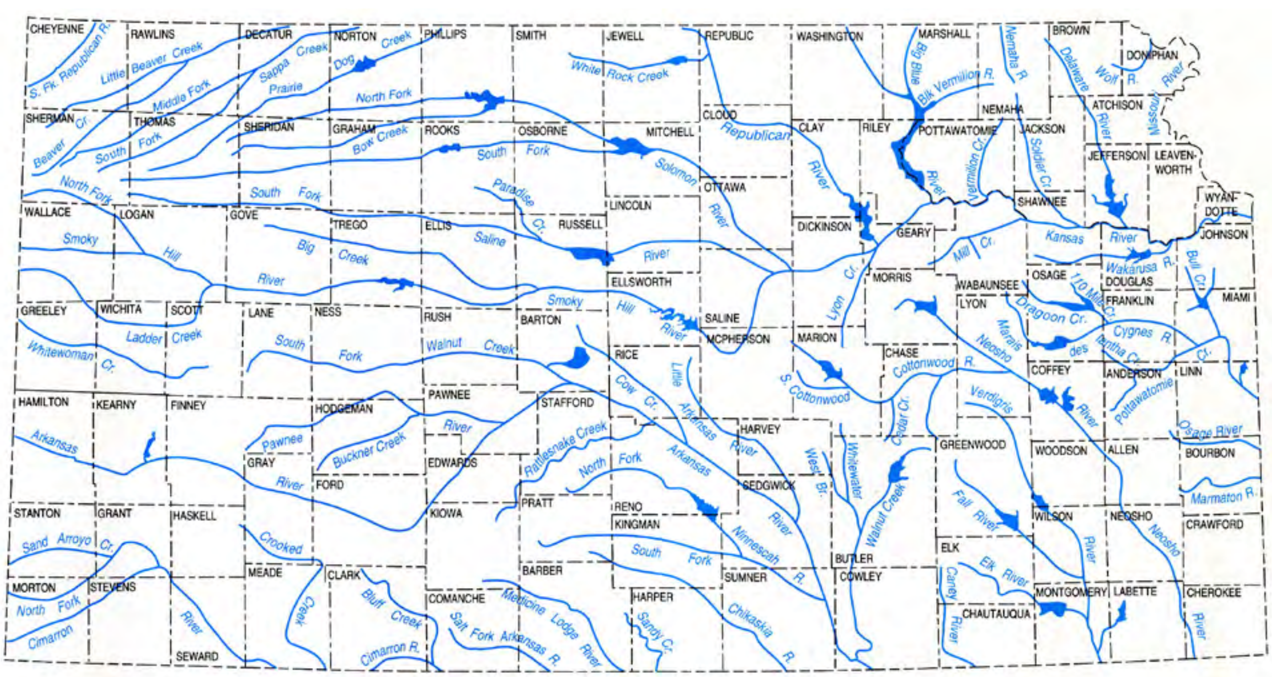


Ground Surface High plains aquifer

Source: 2017 data from the Kansas Geological Survey

FIGURE 3.

Surface water reservoirs in Kansas

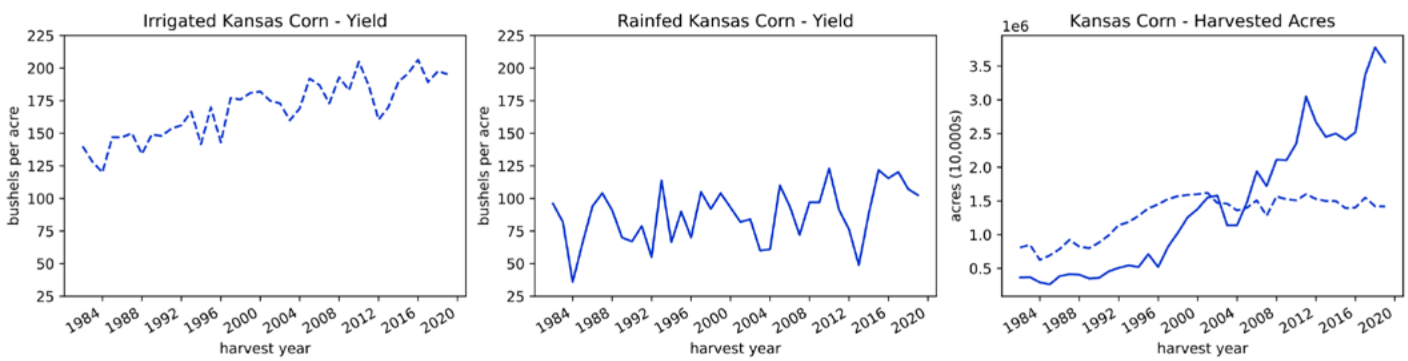


Source: University of Kansas

Kansas' primary crops currently include winter wheat, corn and soybeans. In 2021, Kansas farmers grew corn on 5 million acres. Corn has seen yield increases over the past 40 years, particularly where irrigated: average irrigated yields exceed 200 bushels per acre throughout the state. Average rainfed yields vary from 70 bushels per acre in the west to over 120 bushels per acre in the east. About 30% of Kansas corn acres are irrigated, primarily in western Kansas. While the total number of irrigated acres has remained steady, Kansas has seen an increase in the rainfed area fraction over the past 20 years as dryland corn cultivation expanded (**Figure 4, right**).

FIGURE 4.

Times series graphs for (Left) Kansas irrigated corn yield, (Center) rainfed corn yield and (Right) harvested corn acres

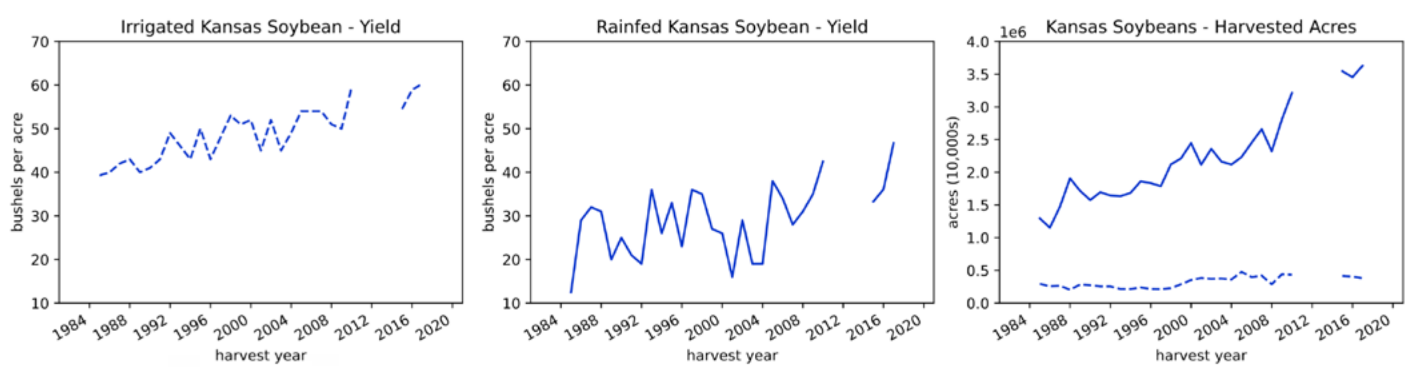


Source: USDA NASS Quick Stats

Soybeans are common in eastern Kansas, grown in rotation with corn or double-cropped with winter wheat. Average rainfed yields range from nearly 30 bushels per acre in the west to over 40 bushels per acre in the east. Average irrigated yields can climb above 60 bushels per acre. Soybeans are primarily rainfed in Kansas (**Figure 5, right**). Total acres have almost doubled over the past 20 years, from 2.5 million acres to about 5 million acres. Rainfed area fraction has fluctuated between 80% and 90% over the past 40 years (**Figure 5, right**).

FIGURE 5.

Times series graphs for (Left) Kansas irrigated soybean yield, (Center) rainfed soybean yield and (Right) harvested soybean acres



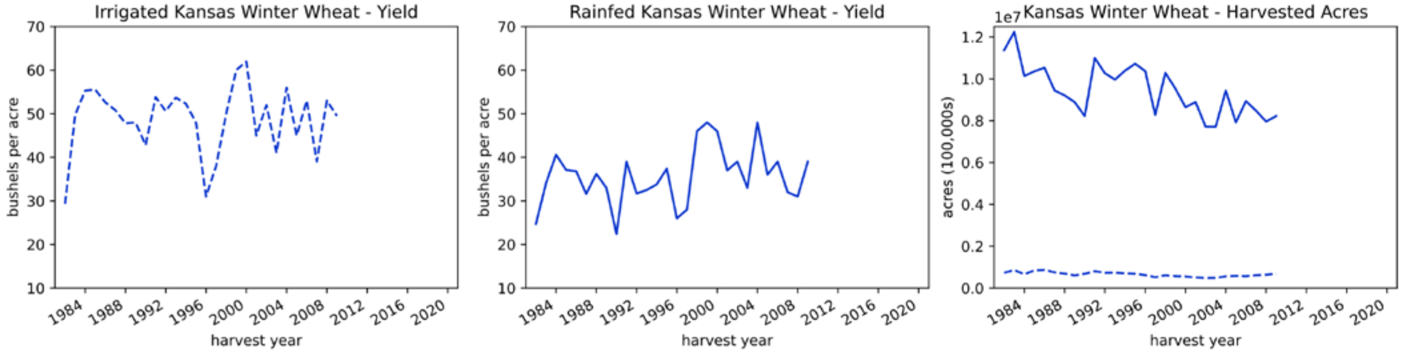
Source: USDA NASS Quick Stats (Data gaps exist where USDA NASS could not make an estimate due to an insufficient number of survey responses. USDA stopped making separate estimates for irrigated/rainfed values in 2019)

Winter wheat is grown throughout the entire state, often double-cropped with summer grains or forage. In contrast to corn and soybeans, Kansas wheat yields have stagnated in the past 20 years (**Figure 6, left and center**). This state-level stagnation obscures offsetting trends in western Kansas (decreasing yields, primarily due to severe drought) and eastern Kansas (increasing yields).[26] Average irrigated yields are around 50 bushels per acre throughout the state. Average rainfed winter wheat yields vary from 30 bushels per acre in the west to 50 bushels per acre in the east. Acreage has been steady around 7 million acres for the past 10 years but is down by 50% from historical highs in the early 1980s. The rainfed area fraction has fluctuated between 92% and 95% for the past 40 years (**Figure 6, right**).

Other crops grown in Kansas include sorghum, sunflower, proso millet, oats, rye, hay and canola. Their acreages are lower compared to the three primary crops. Hay and sorghum are the other leading crops by acreage.

Figure 6.

Times series graphs for (Left) Kansas irrigated winter wheat yield, (Center) rainfed winter wheat yield and (Right) harvested winter wheat acres



Source: USDA NASS Quick Stats

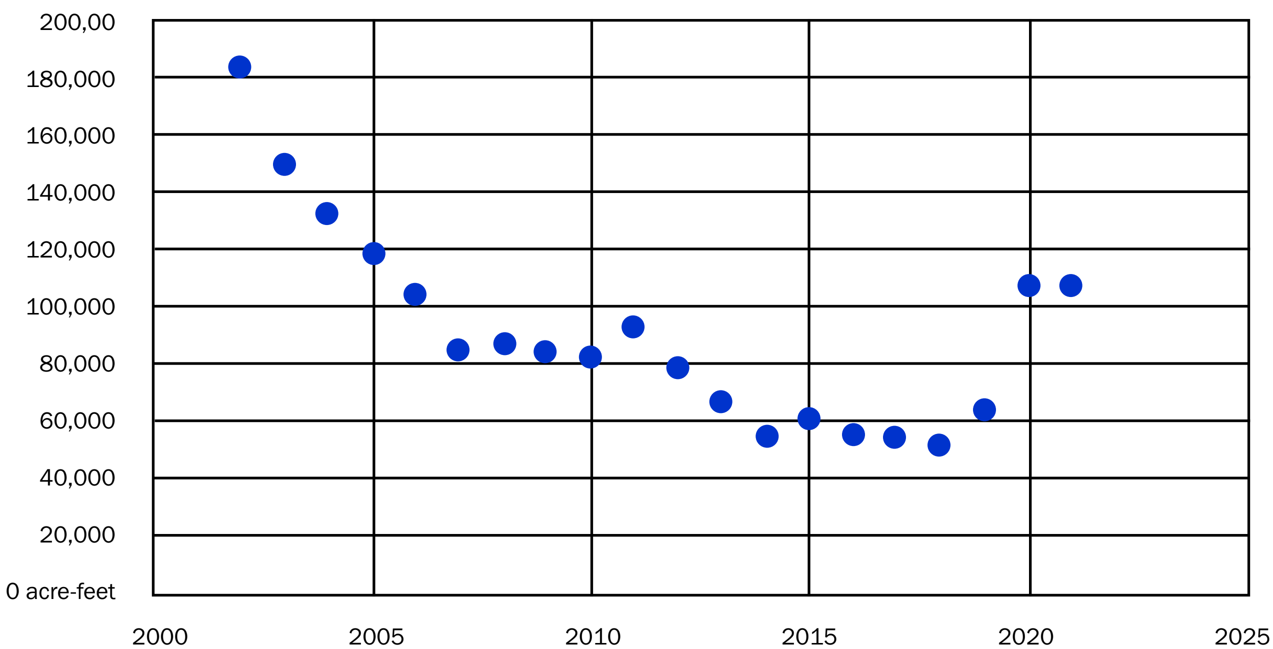
Crop-switching as an adaptation strategy

Irrigation and associated yield increases may at first appear to be an attractive response to climate change; however, biophysical and regulatory limitations on water availability are likely to limit the ability to irrigate in the future. Current groundwater withdrawal rates for irrigation are unsustainable and rapidly depleting water resources.[27] Meanwhile groundwater availability is projected to decrease even further in the future. Given this reality, increasing irrigation in response to growing water scarcity can be considered a "maladaptation" to climate change: It may appear to provide a short-term solution to a climate burden, but is not a true adaptation in the long term, and may in fact damage long-term adaptation by discouraging timely adoption of sustainable climate resilience practices.

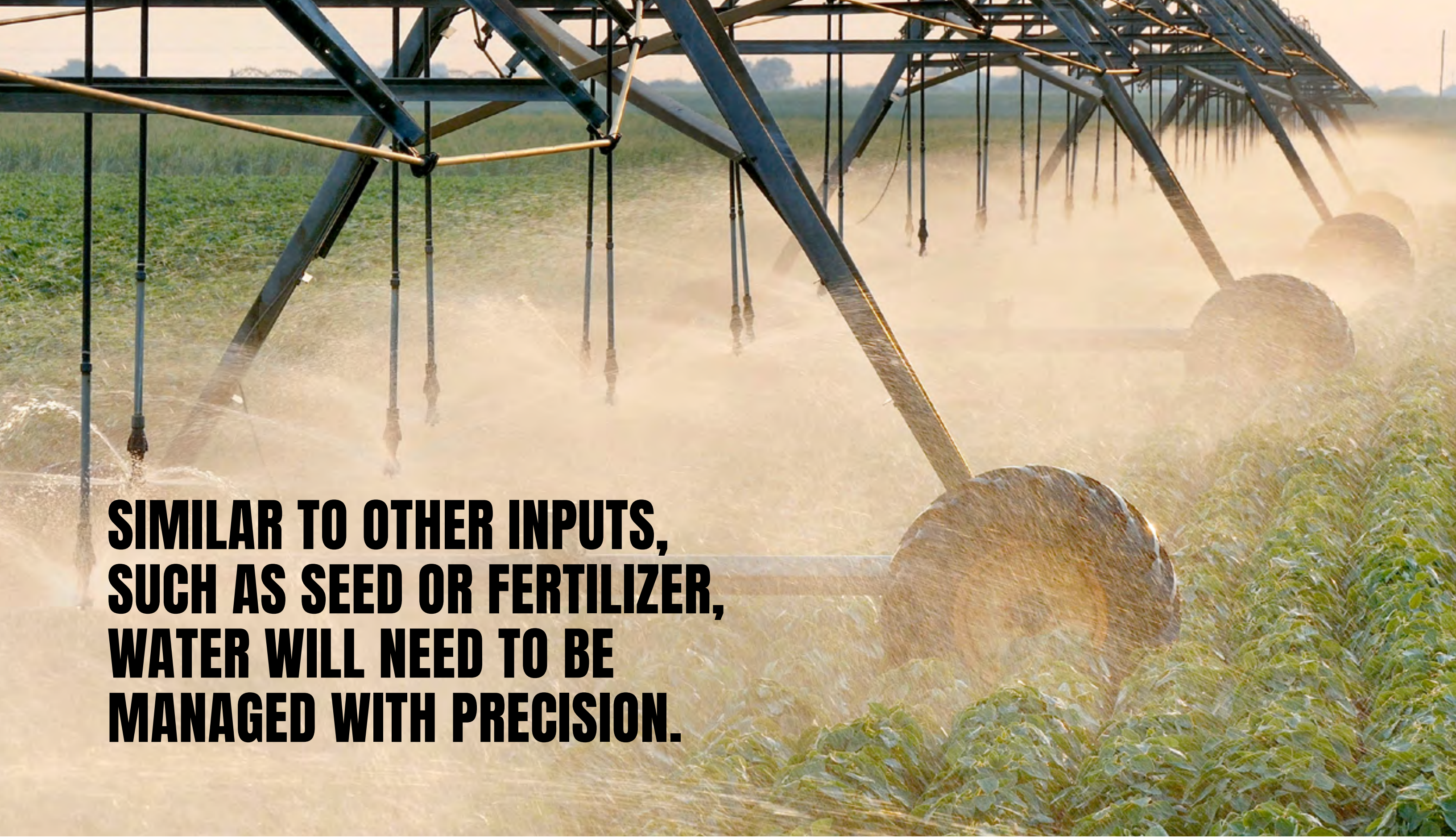
Climate change-driven reductions in precipitation and increased groundwater withdrawals are projected to cause up to a 25% decrease in groundwater storage for Kansas from 2010 to 2060.[28] Similar predictions have been made by researchers attempting to draw relationships between measured groundwater levels from the U.S. Geological Survey and imagery from NASA's GRACE satellite.[29] Modeled impacts of reduced precipitation and rising evaporative losses on Kansas surface water reservoirs suggest there will be a 50% reduction in surface water resources between 2007 and 2050.[30] This projected decrease has also been observed in data for individual reservoirs—like the Cedar Bluffs Reservoir, once previously used for crop irrigation—from 2000 to 2020 (**Figure 7**).

Figure 7.

October reservoir storage for the Cedar Bluffs Reservoir (2002 to 2021)



Such reductions in water availability can be expected to significantly impact farmers and crop production in the state. With these projected decreases in groundwater and surface water, irrigation does not offer a true solution to rising water scarcity. Farmers will need to look to alternative measures to improve water use efficiency.



In a warmer, drier climate, Kansas growers will increasingly be faced with water management decisions. In 2022, the Kansas Water Office released the Kansas Water Plan, which outlines a water management and conservation strategy for the state with an emphasis on locally driven solutions. The plan requires Regional Advisory Committees to identify local goals and develop action plans to address water needs and respond to urgent water depletion. It also mentions use of alternative crops as one piece of the solution.[27] Similar to other inputs, such as seed or fertilizer, water will need to be managed with precision.

To address the dual challenges of a climate burden on yields and shrinking water availability, Kansas farmers are already exploring several adaptation strategies, as outlined in our previous study.[1] These adaptation strategies include more efficient micro and drip irrigation practices, more climate-resilient varieties of conventional row crops, alternative land uses such as solar and wind leasing, and switching to less water-hungry alternative crops.

In this study, we focus on quantifying the impact of crop switching on crop water use. Crop switching—shifting from growing a water-intensive crop to a crop with lesser water needs—represents an effective approach to reduce crop water use and help climate-proof Kansas agriculture. Given constraints on future water supply, we have assumed irrigated cropland acreage will not expand. Our analysis therefore focuses on how rainfed crop production can adapt to climate and water constraints through crop switching.

We conducted a series of interviews with Kansas producers that helped us determine that the following crop switching options were feasible for a subset of Kansas farmers to incorporate by mid-century:

- Corn to sorghum
- Winter wheat to winter rye
- Winter wheat to winter oats
- Soybeans to millet

> **Farmers in Kansas west of I-135 are beginning to treat water decisions with the same seriousness as nutrient management decisions. Crop switching and rotation are part of the solution.**
>
> **John Niemann**
> Niemann Farms, Reno County

These switches were deemed feasible based on a variety of factors, including overlap in growing seasons, ability to replace crops in existing rotations, ability to use the same planting and harvesting equipment, and overlapping supply chains.

Sunflower, hay and canola were also analyzed for yield and water needs, but not considered as candidates for switching from corn, wheat and soybeans, as each of them presented the following unique challenges for our analysis:

- Sunflowers deplete nutrients at a faster rate from the soil compared to row crops. As a result, there seem to be restrictions on planting sunflowers in leasing clauses, limiting their cultivation to a few counties that house sunflower oil processing facilities.
- Hay is used for captive use by farmers owning livestock as well as commercial hay production. Our interviews revealed examples of farmers switching from row crops to forage grass for captive use in the eastern part of Kansas, but not for commercial hay production. An economic and water use analysis of a combined crop and livestock operation was beyond the scope of this project.
- Winter canola is being actively researched as a cover crop and a potential substitute for winter wheat by Kansas State University. However, growers don't consider it to be a good candidate for switching from wheat as the end use as an edible oil dictates a substantially different supply chain and buyer set.

Assumptions and constraints in this study

We set out to identify a future scenario for rainfed Kansas crop production that would simultaneously satisfy the following conditions:

- On an acre-for-acre basis, the nutritional value derived from the 2050 crop choice must be equal to or larger than the nutritional value in 2020.
- At the county scale, water usage from the 2050 crop choice must be equal to or lower than water usage in 2021.

METHODS

Quantifying the nutritional value of crops

Nutrient rich food scores (NRF9.3) are a well-established metric from the literature to measure nutrient density and compare different foods for their relative nutritional value. The NRF9.3 evaluates nine desirable nutrients (protein, fiber, vitamins A, C, & E, calcium, iron, potassium and magnesium) and three nutrients to limit (saturated fat, sugar and sodium). We used data from the Food and Drug Administration's Food Data Central to calculate the NRF9.3 for the seven crops evaluated (field corn, millet, oats, rye, sorghum, soybeans and winter wheat).[31] All values were calculated per 100 grams of food. While increasing atmospheric CO_2 levels are expected to reduce protein content and nutritional value of wheat, we did not include these changes in our modeling.[7]

Predicted Kansas climate in 2050

Choice of climate scenario

Climate scientists use scenarios and global climate models to explore climate change impacts in the future. Scenarios use assumptions about changes in population, energy use, land use change and other factors to predict greenhouse gas (GHG) emissions in the future. Global climate models translate the projected GHG emissions into changes in future climate, represented by changes in temperature and precipitation.

We used a collection of 20 different global climate models, called an ensemble, with an RCP4.5 climate scenario. We used an ensemble of models because they gave us a range of predicted climate changes. We can have greater confidence in the predictions when changes in predicted climate outcomes are similar between different models. The RCP4.5 scenario assumes that GHG emissions will peak in mid-century and then decline. It is a "middle-of-the-road" scenario that results in a global average warming of about 4.3°F or 2.4°C by the end of the century. Society is not currently on track to curb emissions before mid-century so impacts could be much worse than the climate scenario we chose. We modeled climate scenarios for mid-century (2050), but in earlier research we showed that climate change will impact yields of winter wheat in Kansas by 2030 through either climate boosts or burdens.[1]

Global climate model data are available at large scales worldwide. For this type of analysis, we needed "downscaled" data at a scale useful to farming communities. The publicly available climate model data we used had been "downscaled" to a 4km x 4km scale using peer-reviewed methods. This scale is equivalent to about 4,000 acres. See the Appendix for a more detailed discussion of the climate data and downscaling approaches.

Key climate variables that impact crop production

Crop production will be affected by changes in temperature (described below in terms of growing-degree days and failing-degree days) and water availability relative to crop water demand (climate change will affect both water availability and needs). We therefore used a combination of agronomic and water use models to explore the impacts of climate change on crop yields.

For each 4km x 4km area in Kansas, we have a range of predicted changes in seven climate variables for 2050. Those variables were:

- Minimum temperature
- Maximum temperature
- Precipitation
- Vapor pressure deficit (the difference between the amount of moisture in the air and the amount of moisture the air can hold)
- Specific humidity
- Wind speed and direction and
- Downward solar radiation.

With this data we calculated the following crop-specific variables as necessary inputs into our agronomic and water use models:

- **Growing-degree days** are a measure of heat units in a beneficial temperature range. They help to estimate the growth of crops during the growing season.
- **Failing-degree days** are a similar metric as growing-degree days, but they measure heat units in a detrimental temperature range. The accumulated temperatures in this range are, at best, too hot for crops to grow and, at worst, damage or kill the crop.
- **Growing season precipitation** is the accumulated precipitation over the growing season.
- **Crop evapotranspiration**, or crop water demand, is a measure of how much water evaporates from the soil surface and plants "exhale" through their leaves as they grow.

As in our previous study, the balance between growing-degree days and failing-degree days directly impacts crop yields. Now, however, we additionally consider the impact of climate change on crop water availability (for rainfed crops, this is growing season precipitation) and crop water demand. Where crop water demand exceeds crop water availability, yields will decline.

Future crop water demand

Evapotranspiration is the movement of water from the land surface to the atmosphere, a fundamental component of the hydrologic cycle. Estimates of evapotranspiration from farmland are a key tool farmers use to anticipate crop water needs, as crop water use changes throughout a crop's life cycle. We estimated future crop evapotranspiration using a method, based on the Penman-Monteith equation, which provides an estimate of potential evapotranspiration. To estimate daily crop evapotranspiration, we used crop coefficients from the USDA crop coefficient database. Typical crop planting and harvest dates were taken from Kansas State University Extension School and USDA publications.[32,33] Planting dates tend to be earliest in the southeast and latest in the northwest.

Crop water availability

To analyze crop water availability, we developed the crop water index. For each crop, we averaged potential evapotranspiration and crop coefficients (described above) over the growing season, county by county. That gave us crop water use (evapotranspiration) in inches, the same units as precipitation. Then we calculated the crop water index for each crop by subtracting crop evapotranspiration from precipitation.

Negative numbers indicate a shortfall in crop water availability which will lead to reduced yields.

Crop water use efficiency targets

As an input to the decision tool, we created targets for crop water use efficiency in the future. We chose to use the percent decrease in the crop water index from historic (2021) to mid-century (2050) as the target water use efficiency improvement. This means future cropping patterns would not use any additional water than what has been used historically. We calculated the crop water index for corn, soybeans and wheat over the growing season for both the historical and mid-century time frames. The difference between them was then converted to a percentage to become the target for water use efficiency improvement. As discussed previously, the tool is limited to rainfed crops. See the Appendix for a more detailed discussion of the crop water use efficiency targets.

Crop switching decision tool

To imagine a more resilient future crop mix in Kansas in 2050, we developed a crop switching decision tool to guide our research. The goal was to have the same row crop acreage in each county in 2050 as there had been in 2021, but with a new crop mix. We wanted the new crop mix to use no more water than currently used, while maintaining or increasing the amount of nutrition. This tool used the following assumptions about climate and water availability:

- Crops will require more water due to climate change, but both surface and groundwater will be reduced. In other words, there are no new irrigation sources for thirsty crops.

- To decide how much we change crops, we assume there is no new irrigation water available and changes in plant water needs (evapotranspiration) can only be met through changes in precipitation.

Where rainfall can't meet a crop's water needs, a more water-efficient crop must be grown.

- Given the goal of the study, the decision tool assumes that water intensity reduction happens through alternative crops rather than through more efficient irrigation or varieties of corn, wheat or soybeans that require less water.

- The decision tool works through individual crop switching (as shown below), because this better reflects individual farmer decision-making and better aligns with changes that food companies would need to consider.
    - Field corn to sorghum
    - Winter wheat to winter rye
    - Winter wheat to winter oats
    - Soybeans to millet

- The extent of the crop switching is decided by:
    - Mid-century yields
    - Crop water index
    - Nutrient density

It is important to note that mid-century yields are driven by climate, which affects both temperature and water demand availability. Using these assumptions, we calculated water intensity reduction targets for each crop in each county. These calculations factored in the change in the crop water index and the water use efficiency for each crop in units of nutritional value per acre per inch of water used (NRF9.3/ac/in). Then we solved for the number of acres of each crop that would give us a composite water use efficiency score to meet the water intensity reduction target for each county. The composite water use efficiency score is made up of the present-day crop and the crop that it would switch to. See the Appendix for an example calculation.

RESULTS

Nutritional values

NRF9.3 values for the grains under consideration for crop switching are shown in **Table 1**. Crop switching from field corn to sorghum provides an obvious nutrition benefit. Rye compared to winter red wheat is better, but oats provide slightly less nutrition. The switch from soybeans to millet is a decreasing nutritional yield, but millet has a higher water use efficiency. We will explore this further below.

Table 1.

NRF9.3 values for select grains

Grain	FDA code	NRF9.3/100g
Field corn	200014	90.5
Sorghum	200067	111.2
Winter red wheat	200072	129.6
Oats	57602100	128.7
Rye	200062	132.9
Soybeans	11450	115.2
Millet	200031	97.4

Projected changes in climate variables for Kansas by 2050

Kansas is expected to warm significantly in the coming decades, even under more modest emissions paths.[34] Both summer and winter average temperatures are projected to increase 3-5 °F by mid-century.[35] While temperatures will increase dramatically, model projections of average precipitation only show modest changes, with small decreases in summer and fall and small increases in winter and spring. Vapor pressure deficit, a measure of the difference between how much water vapor is in the air and how much moisture the air can hold when saturated, is projected to increase approximately 25% by mid-century, greatly increasing drought risk.

One beneficial side of warming is an increase in growing-degree days, but the double-edged sword of increased summer warmth is increasing failing-degree days, as well as increased crop evapotranspiration. Most of the beneficial increases in warming are overshadowed by the much greater increases in failing-degree days.

Warmer temperatures increase crop water needs. If extra water is not available, crops can become stressed. So, in this study it became clear that water was the limiting factor, and crop evapotranspiration and precipitation would be the driving factors in crop switching.

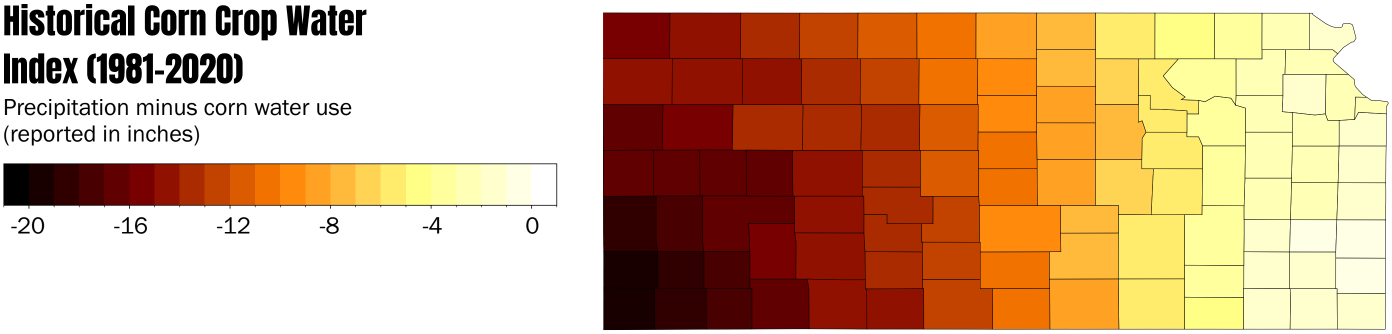
To account for water in the rainfed production system we subtracted crop evapotranspiration from growing season precipitation to obtain the crop water index. Seasonal rainfall tends to provide all eastern Kansas' crop water needs, while central and western Kansas require copious soil moisture or irrigation to reach maturity. This is illustrated in **Figure 8,** showing the historical and projected change in the crop water index for corn. In the future, however, Kansas crops are expected to require more water, particularly in the rapidly warming north. The crop water index would increase for almost all crops throughout Kansas. Winter oats, rye and wheat are likely to have a crop water index decrease in the eastern part of Kansas. In that region, the winter growing season precipitation is expected to keep pace with their evapotranspiration needs.

Figure 8.

Kansas maps showing (Top) historical crop water index and (Bottom) projected 2050 change in crop water index for corn

Historical Corn Crop Water Index (1981-2020)

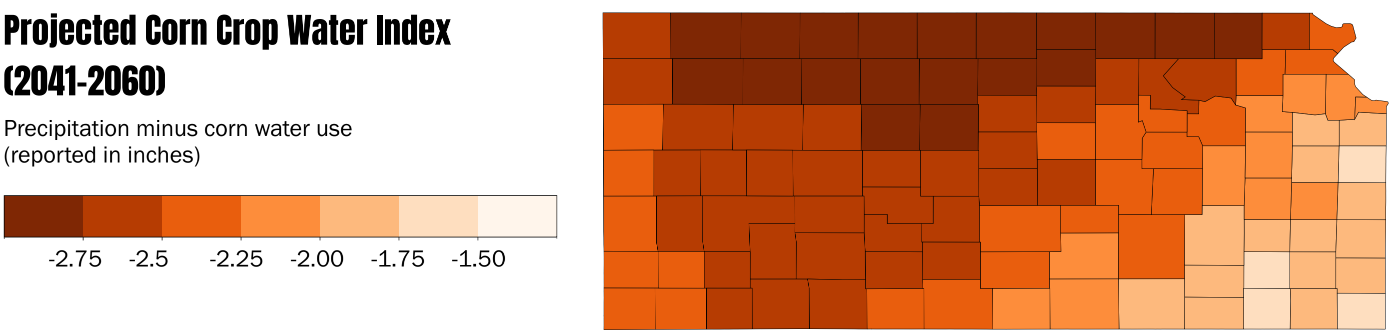
Precipitation minus corn water use
(reported in inches)



Source: gridMET

Projected Corn Crop Water Index (2041-2060)

Precipitation minus corn water use
(reported in inches)



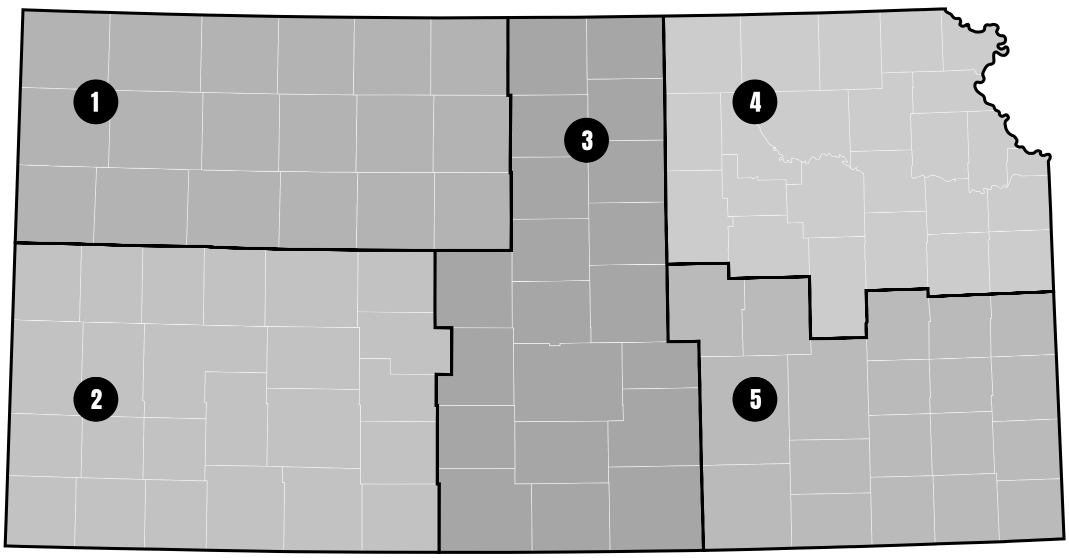
Source: MACA

Decision tool results

The results of the decision tool suggest a new crop mix that could optimize water use efficiency and nutritional value in Kansas' rainfed systems. For each crop in each county, we calculated water intensity reduction targets that factored in the change in the crop water index and the water use efficiency for each crop in units of nutrition per acre per inch (NRF9.3/ac/in). Results are presented by the regions presented in **Figure 9**. In **Table 2** we show the average water use efficiency by region for 2050 with no changes in the crop mix and with the suggested new crop mix. A higher water use efficiency value means it is more water efficient. The percent increase shows how much more water efficient the new crop mix would be compared to the status quo.

Figure 9.

Kansas regions



Source: Kansas Department of Agriculture, Division of Conservation

Table 2.

Average water use efficiency by region

	Average water use efficiency (NRF 9.3 kg/ac/in)		% Improvement in water use efficiency
	2050 status quo	2050 reimagined	
Region 1	57.1	63.5	11%
Region 2	54.1	58.8	9%
Region 3	51.7	62.3	21%
Region 4	80.3	84.5	5%
Region 5	66.9	78.7	18%

The suggested change in rainfed crop acres for each region from 2021 to 2050 are shown in **Table 3**. The change in acres balances the equation to meet the water intensity reduction target for each county. For the acres of each crop shown in 2021, the water needs were projected out to 2050 based on the future climate if the acreage remained the same. Using the difference in historic and projected crop water needs, we calculated the percent reduction in crop water usage for each region. Across the state the alternative crops could reduce water use by 12% on average by replacing water-intensive corn, wheat and soybeans. Crop water use reduction between today and mid-century is illustrated by county in **Figure 10.**

Table 3.

Crop mix by region for historic and future scenarios

2021

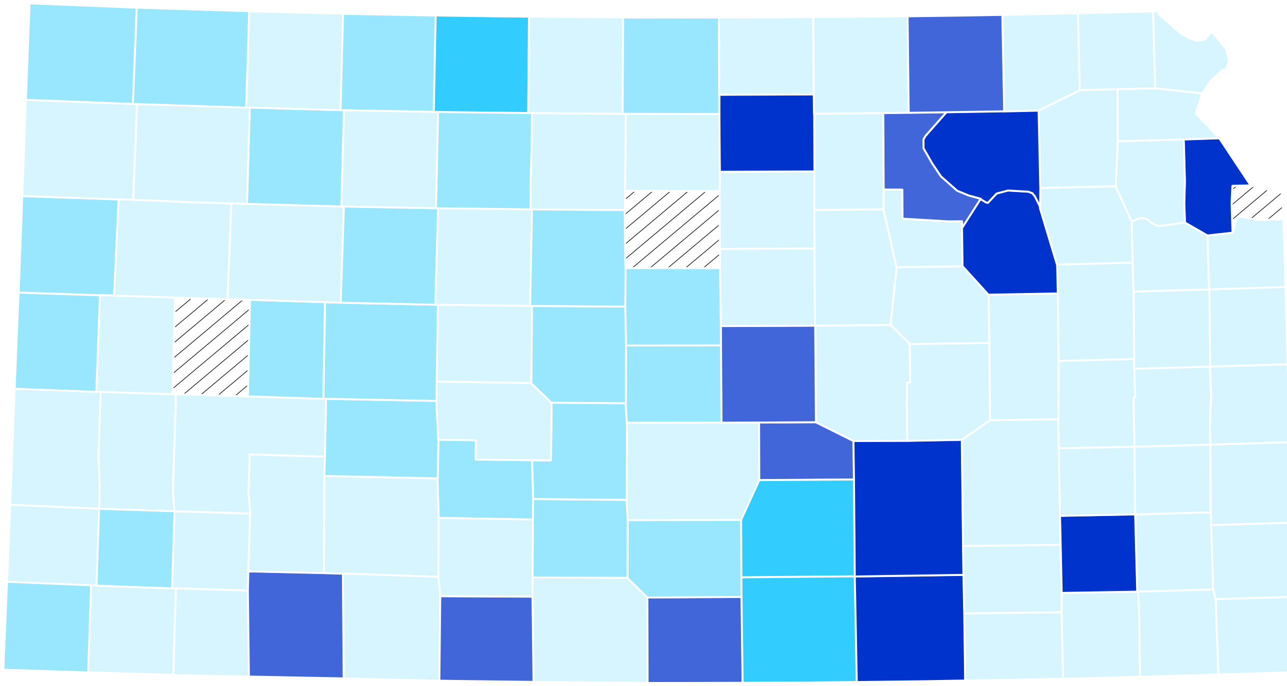
Region	Corn (acres)	Sorghum (acres)	Soybean (acres)	Millet (acres)	Wheat (acres)	Rye (acres)	Oats (acres)	2050 crop water need (acre-feet)
1	1,207,000	660,200	209,660	0	1,239,100	0	0	7,979,031
2	872,000	989,300	105,790	0	1,643,000	0	0	9,383,133
3	581,920	588,700	1,257,300	0	1,970,900	0	200	10,847,049
4	850,880	61,390	1,533,500	0	259,490	0	0	5,962,553
5	551,100	124,060	1,108,930	0	393,150	0	0	4,951,424

2050 projection

Region	Corn (acres)	Sorghum (acres)	Soybean (acres)	Millet (acres)	Wheat (acres)	Rye (acres)	Oats (acres)	Crop water need (acre-feet)	Reduction in crop water usage
1	847,781	1,000,783	124,129	85,531	589,442	376,200	273,458	7,195,564	9.8%
2	632,993	1,228,307	13,102	92,688	1,089,491	422,299	131,210	8,594,075	8.4%
3	382,365	777,555	493,418	763,882	1,802,616	168,194	0	8,753,815	19.3%
4	649,296	239,674	1,420,200	113,300	259,490	0	0	5,576,624	6.5%
5	507,235	167,925	769,451	339,479	375,386	17,039	725	4,138,368	16.4%

Figure 10.

Mid-century crop water use change.



Crop water use reduction in percent relative to 2021 due to reimagined crop mix by 2050. The three counties shown with a hatched area do not have any USDA recorded acreage for wheat, soybeans or corn in 2021.

A potential scenario for a resilient Kansas

Our results suggest that climate change will make it more difficult to grow the current crop mix in Kansas, primarily by increasing the imbalance between crop water demand (which will increase) and crop water availability (which will decrease). Absent additional water supply, this will impact crop yields.

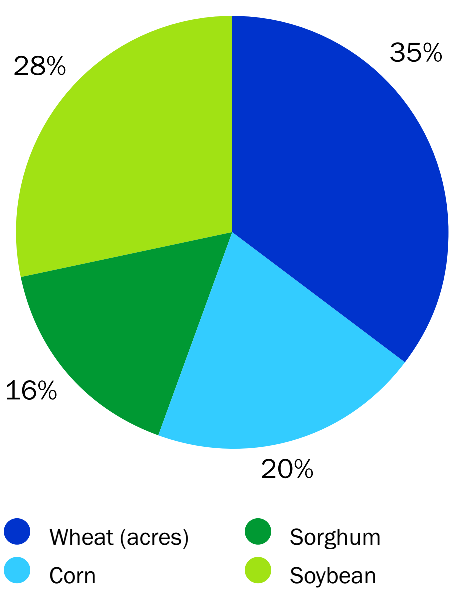
Two recently passed laws in Kansas will strengthen limits on agricultural water use, and provide funding to support water infrastructure projects and water assistance.[36] Our county-level decision tool enables us to explore the extent to which alternative crop mixes—better suited to future climate and water constraints— could be implemented so as to maintain or increase nutritional value and decrease water use. The suggested alternative cropping scenarios would be more resilient to climate change and more sustainable in a region already experiencing water stress.

County-level results are aggregated to state level in **Figure 11.** The proposed future scenario shows a significant increase of nearly 30% in the share of alternative crops from 2021 to 2050. In this reimagined future, rye, oats and millet grow from occasional niche crops to a fifth of Kansas' rainfed crop acreage in 2050 while sorghum grows by 7%.

Figure 11.

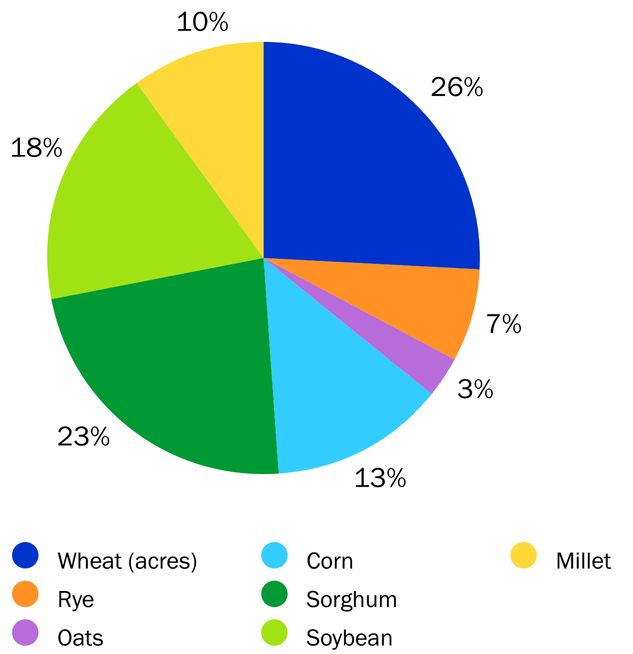
Pie charts showing actual 2021 rainfed crop mix and the projected 2050 rainfed row crop mix for Kansas.

Actual Kansas rainfed crop mix (2021)



**Values may not add up to 100% due to rounding*

Reimagined Kansas rainfed crop mix (2050)

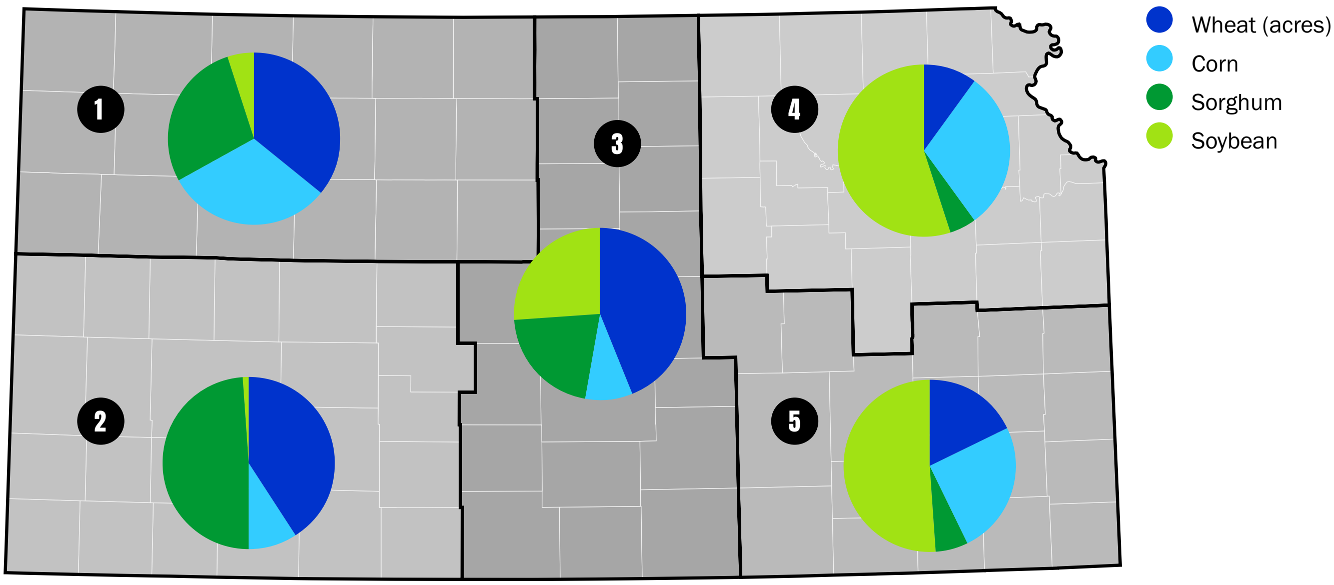


Of course, Kansas shows significant variation in its current crop mix and future climate between its five agricultural regions and indeed within each region on a county-by county basis. **Figure 12** shows the potential change in each region from the baseline (2021) to the reimagined future (2050). In the two western regions crop switching is the most diverse, using all the crop combinations. The northwest region has the highest percentage of additional alternative crops (29%) while the central region has the highest reduction in water use (19%).

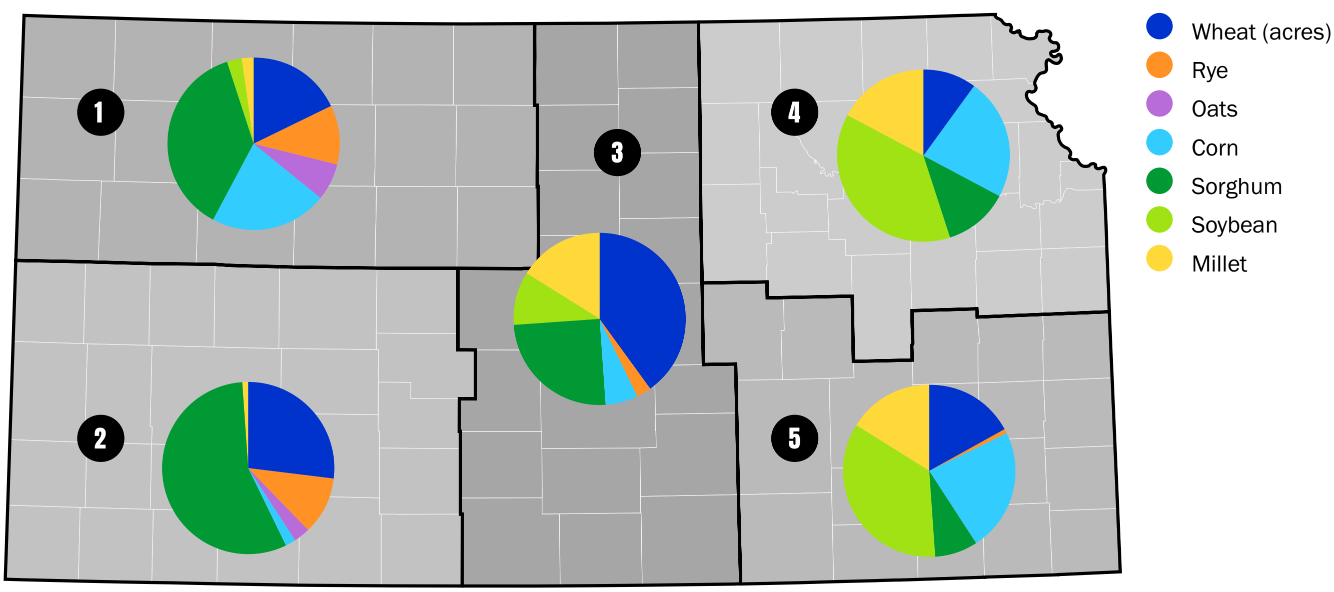
Figure 12.

Actual 2021 and projected 2050 rainfed row crop mix for each of the five agricultural Kansas regions

Actual Kansas rainfed crop mix by region (2021)



Reimagined Kansas rainfed crop mix by region (2050)



As seen in **Figures 13** and **14**, the northwest and southwest regions present a high extent of crop switching that is diverse with contributions from all alternative crops i.e., sorghum, rye, oats and millet. The reimagined 2050 crop mix leads to a 9.8% reduction in crop water use in the northwest region and an 8.4% reduction in crop water use in the southwest region (**Table 3**). This is not surprising, given that these regions show a high number of failing-degree days as well as rising crop water shortfalls for conventional crops.

Figure 13.

Actual 2021 and projected 2050 rainfed row crop mix for northwest Kansas Region 1

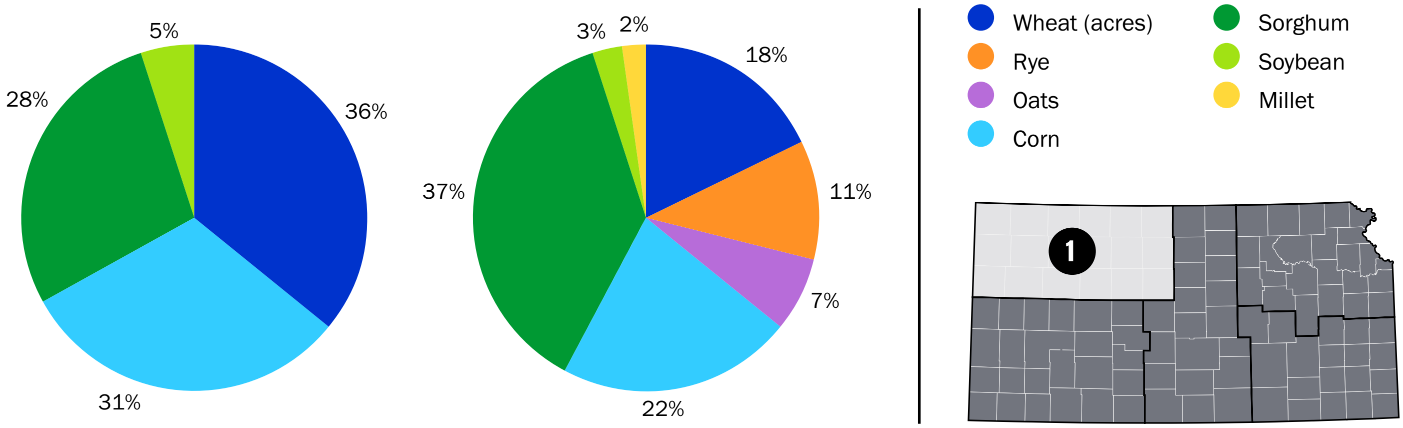
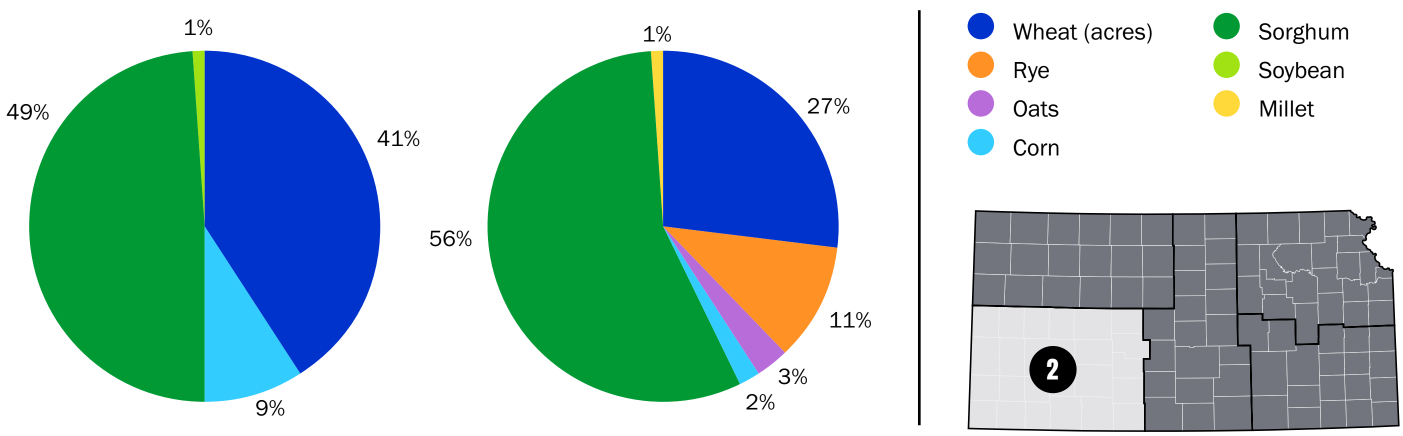


Figure 14.

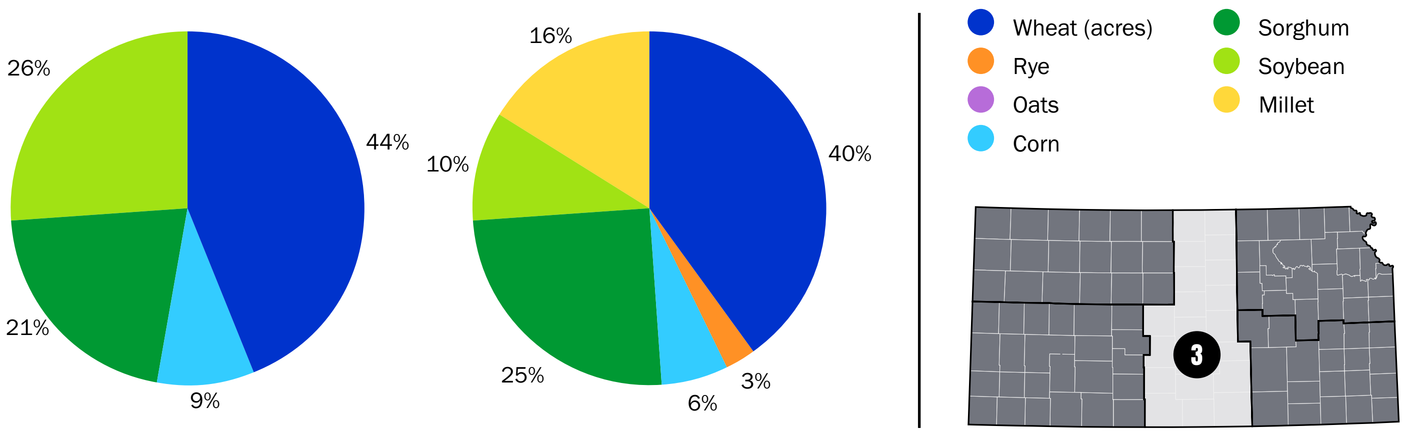
Actual 2021 and projected 2050 row crop mix for southwest Kansas Region 2



The extent of crop switching in the central region (**Figure 15**) results in a 19.3% reduction in crop water use by 2050 (**Table 3**). This is consistent with the large increase in the crop water index for all crops in this region. The crop switching is diverse with contributions from sorghum, rye and millet—but not oats. Because oats have slightly lower nutrition and higher evapotranspiration than rye, they didn't satisfy the nutrition and water use requirements applied in the decision tool.

Figure 15.

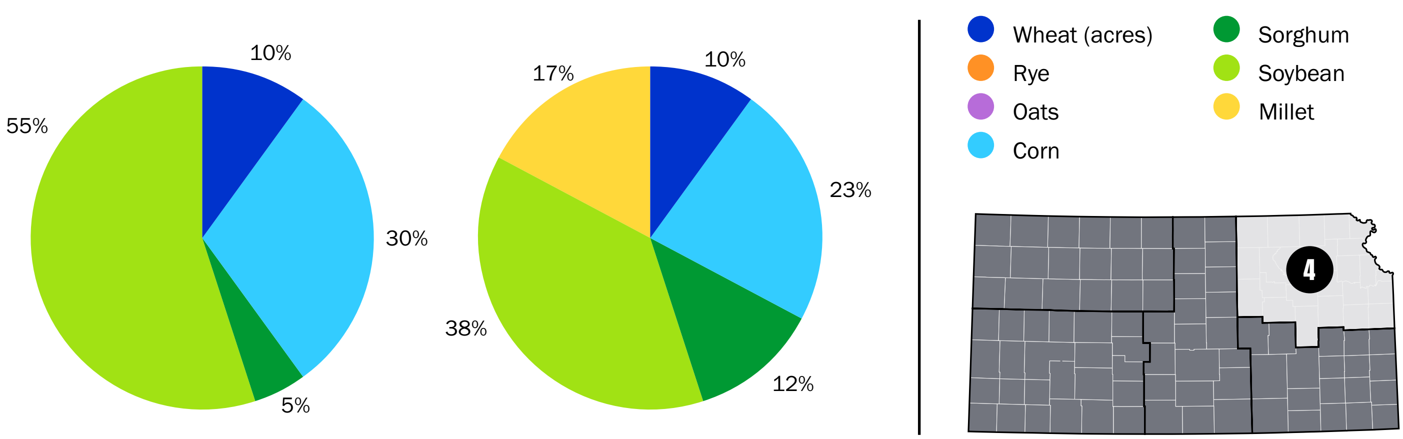
Actual 2021 and projected 2050 rainfed row crop mix for central Kansas Region 3



In the northeast region only soybeans and corn switch to millet and sorghum (**Figure 16**) resulting in a 6.5% crop water use reduction (**Table 3**). Given that, for wheat, the future precipitation over the growing season is projected to be nearly equal to future evapotranspiration, the current acreage under wheat can be maintained.

Figure 16.

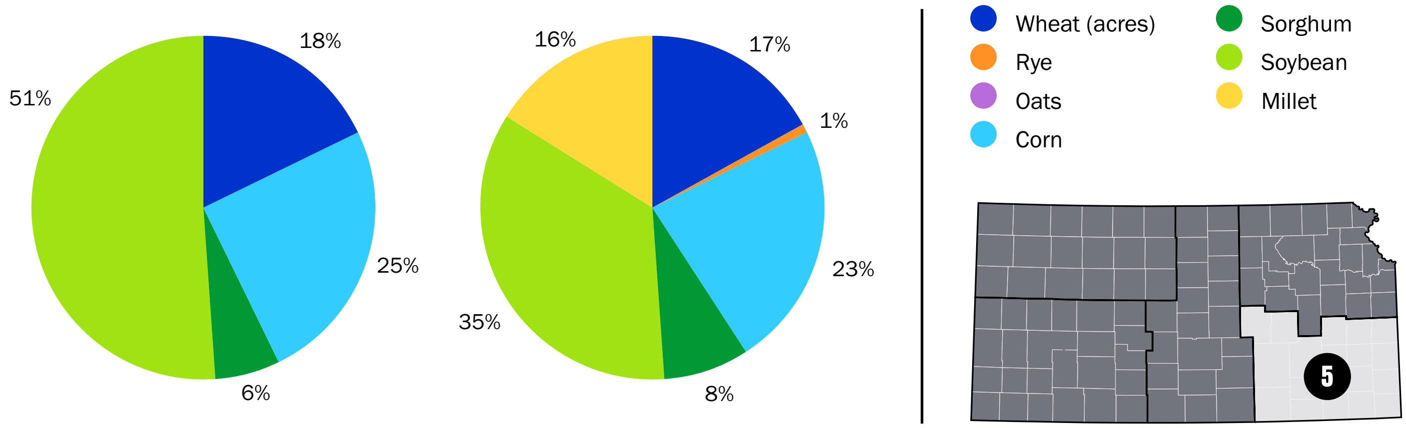
Actual 2021 and projected 2050 rainfed row crop mix for northeast Kansas Region 4



The southeast region also demonstrates how the predicted future increases in both precipitation and evapotranspiration allow current wheat acreage to be maintained under a future climate (**Figure 17**). However, a significant shortfall in precipitation over summer months leads to a high level of switching from soybeans to millet and corn to sorghum. As a result, the crop water use reduction is 16.4% for this region in 2050 (**Table 3**).

Figure 17.

Actual 2021 and projected 2050 rainfed row crop mix for southeast Kansas Region 5



DISCUSSION

Our analysis and decision tool results provide one possible scenario for a resilient Kansas. Even with conservative projections of future climate conditions, we find that **negative impacts of changing temperatures and water scarcity mostly overshadow any climate-induced gains in crop production**, with significant variation across counties and regions. In this future scenario, crops are expected to require more water and precipitation changes are not expected to keep pace with this increased crop water demand for most major Kansas crops. **Thus, farmers face the dual challenge of climate burdens on yields and shrinking water availability**. Crop switching offers one avenue of adaptation for Kansas farmers to continue to produce under these expected climate constraints. We propose a crop switching scenario that would optimize water use efficiency and nutritional value in Kansas' rainfed systems, which would reduce overall water use.

This "Reimagined Kansas" is just one possible pathway to increase resilience; it offers hope that in the face of climatic and water constraints, farmers have a way forward.

Our results show that even modest crop switching in Kansas can result in reduced crop water needs, without sacrificing overall nutritional value. For example, in the southeast region of Kansas, alternative crops could go from 6% of the crop mix to 25%, saving 16% in crop water use by 2050. However, making such changes is not simple.

While it may be in farmers' best long-term interest to switch some or all of their crops as outlined above, farmers are acting within a complex system of constraints and conditions that may make it challenging for such a change to take place. In reference to aquifer depletion and a lack of behavior change, Matt Sanderson, a sociologist surveying farmers across the Ogallala region stated: **"People talk about this as a crisis. This is not a crisis. [...] You don't have a crisis for 40 years. You have a structural problem ."**[37] With the right changes, farmers could shift their practices to ensure a resilient livelihood in a future Kansas, but this will require changes beyond the farmers themselves.

Farmers face a suite of barriers and disincentives to changing their crop mixes:

- **Policy:** Current policy structures like crop insurance can make it more profitable and less risky to grow certain crops while making it less feasible to grow alternative crops. Some policy structures may also encourage maladaptive practices such as continuing to grow corn in increasingly water-scarce areas.[38]
- **Infrastructure:** Switching to alternative crops may require different machinery and infrastructure, which presents logistical and cost barriers for farmers.
- **Market barriers:** Without a clear market for these alternative crops, farmers will not choose to grow them. Current markets in place primarily demand corn, soy and winter wheat in Kansas, incentivizing farmers to continue growing those crops despite growing water and climatic constraints.
- **Technical support:** Farmers may lack information and resources around growing alternative crops.
- **Equity and ownership:** Beginning and historically underserved farmers face additional and strengthened barriers, including greater difficulty accessing credit and lower rates of land ownership, which restrict long-term decision-making. It is important to note that the above barriers affect different groups of farmers differently: Farmers have varying resources and tools available to them to overcome some of these barriers, depending on factors like income level, race, land ownership and operation size, history of farming, and gender, among other factors.

While this is not an exhaustive list of the myriad forces influencing farmer decisions around crop mixes, these are key barriers in the Kansas agricultural system playing into farmer decision-making. Thus, in considering the proposed "Reimagined Kansas" scenario presented here, we must consider pathways to overcome the above barriers and support Kansas farmers' decisions around resilient crop mixes. A deeper systems analysis of the key barriers and pathways for resilient crop mixes will be explored in another paper. Here, we briefly put forth some thoughts on potential pathways and opportunities to support farmers in adopting alternative crops.

Pathways for farmer adoption of alternative crops will require changes across the multiple barriers outlined above. Such a shift could require changes in policy to incentivize and support alternative crops and those producing them. It would require initiatives such as the USDA Rural Economic Development Loan & Grant Program to finance farmers making these climate-resilient investments in equipment and infrastructure. Financing solutions will also need to be tailored to the specific needs of historically underserved farmers. Food companies could work with farmers to create reliable markets for these alternative crops, and with support could begin a reformulation process to prioritize resilience in their products and supply chains. Increased funding for extension services to bolster resources and expertise around alternative crops could expand the information and technical support available to farmers growing these more resilient crops.

These examples highlight the need for a multi-pronged approach to supporting farmers in shifting to alternative crops. Above are just some of the changes needed to support such a shift. Promisingly, the 2022 Kansas Water Plan notes the need for some of the above system shifts, stating that policies including crop insurance, banking and property valuation should "encourage and reward" water conservation practices including the growing of alternative crops.[27] Hopefully, this will be the beginning of a system-level shift that will support Kansas farmers to be resilient and continue to feed the world into the future.

CONCLUSION

Our analysis shows that climate change will affect current rainfed cropping systems across Kansas both directly (through changes in temperature) and indirectly (through temperature-driven changes in crop water needs and availability). Current and projected future limitations on both surface water and groundwater supplies are likely to preclude the conversion of rainfed to irrigated production. State-level legislation is likely to make it increasingly difficult to access new sources of water, and in many parts of the state current water use will need to be cut back.

To continue their businesses, producers will need to grow crops better adapted to the predicted future climate and water supplies. The good news is that this can be done in ways that maintain or even increase nutrition.

In this study we have shown how even modest switching from more water-demanding crops such as corn, wheat and soybeans to sorghum, rye, oats and millet could reduce crop water needs for Kansas by 12%. Acreage under these alternative crops would increase from 16% in 2021 to 43% by 2050. More efficient irrigation and new water efficient varieties of conventional crops can get us further on the path to sustainable water use. As it turns out, in this reimagined future there are also benefits of increasing nutrition per acre.

To achieve profitability at these significantly increased volumes, new uses and markets will need to be created. Sorghum and millet will have to move beyond animal feed and biofuels towards significant human consumption. Rye and oats will have to move from niche products into the mainstream. This is a great opportunity for food companies to innovate, differentiate themselves from their competition and also contribute to a more sustainable future.

Changing crop insurance frameworks could help support and reward farmers for growing alternative, more climate-resilient crops.[38] Expanding crop insurance policies for adaptive alternative crops across more counties can provide producers with a key risk management tool for switching crops.

We hope farmers and farmer associations will use this report to determine which alternative crops are feasible in their counties and consider piloting them in light of their changing water availability. USDA and the Kansas Department of Agriculture could use this report to fund research on growing rye and oats in Regions 1 and 2 and millet in Regions 3, 4 and 5, so that information on best practices and yield can be shared with farmers. The Kansas Department of Water Resources along with Regional Advisory Committees could use this study and the academic research that it cites to develop projections on the impact of climate change on surface and groundwater availability by county and make agricultural water recommendations accordingly. Despite the climate challenges Kansas agriculture will increasingly face in the coming years, our findings highlight a “reimagined” path forward for Kansas farmers to continue to cultivate crops and support global nutrition into the future.

APPENDIX: DATA AND METHODS

Grower interviews

In order to get grower perspectives, we interviewed the individuals shown in **Table A1**. We attempted to capture the geographic and demographic diversity of Kansas farmers in these conversations. The types of questions asked of the growers included:

- What drives revenue, capital and operational expenses for your operations?
- What is the threshold net income/acre for you?
- What new crops have you tried cultivating on the farm in the last five years? What are your considerations for switching to alternative crops?
- Have you recently gone through or anticipate going through a change in watering the crops e.g., rainfed to irrigation, flood irrigation to drip irrigation?
- To what an extent do water and irrigation concerns drive your crop choices?
- Do you use any regenerative agriculture practices on your farm? What is the motivation for choosing these practices?

Table A1.

Grower interviewees, their organization, county and Dept. of Ag. conservation region

Name	Organization	County	Region
Dr. Lucienda Stuenkel	Stuenkel Farms	Washington	4
Dr. Johnella Holmes	Kansas Black Farmers Association	Graham	1
Lon Frahm	Frahm Farms	Thomas	1
Keith Thompson	Thompson Farms	Osage	4
Dale Helwig	Kansas Grassland and Forage Council	Several in SE Kansas	5
Mary Howell	Howell Farms	Marshall	4
Nick Guetterman	Guetterman Farms	Miami	4
Darin Williams	Williams Farms	Coffey	5
Brice Custer	Custer Farms	Ellis	1
John Niemann	Niemann Farms	Reno	3

Climate analysis

Historical climate data

This study uses historical climate data from the gridMET dataset. gridMET is a dataset of daily high-spatial resolution (~4-km, 1/24th degree) surface meteorological data covering the contiguous U.S. from 1979 through present day.[39] To achieve high spatial resolution gridMET superimposes interpolated daily departures of monthly averages from NLDAS-2 (reanalysis) over monthly data from the PRISM dataset.

Future climate projections

The Multivariate Adapted Constructed Analogs (MACA) dataset was used for future climate projections.[40] MACA uses daily data from global climate models (GCMs) and historical observations. GCMs produce data at high spatial scales that do not allow a county-by-county analysis. MACA downscales the data using a statistical method. These statistical methods contrast with so-called dynamical methods, which rely on regional climate models nested in a global climate model. Dynamical downscaling suffers from biases introduced by the driving GCM and computational intensity. Statistical downscaling is comparatively computationally efficient, yet itself has limitations associated with the assumption of stationarity and questionable fidelity to some first principles of meteorology. The MACA data set consists of output from 20 Global Climate Models (GCM) produced by 13 climate research centers.

While a large ensemble increases computation costs, it is key for understanding the differences between internal variability (noise) and changes emerging due to anthropogenic global warming (signal). This is particularly important for the climate scenario we chose, RCP4.5, which has lower emissions than the higher warming scenario RCP8.5 and consequently a lower signal to noise. With the deceleration of emissions growth in recent years and advances in non-fossil energy sources, RCP8.5 is now viewed as a “worst case” scenario rather than `business as usual.’[41] For this reason, we find RCP4.5 to be a more useful scenario to study future changes.

Localization

Rather than average climate data over the entire area of each county, we implemented a weighted average using historical crop growing areas. In other words, we produced a county-average by up weighting the areas with more intensive crop growing and down weighting the areas with little or no crop growing, like urban areas and inland waters (e.g., lakes, rivers). This is arguably better than averaging all of the gridded data for a county together, particularly for large counties with mixed land-use or a large fraction of inland waters.

The weighting scheme was implemented as follows. First, we developed historical crop growing baselines for each use case. These were determined from USDA CropScape maps with 30 meter resolution.[24] For each 30 meter grid cell in each state, we determined the crop frequency from 2017 to 2021. Then we computed the fraction of each 4km climate data grid cell with any crop cultivation from 2017 to 2021 (crop frequency>0). Then for each county, grid cell weights were computed by dividing each grid cell’s crop area fraction by the sum of the crop area fractions within the county. Finally, crop area-weighted county climate data were formed for each climate variable as an area-weighted average of the gridded climate data using the crop area fraction weights. In other words, each 4km x 4km grid cell in a county is weighted by its crop area fraction. Grid cells with a large crop area fraction will contribute more to the county average than grid cells with a small crop area fraction (e.g., due to urbanization, water or conservation).

Climate variables

gridMET and MACA provide daily 4km resolution for a variety of climate variables. We downloaded and localized maximum temperature, minimum temperature, precipitation, relative humidity, vapor pressure deficit, downward shortwave radiation and wind speed. These data and model outputs were used to calculate indicators important to crop yield, growing-degree days, failing-degree days and the crop water index.

For the climate statistics, we chose a historic period of 1981-2020, a span that captures a generation of farmer experience with the modern climate. For the future mid-century period we chose 2041-2060, a standard definition for studying medium-term climate change used by the IPCC.[42]

Crop evapotranspiration

To understand future crop water needs, we estimated crop evapotranspiration for the gridMET historical period and MACA past and future periods. We used the FAO's standardized crop evapotranspiration formula, based on the Penman-Monteith equation. The Penman-Monteith equation provides an estimate of potential evapotranspiration for a standardized surface. To calculate daily potential evapotranspiration, the Penman-Monteith equation requires meteorological inputs that are provided or can be inferred by the gridMET and MACA climate products.

To move from potential evapotranspiration to an estimate of daily crop evapotranspiration, we multiplied potential evapotranspiration by crop coefficients. Crop coefficients are time-varying parameters that reflect how crop water use changes in relation to potential evapotranspiration throughout the crop's life cycle. For summer crops, we used the USDA crop coefficient database. For winter wheat, we used the winter wheat crop coefficients developed by Irmak et al. For less well-studied winter crops, we used the winter wheat profile developed by Irmak et al., with intermediate crop coefficients adjusted to USDA cited values.

A final requirement for explicit crop water use projections is a crop calendar. The crop calendar defines the dates between planting and harvest, allowing crop evapotranspiration calculations to be done during the time of year when the crop is in the ground. Typical crop planting and harvest dates were taken from Kansas State Extension and USDA publications.

With (1) potential evapotranspiration; (2) crop coefficients; and (3) time of planting and harvest, we can calculate crop water use in inches for a given growing season, the same units as precipitation.

Agronomic modeling

To estimate how climate change will impact crop yields, we used a crop growth model developed by leading scientists. Using 40 years of historical yield data, the model developed a linear relationship showing how yield has increased over time. We made an optimistic assumption that crop technology innovations in the future would keep pace with past innovations and that management practices would continue to improve at historic rates. However, there is no guarantee that crop yields will continue a linear increase indefinitely.

For each crop, the model includes a variable representing the impact of continued technological development on yields, based on the historical growth in yields described above. Each model also includes the following climatic variables: growing-degree days, failing-degree days, growing season precipitation and crop evapotranspiration. We modeled yields of irrigated and rainfed systems separately, since the two systems produce very different yields. Only the rainfed yields were used in the crop-switching decision tool. The output of the model results in either a climate boost or burden on projected crop yields.

Yield projections for 2050 are one of several inputs to the decision tree model developed by the study team. These estimates are based on an understanding of historical crop-climate relationships and a forward projection of technology/management trends as well as climate. The climate observations and projections described in the previous section are combined with historical yield data from USDA. USDA National Agricultural Statistics Service (NASS) Quick Stats database provides county-level data. However, to protect data quality and grower privacy, USDA does not publish estimates if an insufficient number of survey responses are received. Econometric-type statistical models are developed from county-level data where at least 15 years are available. This was possible for Kansas corn, soybeans, sorghum and winter wheat. A paucity of county-level data required a different approach for millet, oats and rye. Johansson et al., (2017) noted that USDA survey response rates have been falling since the 1990s.[43]

Importantly, yields were disaggregated by irrigated and rainfed systems. Making inferences using USDA's aggregated crop survey data could lead to erroneous crop-climate conclusions, particularly where the fraction of irrigated-rainfed acreage has changed over time. The decision tool relies on yield projections for rainfed systems; however, for completeness we modeled both rainfed and irrigated systems. County-level agronomic modeling results are available in a spreadsheet included with the supplementary material. They are disaggregated into rainfed and irrigated yields for each county. We also include aggregated results for regions 1-5. This helps to reduce some of the county-to-county variability and provides some clarity on regional variation around the state. USDA stopped disaggregating estimates by irrigation practices in 2019. Thus our methods are reproducible although perhaps not repeatable with longer time series.

Statistical modeling

The previous study developed multiple linear regression models trained on historical yield with a linear time term and several linear crop-climate terms (e.g., growing-degree days and failing-degree days for Iowa corn and Minnesota soybeans; fall freeze days; spring failing-degree days; and spring precipitation for Kansas winter wheat).[1] This study continued this model framework, albeit with a more consistent model specification across crop systems. Specifically we modeled yield (Y) following Rising and Devineni, whose work is built upon a larger body of crop-climate relationship research:

$$Y = \alpha_0 + \beta_1 t + \beta_2\ GDD + \beta_3\ FDD + \beta_4 CWI$$

where α_0 is a constant coefficient; t is a time-term represented by the calendar year; GDD are growing season total growing-degree days, defined by daily mean temperature above a crop-specific baseline threshold (limiting daily maximum temperature to a crop-specific extreme threshold); CWI are growing season total failing-degree days, defined by daily maximum temperature above a crop-specific extreme threshold; and CWI is a crop water index, defined as the difference of growing season total precipitation minus growing season total crop evapotranspiration.[44] Each crop-climate predictor (GDD, FDD, CWI) is centered by removing the 1981-2020 time mean prior to fitting.

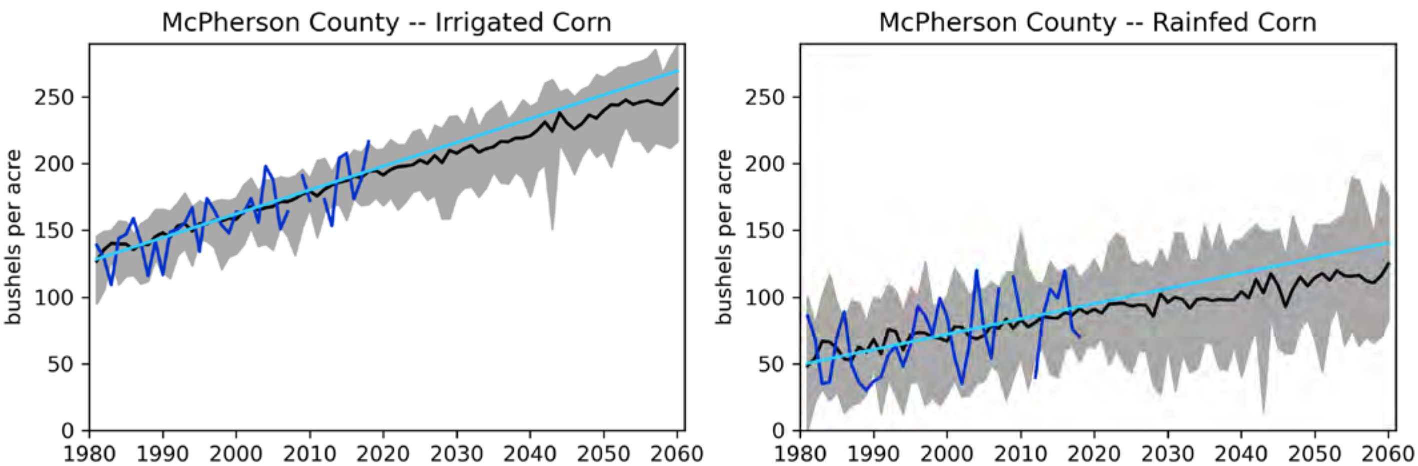
Coefficients for the historical period 1981-2020 were computed and then applied to localized data from 20 downscaled climate model simulations under the historical forcing 1981-2005 and RCP4.5 future scenario 2006-2060. The results were consistent with theoretical considerations: the coefficient for growing-degree days was positive signed across nearly all counties; the coefficient for failing-degree days was consistently negative; and the coefficient for crop water index varied from negative in the east where the index is near zero on average to positive in the west where the index is negative (a deficit of water).[45,46]

The resulting yield projections therefore include a linear trend component based on historical observations and a climate impact component associated with changes in growing-degree days, failing-degree days and the crop water index. The climate impact component can be described as a boost if positive and a burden if negative. We inputted the ensemble mean yield projection to the decision tool since it is the steady predictable part of the projections; however, it should be noted that for many counties and crops there is an appreciable range across the models (e.g., **Figure A1**). This ensemble spread is greater for rainfed systems than irrigated systems, reflecting the greater sensitivity of rainfed yields to climate and the significant internal variability (i.e., year to year) of Kansas climate represented in the model.

Figure A1.

Irrigated and rainfed corn yields in McPherson County, central Kansas.

Historical observations (blue), historical trend extrapolated (cyan), model ensemble mean (black), model ensemble range (gray).

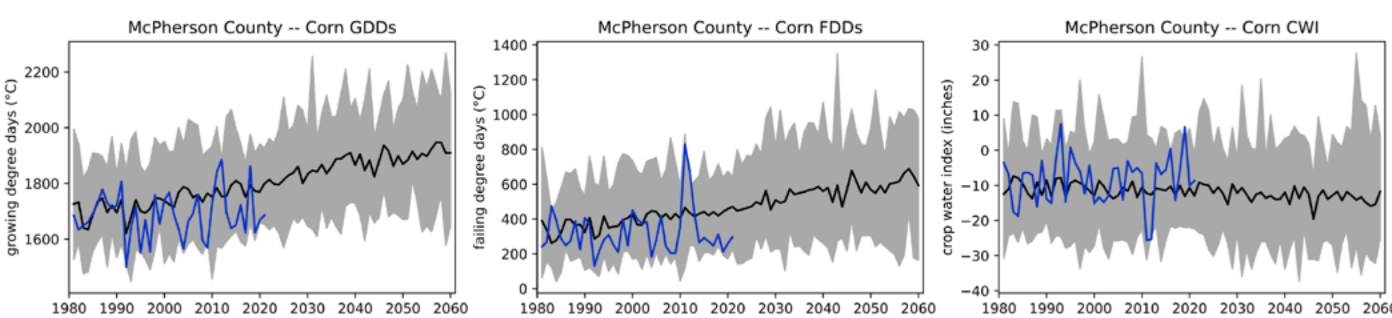


This internal variability is part of the irreducible uncertainty that farmers are familiar with planting crops each year (**Figure A2**). Notwithstanding this variability, a climate change signal is discernible in the noise for McPherson County. Averaging over larger areas like regions helps to reduce the model range, and it should be noted that the range varies by crop, season and region.

Figure A2.

McPherson County crop climate projections

McPherson County crop climate projections based on historical simulations and RCP4.5 simulations from the MACA downscaled dataset. Growing-degree days and failing-degree days tend to increase, whereas the crop water index decreases due to increasing evapotranspiration. Increasing failing-degree days result in a climate burden for McPherson County corn cultivation.



Proxy modeling

County-level data supporting statistical modeling were not available for all crops. There are currently only 25,000 acres of oats, <10,000 acres of rye and no reported millet acres in Kansas, so county-level data are not abundant across the state. Historical time series are equally rare. Thus, making projections for 2050 required us to take a different approach than with corn, soybeans, wheat and sorghum. Based on input from agronomy experts, we leveraged a proxy modeling framework for oats, rye and millet. For oats and rye, state average data formed the basis of our method:

1. Gather historical state-average yield data.
2. Estimate county-level historical yields by scaling the state-average historical yield by the ratio of county-level rainfed winter wheat yield to state-level rainfed winter wheat yield. This assumes that oats and rye yields vary geographically the same way as winter wheat yields.
3. Estimate county-level 2050 linearly extrapolated yields by scaling the state-average 2050 linear trend yield by the ratio of county-level rainfed winter wheat 2050 linear extrapolation to the state-level rainfed winter wheat yield 2050 linear extrapolation. As a result, the geographic pattern of winter wheat historical yield linear trends is built into those for oats and rye.
4. Estimate the county-level 2050 climate boost/burden by multiplying the county-level historical yield by the ratio of county-level rainfed winter wheat climate boost/burden to the county-level rainfed winter wheat historical yield.
5. Estimate the county-level 2050 climate-impacted yield by adding the 2050 climate boost/burden to the 2050 linear extrapolation yield.

For millet, data from the nearby states of South Dakota and Colorado formed the basis of the historical yields. A linear combination of South Dakota and Colorado state-average yields were used for Kansas estimated millet yields, using entirely South Dakota in the east and entirely Colorado in the west. The modeled sorghum yield climate boost/burden (as a % of historical yield) was applied to the millet linear trend projection for 2050 to get the 2050 climate-determined millet yield projection.

Summary

Across Kansas, we project corn and sorghum yields to increase slightly by 2050 despite increasing climate-induced burdens on yields. Consistent with the previous study, we project winter wheat, soybean, millet, oats and rye yields to stagnate by 2050 under continued burdens from climate change. While there may be outlier cases of increasing yields for select counties under climate change, the overall picture is one of increasing heat and water stress. Maintaining economic production despite climate change will require new adaptive strategies, including crop switching.

Crop switching decision tool

The crop switching decision tool is how we came up with the reimagined future for Kansas row crop agriculture. The goal is to use the same acreage under row crops in each county in 2050 that is in production in 2021, but with a changed crop mix. The changed crop mix should reduce water use while maintaining or increasing the amount of nutrition. The individual crop switching cases being considered were derived from grower interviews already underway in Kansas or other Great Plains states such as Nebraska and North Dakota. The following crop switching cases were used:

- Field corn to sorghum
- Winter wheat to winter rye
- Winter wheat to winter oats
- Soybeans to millet

The extent of the crop switching is determined by:

- Mid-century yields
- Evapotranspiration over the growing season
- Difference between evapotranspiration and precipitation over the growing season
- Nutrient density

Nutritional value

Nutritional value was calculated using the nutrient rich food score (NRF9.3) metric. NRF 9.3 is the unweighted sum of percentage daily values (DVs) for nine nutrients to encourage, minus the sum of percentage maximum recommended values (MRVs) for three nutrients to limit, calculated per reference amount and capped at 100% DV. [47] All values calculated per 100 grams. The nutrients to encourage are protein, fiber, vitamins A, C and E, calcium, iron, potassium and magnesium. The nutrients to limit are saturated fat, sugar and sodium.

Table A2.

NRF9.3 values for select grains

Grain	FDA code	NRF9.3/100g
Field corn	200014	90.5
Winter red wheat	200072	129.6
Soybeans	11450	115.2
Sorghum	200067	111.2
Rye	200062	132.9
Oats	57602100	128.7
Millet	200031	97.4

The percentage DVs and MRVs were calculated by using data on individual grains from the Food and Drug Administration Food Data Central. NRF9.3 values for the grains under consideration for crop switching are shown in **Table A2**.

Crop water use efficiency targets

Crop water use efficiency improvement targets between 2021 and 2050 were derived by estimating the decrease in crop water index (precipitation minus crop evapotranspiration) for a conventional crop over the growing season from historical to mid-century (2050). The decrease in crop water index from historic to mid-century as a percent of crop water needs (evapotranspiration for mid-century) was used as the target crop water use efficiency improvement. The method for estimating evapotranspiration and precipitation for historical and mid-century time frames is described in the Climate Analysis section of the report.

Example calculation: Switching corn to sorghum in Norton County

To estimate change in acreage between corn and sorghum for Norton County from 2021 to 2050, we should define water use efficiency metrics first. We define water use efficiency (WUE) as NRF9.3/acre/inch of crop water use. WUE is calculated by the following equation:

WUE = (Yield*NRF9.3* Crop Density) / (ET)

Detailed calculation of WUE for field corn and sorghum is shown in **Table A3**.

Table A3.

Decision tool inputs for corn to sorghum

Crop	Crop density (g/bu)	NRF9.3 / kg	2021 acres	2021 yield (bu/ac)	2021 ET (in)	Water use efficiency (bu/ac/in)	Water use efficiency (NRF9.3/ac/in)
Field Corn	25450	0.091	124,000	80	26	3.0	70.5
Sorghum	25450	0.111	22,600	73	21	3.5	97.6

Combined WUE is derived by multiplying WUE (NRF9.3/ac/in) for corn and sorghum with their acreage in 2021 and added up. Combined WUE for corn and sorghum in 2020 (NRF9.3/in) = 71.9. Given the decrease in crop water index between the historical period and mid-century, the target increase in WUE for corn and sorghum in 2050 is 10%. Hence the target combined WUE for field corn and sorghum = 79.2 (10% rise)

In order to get to a combined WUE of 79.2 in 2050 under more challenging ET conditions, we need to increase acres under sorghum and reduce acres under corn. WUE for corn and sorghum in 2050 = 79.2 with 54,309 acres under corn and 92,291 acres under sorghum. Detailed calculations are shown in **Table A4**.

Table A4.

Decision tool outputs for corn to sorghum

Crop	Crop density (gms/bu)	NRF9.3 / kg	2050 yield (bu/ac)	2050 ET (in)	Water use efficiency (bu/ac/in)	Water use efficiency (NRF9.3/ac/in)	2050 acres
Field corn	25450	0.091	85	29.8	2.9	66.8	54,309
Sorghum	25450	0.111	71	23.2	3.1	86.4	92,291

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