Land Use in a Warming Climate: Balancing Agriculture, Renewable Energy, and Conservation for Nebraska

October 2023

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Executive Summary

Climate change is the defining environmental challenge of the 21st century. The urgency of reducing greenhouse gas emissions using zero-carbon energy sources has never been greater. Solar and wind energy have demonstrated impressive cost reductions and deployment increases over the past 20 years. The passage of the Inflation Reduction Act has provided significant financial incentives to accelerate this deployment and help the United States meet its Paris Agreement emission reduction targets. In order to get to the next level of renewable deployment significant land resources would be needed. In states like Nebraska this creates a perceived conflict with crop agriculture, one of the mainstays of the region's economy that generated $16 billion value in 2022. However, climate change driven burdens on crop yields and water availability will render certain areas less attractive for agriculture, thereby creating an opportunity for preferentially locating large-scale renewables in those areas.

This report outlines how land use decisions might evolve by 2050. Using climate science, agronomy, and energy modeling, we project likely changes in crop agriculture and renewable energy production, providing crucial insights for Nebraska's long term resilience and prosperity. **Key messages are as follows:**

- **More heat:** Mid-century temperatures throughout Nebraska will be significantly warmer. Southern Nebraska counties will see the largest increase in extreme heat.
- **More crop water stress:** Climate change driven increases in crop water demand will be concentrated in Central Nebraska.
- **Higher yields, but increases stunted by climate:** Although absolute yields will rise thanks to biotechnology and farming practice improvements, there will be significant climate burden on yields.
- **Opportunities for renewable energy:** Solar and wind levelized costs of energy are already competitive with fossil fuels and will be present even greater cost savings by 2050. Western and Southern Nebraska will likely exhibit the greatest cost decreases. There is plenty of low-impact capacity available for both solar and wind energy; an order of magnitude higher than current installed capacity for power generation.
- **Agrivoltaics could provide co-benefits for growers:** Agrivoltaics present an opportunity to significantly cut irrigation and equipment fuel costs as well as generate additional income for farmers while using a very small fraction of their land.

So what? This study is intended for all stakeholders affecting and affected by land use decisions in Nebraska including farmers, grower associations, county officials, utilities, and the Nebraska Public Service Commission. Farmers should view agrivoltaics and conventional solar as an opportunity to cut irrigation and equipment fuel costs and improve their profitability. Officials in counties with reduced water availability and stagnating yields should consider solar and wind leasing on marginal farmland to protect their tax base. The Nebraska Public Service Commission should use this analysis to prioritize utility-scale renewable projects in counties with high climate burden on yields and/or water needs needed to ensure long-term resilience and prosperity.

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Introduction

Nebraska is renowned for its innovation and commitment to the public, and the support for transitioning to 100% renewable energy is clear. With the passage of the Inflation Reduction Act, the stage is set for rapid change. According to an analysis conducted by the Rocky Mountain Institute, Nebraska's rural economy could be the recipient of over $1.4 billion in revenue generated by wind and solar projects within the span of this decade. However, renewable energy deployment demands significantly more land than fossil fuel power generation, bringing into a perceived conflict with crop agriculture–a significant part of Nebraska's economy and culture. The US Department of Agriculture estimates that the value of crop production in Nebraska was $16 billion in 2022 with corn and soybeans accounting for $14 billion.[1] This report outlines how landscape and land use decisions might evolve by 2050. Using climate science, agronomy, and energy modeling, we project likely changes in crop agriculture and renewable energy production, providing crucial insights for Nebraska's long term resilience and prosperity.

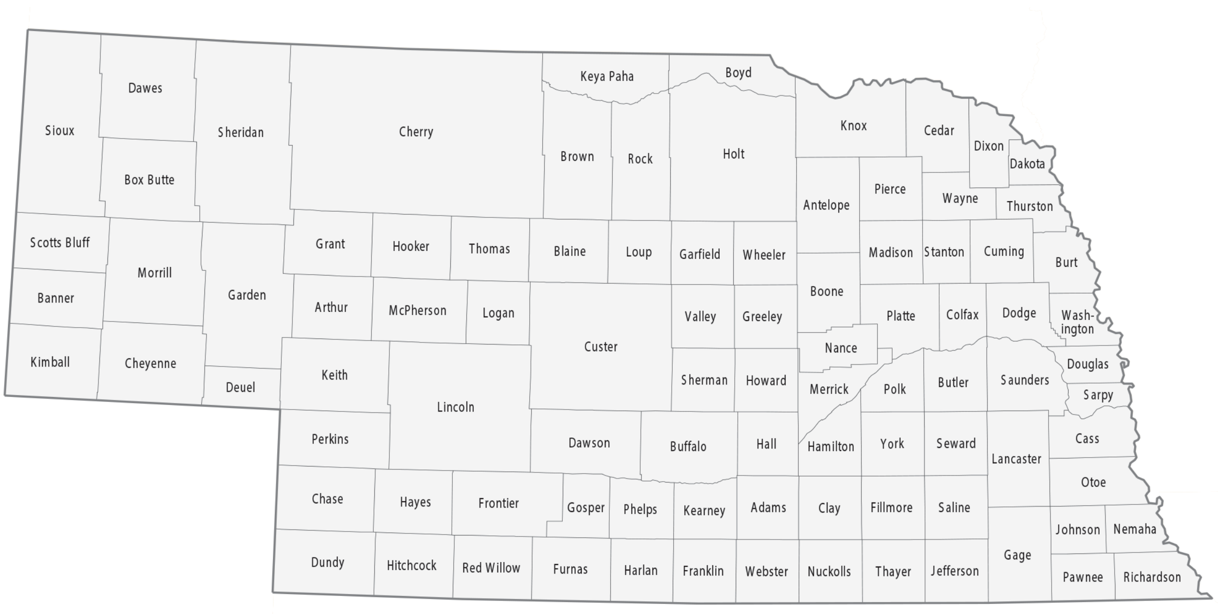

Figure 1. Nebraska's 93 counties.

Nebraska Climate in 2050

Nebraska is expected to warm significantly in the coming decades.[2] Both summer and winter mean temperatures are projected to increase approximately 5°F by midcentury.[3] Projections of mean precipitation are more complex, with models showing small increases in annual precipitation, small

[1] USDA State Agriculture Overview: Nebraska
https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEBRASKA
[2] Kloesel K, et al 2018 Northern Great Plains. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II doi:10.7930/NCA4.2018.CH23
[3] Hegewisch KC, and Abatzoglou JT. ' Future Boxplots' web tool Climate Toolbox accessed November 2022.

decreases in summertime rainfall, and more variability in rainfall. Summertime vapor pressure deficit, a measure of the difference between how much water vapor is in the air and how much it can hold, is projected to increase approximately 40% by midcentury, greatly increasing drought risk. The atmosphere will cause stress to the landscape by demanding more water be evaporated from the land surface and be transpired by crops and natural vegetation alike.

Key climate variables that impact crop production

When sunlight, heat, and water are present in moderate quantities, crops flourish. When too much or too little heat and water occur, plants experience stress. To assess future corn and soybean profitability we analyzed key basic and derived climate variables that impact crop production in Nebraska. These data were drawn from both historical observations and future climate projections under the representative concentration pathway 4.5 (RCP4.5) scenario. See Appendix A for details.

Basic variables analyzed include: maximum daily temperature, minimum daily temperature, daily total precipitation, daily mean vapor pressure deficit, daily mean wind speed, daily mean downwelling solar radiation at the surface, and daily mean specific humidity. From these basic variables we derived crop-specific variables including: growing degree days (heat units in the beneficial temperature range), failing degree days (heat units in detrimental temperature ranges), and crop evapotranspiration (crop water demand). For each crop, we averaged or integrated variables over its growing season, county by county. The length of the growing season was set by historically observed planting and harvest dates from USDA survey data.[4]

Projected changes in climate variables for Nebraska by 2050

Growing degree days

Growing degree days approximate the amount of time a given crop experiences ideal temperatures. In colder climates insufficient growing degree days can limit yield. Historical and midcentury projected change in corn growing degree days are shown in **Figure 2**. Most Nebraska corn growing regions are projected to see a 15% boost in growing degree days by midcentury, with the largest increase in the northeast. The trend and geographic pattern in growing degree days is similar for soybeans (not shown).

Failing degree days

Failing degree days approximate the amount of time a given crop is exposed to detrimental heat. Crops that experience above average failing degree days may see reduced yield. Historical and midcentury projected change in corn failing degree days are shown in **Figure 3**. The trends in

[4] National Agricultural Statistics Service 2010 Usual Planting and Harvesting Dates for U.S. Field Crops *USDA Technical Report* https://usda.library.cornell.edu/concern/publications/vm40xr56k

failing degree days is much more dramatic than growing degree days, with most of the state seeing a near-doubling in damaging heat. Already relatively hot southern counties are projected to see the largest increases in failing degree days. Trends and geographic patterns for soybeans are very similar to those seen for corn (not shown).

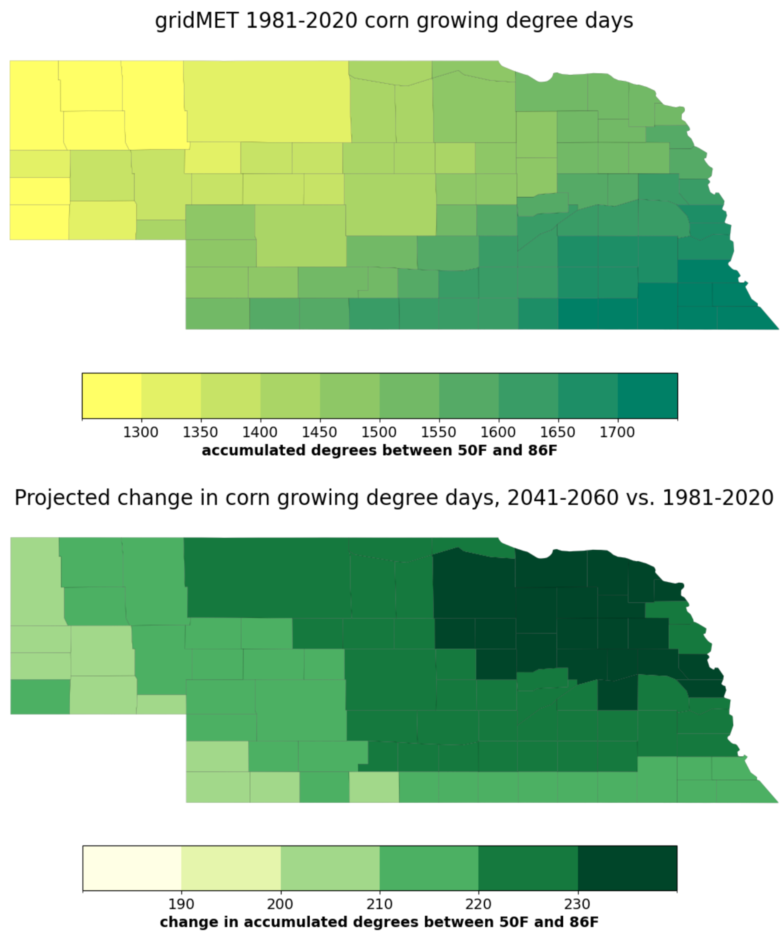

Figure 2. (*upper*) recent growing degree days (GDD) and (*lower*) projected 2050 change in GDD for corn.

Crop water index

Crop water index (CWI) measures the difference between actual rainfall and how much water a crop would ideally use. A more negative crop water index denotes a crop being exposed to a larger water deficit. This variable does not account for irrigation. Crops with highly negative crop water indices may be grown in regions with irrigation, which supplements rainfall and lessens water stress.

Historical and midcentury projected change in corn crop water indices are shown in **Figure 4**. Eastern Nebraska has only lightly negative crop water indices, a sharp contrast to very negative crop water indices in the harsher western Nebraska climate. Global warming is projected to expand the belt of deficit crop water index east. The largest decreases in crop water index are seen in central and eastern Nebraska, with relatively small changes projected for the already dry west. While soybeans need less water, the trend and geographic pattern for soybean CWI is similar to corn (not shown).

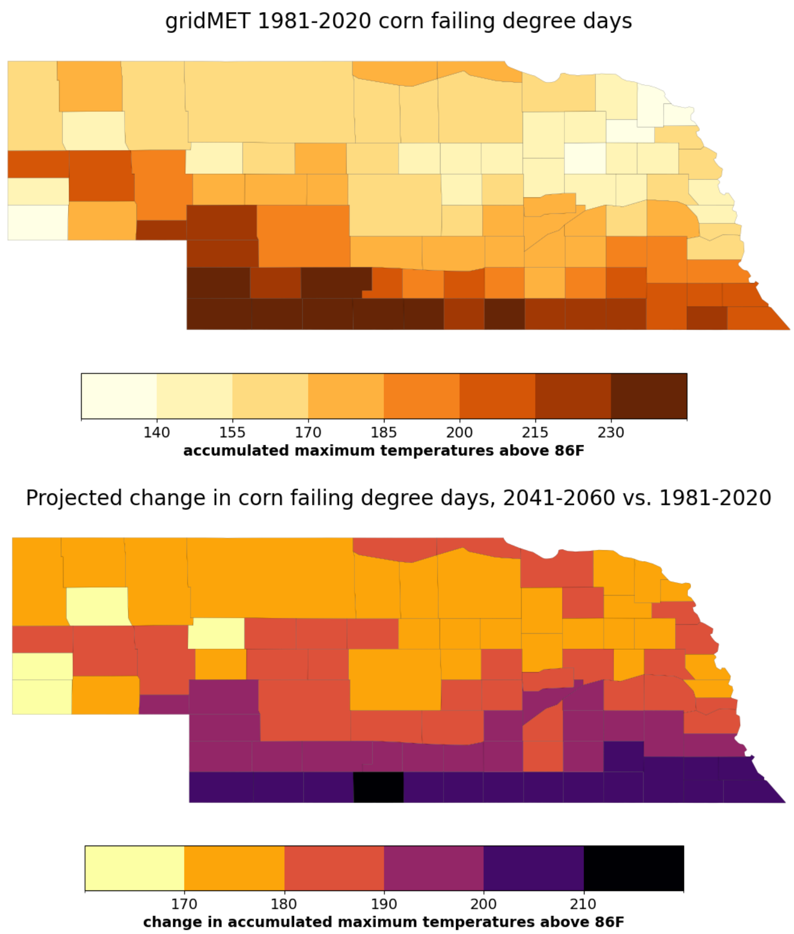

Figure 3. (*upper*) recent failing degree days (FDD) and (*lower*) projected 2050 change in FDD for corn.

Nebraska Agriculture in 2050

In order to explore Nebraska agriculture in 2050, this section includes a comprehensive analysis that spans four decades of agricultural data from 1981 to 2022, focusing on Nebraska's cornerstone crops: corn, soybeans, and hay. Utilizing advanced crop yield modeling techniques, we project the impact of climate change on corn and soybean yields in the year 2050. This section aims to provide a nuanced understanding of how climate change could impact the agricultural landscape of Nebraska, offering insights that are crucial for both the general public and policymakers.

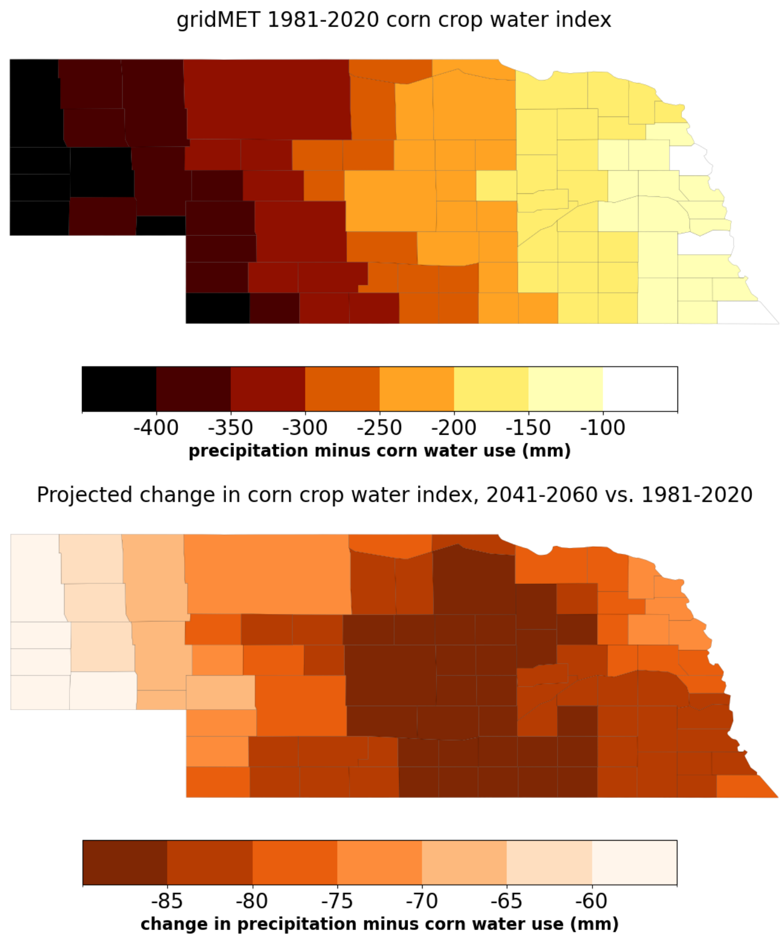

Figure 4. (*upper*) recent crop water index (CWI) and (*lower*) projected 2050 change in CWI for corn.

Historical context

Over the past 40 years, Nebraska's agricultural output has seen significant growth, driven by a combination of factors including technological advancements, improved farming practices, and increased investment in agricultural research. Corn, soybeans, and hay have remained the state's cornerstone crops, each experiencing its own trajectory of growth.

Corn

Nebraska corn acreage grew from about 6 million acres in the early 1980s to just short of 9 million acres in the 2020s (**Figure 5**, aggregated acres are the sum of rainfed and irrigated). A little more than half of those corn acres are irrigated, although dryland corn (i.e. rainfed) acres have been trending upward since the early 1990s.

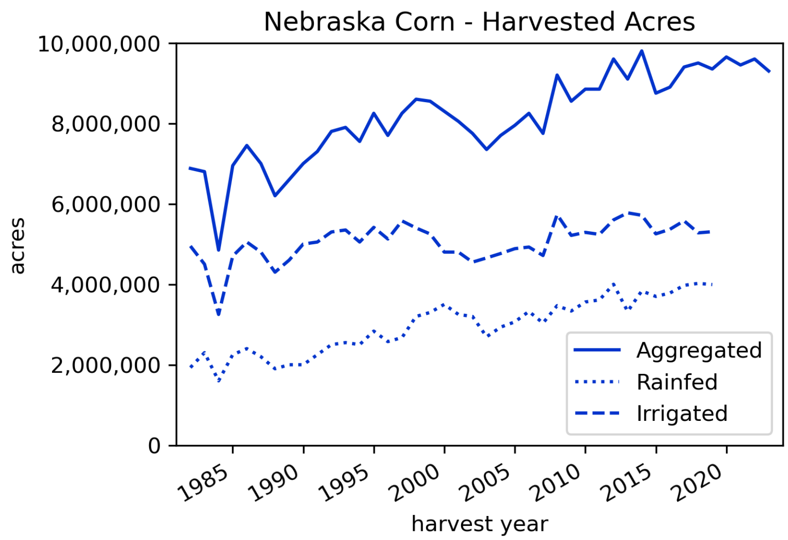

Figure 5. Nebraska corn harvested acres. Disaggregated rainfed and irrigated acres are shown along with aggregated acreage (rainfed+irrigated). Source: USDA NASS QuickStats.

Nebraska state-average corn yields have risen from about 110 bushels per acre in the early 1980s to about 170 bushels per acre in the 2020s (**Figure 6**). Irrigated corn yields are higher than rainfed dryland corn yields. The rainfed corn yields are considerably more variable from year to year than irrigated corn yields, suggestive of the important effects of water stress on crop production. This factor is particularly clear when comparing irrigated and rainfed corn yields during the drought year of 2012.

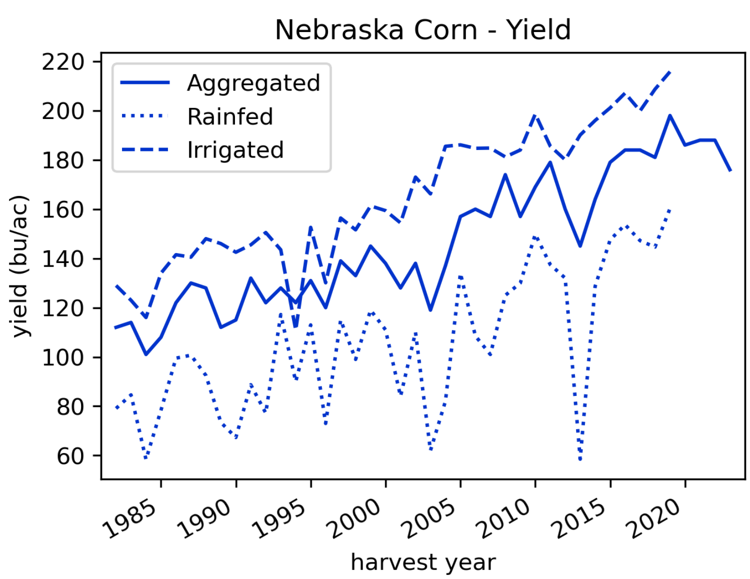

Figure 6. As in Figure 5, but Nebraska corn yields. Source: USDA Survey Data, NASS QuickStats.

County-level yields tend to be higher in the east than the west due to a longer growing season and more rainfall. This east-west gradient also shows up in a proxy for corn production risk produced by the University of Nebraska-Lincoln Institute of Agriculture and Natural Resources.[5] Using crop insurance premium calculation data, they quantified the county crop insurance reference rate. High reference rates imply higher historical payments and consequently more production risk and a higher crop insurance premium. Reference rates are calculated at the county, crop, and practice (irrigated vs. non-irrigated or summer fallow and continuous crop).

Maps depicting county-level reference rates by practice are shown in **Figure 7** (corn) and **Figure 8** (soybeans). Irrigated and rainfed corn production are both relatively risky in western Nebraska where the growing season is shorter and precipitation is lower. Central Nebraska is less risky from an irrigated agriculture standpoint, but still relatively risky in terms of rainfed production. Eastern Nebraska is the least risky production area for agriculture, particularly the counties along the Iowa border. County-to-county differences are influenced by variations in water availability, soil quality, infrastructure, pest and disease pressure, and local policy. While we have not untangled their individual contributions to risk, the maps shown do highlight overall regional variation.

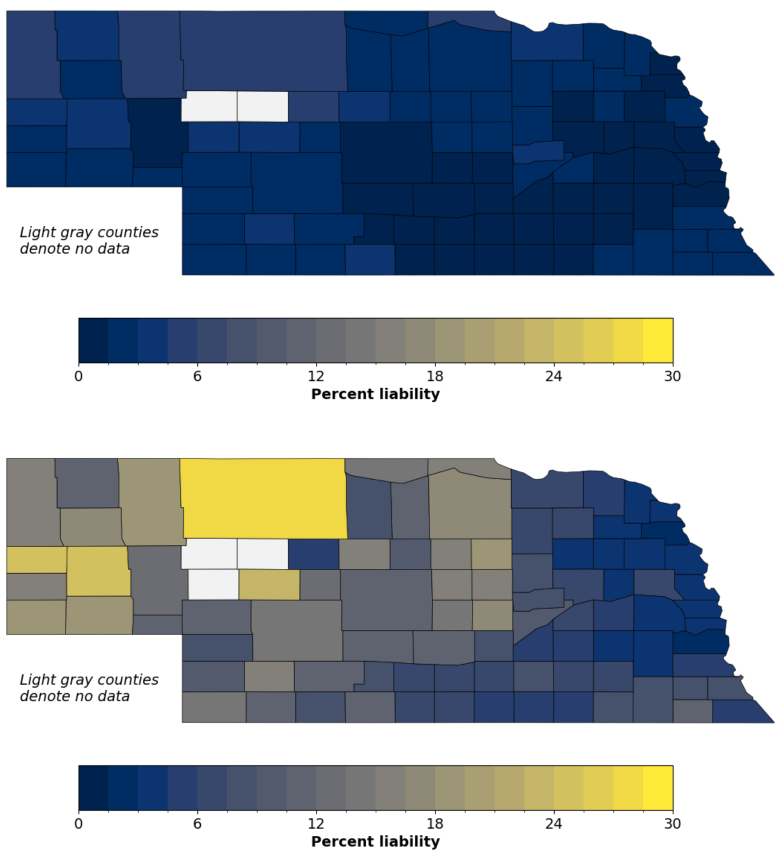

Figure 7. County-level corn production risk based on crop insurance information for (top) irrigated and (bottom) rainfed production. Numbers indicate the fraction of liability expected to be paid to farmers. Source: UNL CropWatch

[5] Walters C, Groskopf J, and O'Donnell E 2016 Nebraska Corn Production Risk by County using Crop Insurance Data. *UNL CropWatch*

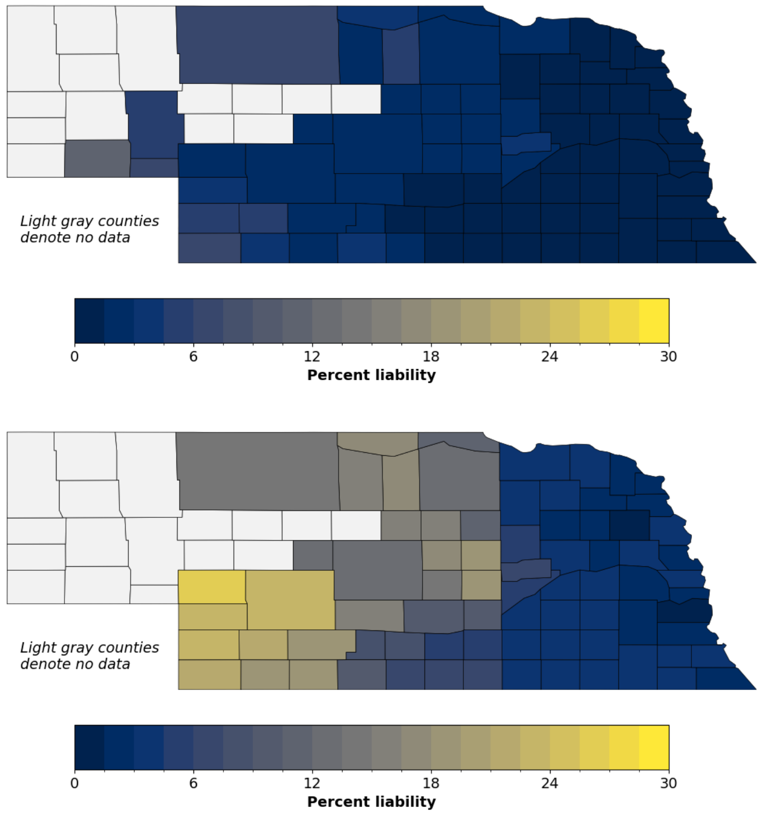

Figure 8. County-level soybean production risk based on crop insurance information for (top) irrigated and (bottom) rainfed production. Source: UNL CropWatch.

Viewed in historical context, Nebraska corn production has been particularly robust, benefiting from double cross hybrids in the 1920s through 1950s, single cross hybrids in the 1960s through 1980s, and genetically modified varieties in the 1990s through present. The latter are more herbicide- and pest-resistant, leading to higher yields, increased farm income, and reduced pesticide use.[6] The use of precision agriculture, which involves GPS-guided machinery and data analytics, has also contributed to higher yields per acre.[7] This technology-driven improvement in corn yields is seen in irrigated and rainfed yields. We expect this trend to continue based on continued private sector research and development.

Soybeans

Nebraska soybean acreage doubled during the 1990s and continued to rise slowly in the 2010s (**Figure 9**). Whereas rainfed corn acres continue to increase, rainfed soybean acres plateaued after the year 2000. Most of the growth in soybean acres since then has been from small increases in irrigated acres.

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[6] Van Acker R, Rahman MM, and Cici SCH 2017 *Oxford Research Encyclopedias: Environmental Science* doi: 10.1093/acrefore/9780199389414.013.217

[7] Schimmelpfennig D 2016 *USDA Economic Research Report* doi: 10.22004/ag.econ.249773

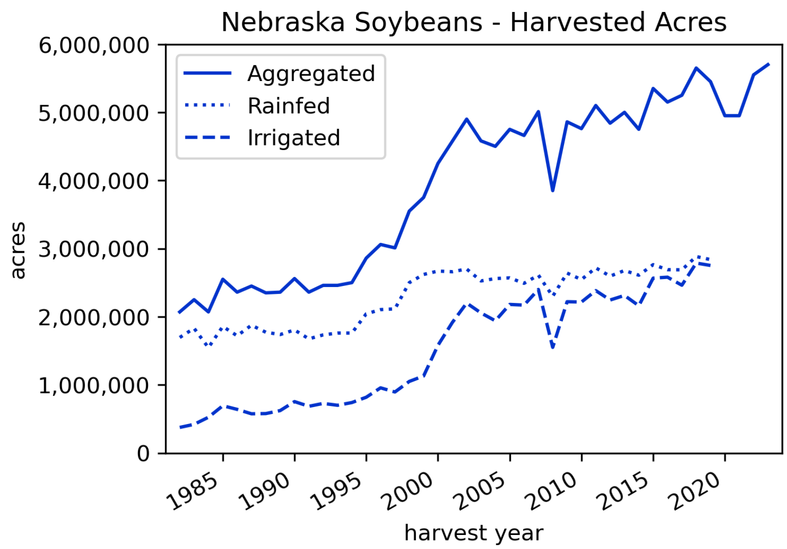

Figure 9. Nebraska soybean harvested acres. Disaggregated rainfed and irrigated acres are shown along with aggregated acreage (rainfed+irrigated). Source: USDA NASS QuickStats.

Soybean yields in Nebraska have increased over the past 40 years (**Figure 10**, aggregated acres). Similar to corn, this is true for both irrigated and rainfed production systems. Also like corn, year-to-year variability in yield is larger in rainfed production than irrigated production. The drought year of 2012 stands out in the rainfed production time series.

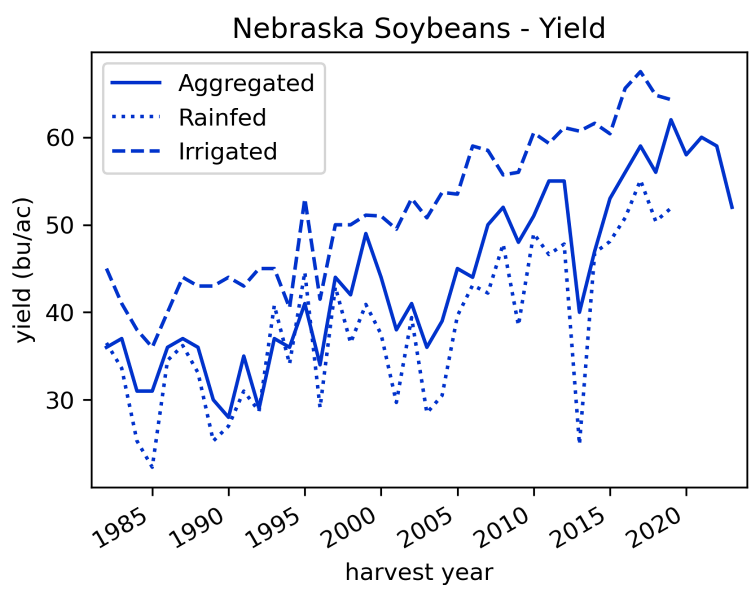

Figure 10. As in Figure 9, but Nebraska soybean yields. Source: USDA Survey Data, NASS QuickStats.

Crop-climate relationships

We modeled historical relationships between weather/climate factors and crop yields for corn and soybeans using data and statistical methods. The multiple linear regression model predicts historical yield based on 4 factors: (1) a linear time-trend that represents technology improvements, (2) growing degree days that represent beneficial heat, (3) failing degree days that represent detrimental heat, and (4) and crop water index that represents water availability. Each climate variable is tailored to the specific crop thresholds and accumulated over the crop-specific growing season. We trained the model on county-level yield data and climate data localized over agricultural areas within each county. See Appendix B for methodological details.

Future projections

We explored future Nebraska crop yields at the county-level by applying future climate projections to the historical crop-climate relationships from our statistical model. We assumed that the crop-climate relationships of the past would be the same in the future and that technological innovation would continue for both crops (i.e. using the same regression coefficients for growing degree days, failing degree days, and crop water index; extrapolating the historical linear trend in yield through 2050). See Appendix B for methodological details.

Corn

We expect technological improvements to continue to push Nebraska corn yields higher through 2050; however, our modeling suggests that climate will act as a burden on these increases (**Figure 11**). The size of this burden varies from county to county, ranging anywhere from 0-7% of historical yields. In a few Western Nebraska counties, climate change may act as a boost by extending the growing season. Overall, climate change will drag Nebraska corn yields down while innovation pushes them up. If technological improvements do not continue at the same pace of the past 40 years, then climate factors may win out and yield increases could stagnate.

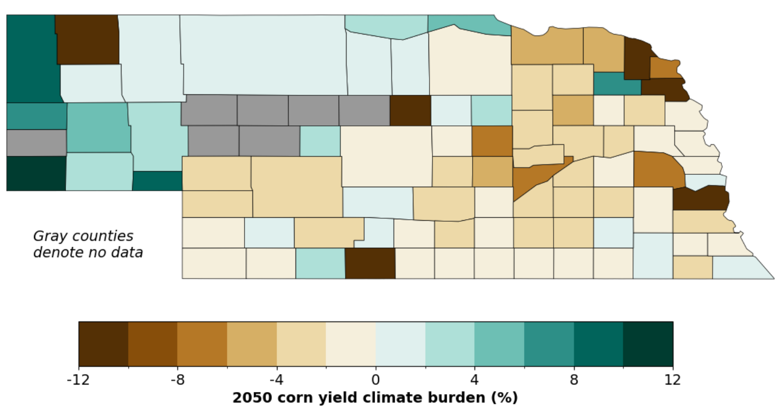

Figure 11. Map of aggregated corn yield climate burden at 2050, shown as a fraction of recent yields.

Stagnating yields could impact income and profits throughout the agricultural value chain. Reduced profitability may deter both public and private investment in agricultural research and infrastructure. Corn is a primary feedstock for livestock. Stagnating yields could also increase feed prices, affecting the meat and dairy industries. On the other hand, climate burdens on corn yields could also catalyze a push to diversify into other more resilient crops requiring new skills and technologies. It may also create room for other climate adaptation strategies, like agrivoltaics, which combine agriculture and solar photovoltaics (PV).

The varying climate burdens on Nebraska corn yields are shown for two counties in **Figure 12** (Lincoln) and **Figure 13** (Pawnee). In Lincoln County, located in West-Central Nebraska, irrigated corn shows little to no burden as the future projection follows the historical trend line. The effects of heat may be buffered by water availability there. Conversely, rainfed corn yields show a 10-15 bushel climate burden by 2050, evidenced by the ensemble-average line falling below the historical trend line (right panel). Despite the ensemble range showing some bumper crop years, it also shows some meager years with low yields. Overall, rainfed corn yields stagnate in Lincoln County, lending some credence to the caution in the previous paragraph.

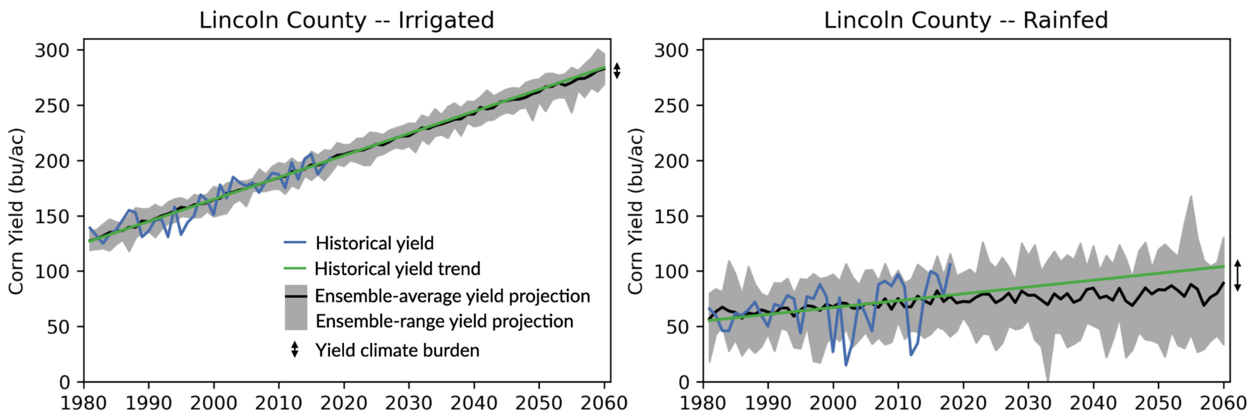

Figure 12. Corn yield projections for Lincoln County Nebraska. (left) irrigated. (right) rainfed. Historical yields shown in blue. Historical yield trend shown in green. Modeled yields shown in black (average) and gray (range).

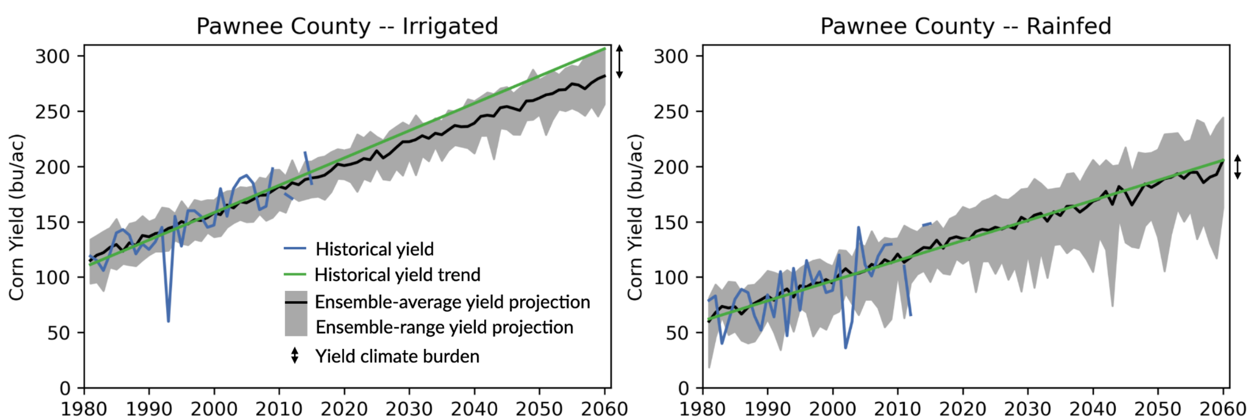

Figure 13. Corn yield projections for Lincoln County Nebraska. Display same as Figure 12.

Pawnee County in Southeastern Nebraska also exhibits climate burdens in our projections. In that case, yields rise for both irrigated and rainfed production systems. Unlike Lincoln County, a climate burden appears in projections for both irrigated and rainfed practices in Pawnee County. The burden for rainfed yields is more slight than for irrigated yields. This highlights how attention to production practices and geography is important for future land use planning. Irrigation is not a silver bullet for climate change adaptation in agriculture. There are limits on surface water and groundwater available for agriculture, and climate burdens do appear in irrigated crop yield projections (e.g. Pawnee County).

Soybeans

We also projected Nebraska soybean yields by mid-century. Like corn, we anticipate continued increases in soybean yields as new technologies and practices are adopted by growers. Our projections show a climate burden averaged across the state. Compared to corn, the climate burdens on yield are slightly less both at the county and state level.

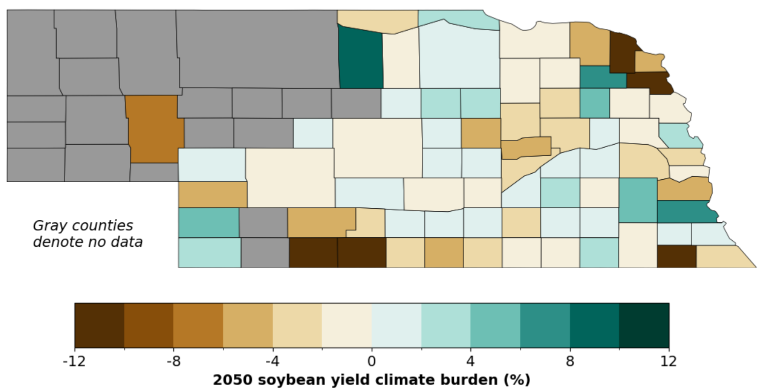

Figure 14. Map of soybean aggregated yield climate burden at 2050, shown as a fraction of recent yield.

When mapped, it is clear that most of the state will see a climate burden, however there are some counties with a slight boost (**Figure 14**). There is not a systematic pattern to the counties with a small boost, and additional analysis is warranted to better understand those county-level nuances. Given the uniform increases in temperature and consistent temperature-yield relationships, the pattern is potentially caused by differing sensitivity to rainfall changes.

Notwithstanding these details, the overall pattern of soybean yield changes by 2050 is an increase due to technological improvements tempered by climate burdens associated with increased extreme heat, changing precipitation patterns, and greater evapotranspiration.

Nebraska Renewable Energy in 2050

Projected changes in Renewable Energy Costs for Nebraska

Solar Photovoltaic Energy: Levelized Cost of Energy

The levelized cost of energy (LCOE) for utility-scale solar photovoltaic (PV) energy is already competitive with fossil fuels in Nebraska. Our estimates for solar PV LCOE in 2020 range from \$38/MWh to \$44/MWh (**Figure 15**). The cost for coal fired power for existing power plants is

$52/MWh and for new power plants is $68/MWh or higher, according to Lazard.[8] By 2050 the LCOE becomes even more competitive, ranging from $30/MWh to $36/MWh. The western portion of the state presents the greatest decrease.

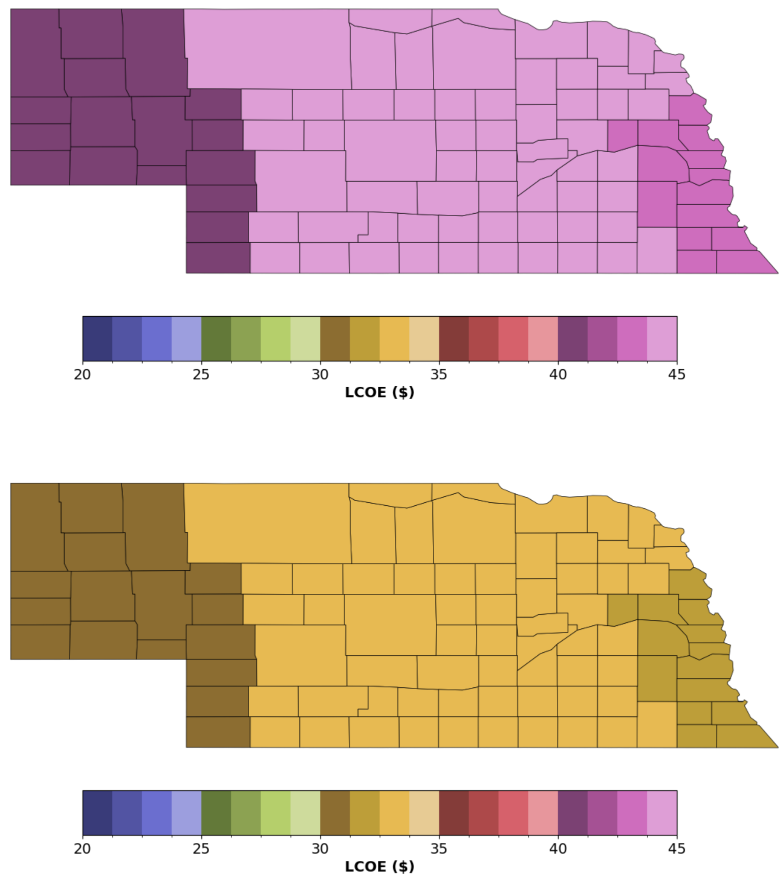

Figure 15. (*upper*) Solar PV energy LCOE in 2020 and (*lower*) solar PV energy LCOE in 2050 ($/MWh).

Wind Energy: Levelized Cost of Energy

The levelized cost of energy for utility-scale wind energy is already competitive with fossil fuels in Nebraska. Our estimates for solar PV LCOE in 2020 range from $28/MWh to $32/MWh (**Figure 16**). Cost for coal fired power for existing power plants is $52/MWh and for new power plants is $68/Mwh or higher, according to Lazard.[9] By 2050 the LCOE becomes even more competitive ranging from $21/MWh to $26/MWh. The western and southern parts of the state present the greatest decrease.

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[8] Lazard 2021 LCOE+ Database

[9] Lazard 2021 LCOE+ Database

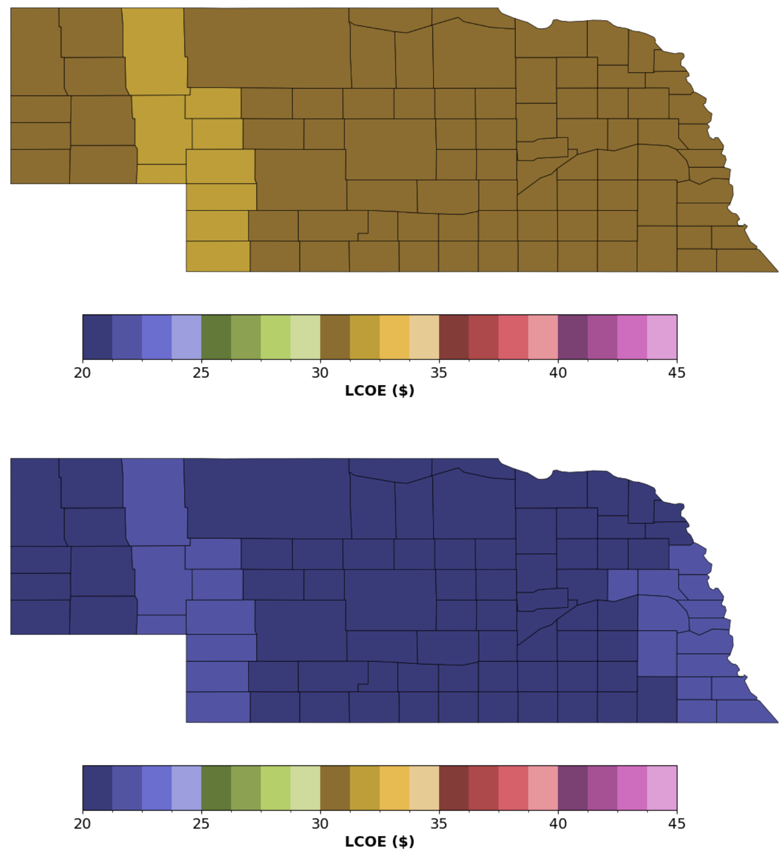

Figure 16. (*upper*) Wind energy LCOE in 2020 and (*lower*) wind energy LCOE in 2050 ($/MWh).

Solar PV and Wind Energy: Low-Impact Capacity

Although LCOE may be the same in two counties, the available low-impact capacity may be very different due to differences in size and presence or absence of critical habitats. Although higher cost than wind, solar has a significantly higher available capacity without affecting critical ecosystems. There is significant variation in available capacity by county but plenty of low-impact capacity available: 66 GW for wind power and 797 GW for solar PV (**Figure 17**). The current electric power capacity for Nebraska is 11 GW.

Agrivoltaics Analysis

On-farm use of solar PV energy, especially agrivoltaic designs, present a unique technology for agriculture and renewable energy to co-exist. We analyzed the impact of installing an agrivoltaics system on a hypothetical 1,000 acre farm in Phelps county with a corn/soybean rotation. Phelps county has good solar resources with projected 2050 LCOE at $33/MWh but relatively low potential capacity at 140 MW due to its small size. Therefore the case for finding additional land for solar installation hinges on an agrivoltaics business case. One major challenge lies in the demand for irrigation on cropland. Phelps county has a high percentage of irrigated acres, 92% for corn. We analyzed the impact of meeting the energy needs for irrigation with agrivoltaic systems rather than the incumbent diesel.

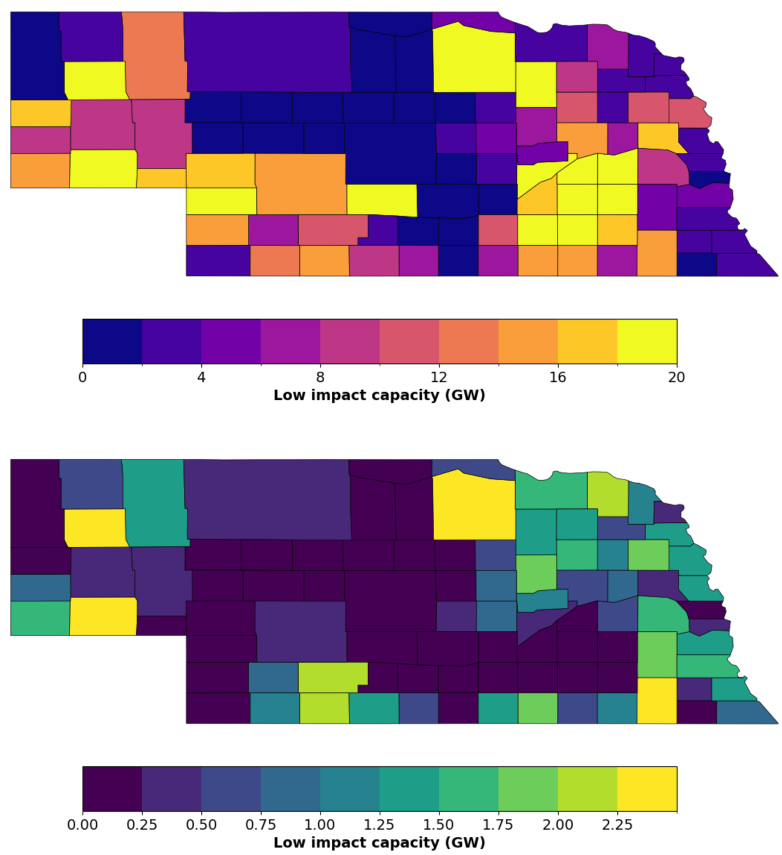

Figure 17. (*upper*) Solar PV energy and (*lower*) wind energy low-impact capacity by county (GW).

According to our analysis, a 164 kW tracker stilt mounted agrivoltaic system will generate sufficient electricity to meet the irrigation energy needs for this hypothetical 1000 acre farm. In 2020, the diesel costs to serve the irrigation needs are $18,231 and using an agrivoltaics design to meet irrigation needs costs $11,867. By mid-century the economic incentives to switch from diesel to agrivoltaics is even larger. Changes in the crop-water index due to climate change and moderately rising Diesel prices (2.5% between 2023 and 2050) leads to irrigation fuel costs of $47,736 for the same farm in 2050; falling Solar costs keep the increase very small to $13,203 leading to cost savings of $35,000, improving net-income by 3.5%. In order to meet the irrigation needs only 2.2 acres are needed for the agrivoltaics system. By increasing the land under agrivoltaics to just 15 acres on this 1,000 acre farm, farmers can save an additional $25,000 in equipment fuel and generate $38,000 in additional electricity sales income for farmers per year.

Conclusions

Nebraska stands as a testament to innovation and commitment to public interests. Armed with information about the projected temperatures of the future, Nebraska is poised to navigate the challenges posed by a warming climate. Furthermore, the overwhelming support for renewable energy across party lines showcases the state's readiness to embrace a sustainable future. However, agriculture remains a cornerstone of Nebraska's economy and cultural identity. As we look forward, it is crucial to consider how the projected changes in crop agriculture and renewable energy production will alter the state's landscape by 2050.

Temperatures will increase throughout Nebraska by 2050. The already-hot southern counties will witness the largest increase in extreme heat. Across the entire state stress from extreme heat nearly doubles by the middle of the century and the already-hot southern counties will experience the largest increase. Hotter temperatures will demand more water from the crops, in turn increasing crop water needs thus driving the need for increased irrigation. The largest increase in crop water needs happens in central Nebraska, where an extra 80 millimeters (3+ inches) would ideally be needed for corn. Increased irrigation will create additional pressures on underground sources of water such as the Ogallala aquifer.

Although absolute yields will rise thanks to technology improvements, there will be a significant climate burden on yields due to rising extreme heat and water needs. Climate burden on yield will be higher for rainfed crops compared to irrigated crops, for example, rainfed corn in Lincoln county is projected to experience a 16%, or 14 bushels/acre, climate burden on yield.

As conditions get more challenging for growing corn, solar PV and wind power become more attractive due to the decreasing levelized cost of energy. Solar and wind costs are already competitive with coal power at $60/MWh. Further decreases bring the cost of Solar down to $30-$36/MWh and Wind to $21-$26/MWh by 2050 and will present even greater cost savings. Western and southern regions of the state present the greatest decrease. There is plenty of low-impact capacity available in Nebraska for both solar and wind; an order of magnitude higher than current installed capacity for power generation.

Agrivoltaics present an opportunity to significantly cut irrigation and equipment fuel costs as well as generate additional income for farmers while using a very small fraction of their land. Therefore, farmers should view agrivoltaics and conventional solar as an opportunity to cut irrigation and equipment fuel costs and improve their profitability. Officials in counties with reduced water availability and stagnating yields should consider solar and wind leasing on marginal farmland to protect their tax base. The Nebraska Public Service Commission should use this analysis to prioritize utility scale renewable projects in counties with high climate burden on yields and/or water needs.

This report has harnessed the best of climate science, agronomy, and energy modeling to predict these changes, and the findings will be instrumental in guiding land use decisions for a resilient and prosperous Nebraska.

Appendix A: 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 US from 1979 through present day.[10] 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.[11] 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.'[12] 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 area. 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

[10] Abatzoglou JT 2013 Development of gridded surface meteorological data for ecological applications and modelling *Int. J. Climatol.* **33** 121–131 https://doi.org/10.1002/joc.3413
[11] Abatzoglou JT, and Brown TJ 2012 A comparison of statistical downscaling methods suited for wildfire applications *Int. J. Climatol.* **32** 772–780 https://doi.org/10.1002/joc.2312
[12] Hausfather Z 2019 The high-emissions 'RCP8.5' global warming scenario *Carbon Brief* *https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario/*

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 is 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.[13] For each 30 meter grid cell in the state, we determined crop frequency 2013 to 2022. Then we computed the fraction of each 4 kilometer climate data grid cell with any crop cultivation 2013 to 2022 (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 with the gridded climate data and gridded crop area weights.

Climate Variables

gridMET and MACA provide daily 4 km 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.

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 IPCC definition for studying medium-term climate change.[14]

Crop water index calculation

We use the FAO's standardized crop evapotranspiration formula, based on the Penman-Monteith equation.[15] The Penman-Monteith equation provides an estimate of potential evapotranspiration, 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 multiply 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[16]. For summer crops we use the USDA crop coefficient database.[17]

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[13] USDA 2023 CropScape https://nassgeodata.gmu.edu/CropScape/
[14] IPCC 2021 Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis.* [Masson-Delmotte, V et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32
[15] FAO accessed Nov. 2022 Penman-Monteith equation https://www.fao.org/3/x0490e/x0490e06.htm
[16] Kansas State Extension, accessed Nov. 2022 Evapotranspiration https://mesonet.k-state.edu/about/evapotranspiration/
[17] Martin and Gilley 1993 Irrigation Water Requirements *USDA* https://www.wcc.nrcs.usda.gov/ftpref/wntsc/waterMgt/irrigation/NEH15/ch2.pdf

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 USDA data.[18]

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.

[18] National Agricultural Statistics Service 2010 Usual Planting and Harvesting Dates for U.S. Field Crops *USDA* https://usda.library.cornell.edu/concern/publications/vm40xr56k

Appendix B: Agronomic Modeling

Overview

Crop yields were disaggregated by irrigated and rainfed systems and modeled separately. 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 climate burdens reported in the main text represent aggregated statistics. We computed these assuming the same ratio of irrigated to rainfed acres for the year 2050. In other words, we created aggregated 2050 yield projections as a weighted average of irrigated and rainfed yield projections. 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 using the methods above.

Statistical Modeling

Two Degrees Adapt previously 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).[19] This study continued this model framework, albeit with a more consistent model specification across crop systems. Specifically we modeled yield (Y) following the methods of Rising and Devineni[20], 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); FDD 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. 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 county by county. 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;[21] and the coefficient for crop water index varied from negative in the east where the

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[19] EDF 2022 How Climate Change Will Impact U.S. Corn, Soybean and Wheat Yields: A county-level analysis of climate burdens and adaptation needs in the Midwest.
[20] Rising J, and Devineni N 2020 *Nature Comm.* **11** 1
[21] Butler E, and Huybers P 2013 Adaptation of US maize to temperature variations. *Nature Clim Change* **3**, 68–72 https://doi.org/10.1038/nclimate1585

index is near zero on average to positive in the west where the index is negative (a deficit of water).[22]

The model proved to be effective, explaining a majority of the variability in corn and soybean yields for irrigated and rainfed systems. Averaged across 93 counties, the model explained 64% of the variance of rainfed corn yields and 79% of the variance of irrigated corn yields. Results were similar for soybeans.

Future Climate Impacts on Yield

As described in the text, the historical coefficients were re-applied to localized data from 20 downscaled climate model simulations under the historical forcing 1981-2005 and RCP4.5 future scenario 2006-2060.

The resulting future 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 input the ensemble mean yield projection to the associated StoryMap 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. 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 Nebraska climate represented in the model.

[22] Nix HA, and Fitzpatrick EA 1969 An index of crop water stress related to wheat and grain sorghum yields, *Agricultural Meteorology*, **6**, 321-337

Appendix C: Renewable Energy Analysis

Levelized Cost of Energy

Levelized cost of energy (LCOE) is a metric used to compare costs of different sources of electricity generation as well as different geographic locations for the same source of electricity. Renewable energy sources present a significant geographic variation given the difference in availability of water, geothermal activity, sunlight, and high-speed wind. LCOE represents the cost of electricity generation per unit of energy e.g. kilowatt-hours. LCOE is computed by using the capital expenditure for a solar or wind farm and capacity factor. Capacity factor is expressed as a % of energy generated with 100% meaning a source generating electricity 24x7. For context, Nuclear power plants that shut down only for refueling and repairs once every two years have capacity factors of 90% to 95%. To calculate capacity factors for solar photovoltaic, county averages of solar insolation (W/m^2) and the number of sunshine hours were estimated using data from National Renewable Energy Laboratory's Renewable Energy Atlas.[23] To calculate the capacity factors for wind, wind speeds across the year were estimated using the same resource. Capital costs for solar PV and wind energy for 2020 and 2050 timeframes were sourced from the annual technology baseline (ATB) modeled by the Department of Energy. [24] There are two scenarios in ATB for solar and wind: low-carbon case represents an aggressive cost reduction assuming large scale deployments resulting in steep learning curves and economies of scale. Reference case assumes future cost reductions to be in line with cost reductions in the past decade.

Low-Impact Capacity

Large scale renewable energy projects require more land than conventional power plants with Solar Energy requiring 10 acres per MW of capacity and WInd Energy as much as 85 acres per MW. Therefore, these projects often come in conflict with other land use priorities such as conservation. The Nature Conservancy has done a comprehensive review of critical ecosystems, species and their habitat and created two resources for identifying land for renewable energy projects that protect these critical ecosystems: Site Renewables Right and Power of Place. The methodology for this assessment is published in a peer-reviewed journal.[25] Two Degrees Adapt used the estimates for solar and wind energy capacity derived from this tool on a county-by-county basis.

Agrivoltaics Analysis

We analyzed the impact of installing an agrivoltaics system on a hypothetical 1,000 acre farm in Phelps county with corn/soybean rotation. According to USDA, the average size for a farm in

[23] National Renewable Energy, Renewable Energy Atlas, Innovative Data Energy Applications (nrel.gov)
[24] U.S. Department of Energy, Annual Technology Baseline 2021
[25] Hise C, et al 2022 *Land* 11, 462 https://doi.org/10.3390/land11040462

Phelps county is 921 acres with corn and soybeans dominate the acreage. Hence this choice of hypothetical size and crops is fairly representative. Custom production cost and revenue for irrigated Center Pivot Corn/Soybean derived from Ag Budget Calculator from Univ of Nebraska. We did forward looking inflation adjustments to 2050 for both production costs and revenue at 2.5% per year.

There are several agrivoltaics design choices available including tracker stilt mount, reinforced regular mount, vertical mount. THese designs differ in the height of solar panels, the distance between the panels, ground coverage, and therefore the number of panels needed to achieve a certain capacity. Depending on these design parameters, these systems are used for different purposes such as growing row crops, livestock grazing, and creating pollinator friendly habitats. We used a tracker stilt mount design since it's suitable for row crops.

Tracker stilt mount design agrivoltaics system has 26% higher capex $2.09/Wp vs $1.66/Wp for standard PV mainly due to higher area per capacity (5.9 acre/MW vs 13.8 acre/MW)[26] We estimate that for Phelps county this results in a 38% higher LCOE for this agrivoltaics design compared to standard PV systems translating to $61/Mwh in 2020 and $46/Mwh in 2050.

To serve the irrigation needs of a 1,000 acre Corn/Soybean rotation farm in Phelps county in 2050, 9625 acre-inches of water based on crop-water index in 2020. This translates to 5120 gallons of Diesel and $18,943 in fuel costs according to our analysis. Using standard Department of Energy conversion from Diesel to electricity, this translates to 287,021 kWh. At a conservative 20% capacity factor, this translates to a 164 kW solar PV system. For the tracker stilt mount design with ground coverage of 20%, module density is about 13.8 acres/MW, translating into 2.2 acres for this capacity. At 2.2 acres out of 1,000 acres, yield losses are not significant enough to impact net income.

[26] Horowitz K, et al 2020 Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops *NREL Technical Report* nrel.gov/docs/fy21osti/77811.pdf

Appendix D: Interviews

It is important to understand the context in which land use decisions are made. Narratives among stakeholders are important towards developing an understanding of the decision landscape. Therefore we conducted four interviews to complement the quantitative analysis in the preceding sections. The conversation with the Center for Rural Affairs made us aware of the local nature of renewable ordinances in Nebraska. Conversations with farmers who have experience with solar and wind leasing decisions brought into focus the influence of other farmers as well as family in these decisions. The conversation with the U.S. Department of Agriculture centered around the newly launched Rural Energy for America (REAP) program that may provide funding for on-farm Solar energy applications identified in this report.

List of Interviewees

1. Lindsay Mouw, Center for Rural Affairs
2. Jonathan Burns, U.S. Department of Agriculture, Rural Energy for America Program (REAP)
3. Dan Griffiths, Farmer, Lancaster County
4. Larry Engelkemier, Farmer, Cass County