Climate Change Impacts on Wisconsin Agriculture

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Methods and Supplementary Materials

Please visit www.climatehubs.usda.gov/hubs/midwest/assessing-impacts-climate-change-midwest-agriculture for the methods and supplementary materials associated with this report.

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Agriculture is a critically important aspect of economic and social life across much of Wisconsin. Thirty percent of Wisconsin's land is used for agricultural production. In 2021, Wisconsin's agricultural industry represented $104.8 billion—or 16.4%—of the state's economy and employed 11.8% of the state's workforce. The market value of agricultural products sold totaled more than $11 billion in 2017.[1] Agricultural production in the state is diverse, with key crops including silage and corn grain, soybeans, alfalfa and hay, vegetables, and cranberries. Livestock production is focused on dairy, beef, hogs, poultry, and eggs.[2] The most significant vegetable crops include potatoes, snap beans, cabbage, peas, sweet corn, and carrots.[3] In 2021, Wisconsin ranked first nationally in production of cheese, corn for silage, cranberries, snap beans, and in the top three for milk, oats, potatoes, and green peas. Internationally, Wisconsin ranks first in high-quality ginseng, an understory forest farming product highly valued for its medicinal purposes across Asia. In 2022, Wisconsin exported $4.22 billion of agricultural and food products to 142 countries, and ranks first in the export of specialty cheeses, ginseng roots, prepared and preserved cranberries, mink, bovine semen, prepared and preserved sweet corn, and sausages. Wisconsin's expansive and diverse agricultural productivity means the state is particularly vulnerable to weather and climate variability brought on through a changing climate.

In recent decades, Wisconsin's climate has been changing in a myriad of ways (Table 1), a trend which is projected to continue and intensify.[4] These changes are resulting in significant impacts on the state's agricultural sector.[5]

Observed Changes to Wisconsin's Climate (1979-2021)

Temperature

- Average annual temperatures have increased by 1.6°F between 1979 and 2021.
- Nighttime lows have risen more than daytime highs.
- Autumns and springs have warmed the most compared to their long-term averages, resulting in more than an additional week of the growing season.[4]

Precipitation

- Average annual precipitation has risen significantly (by 4.9 inches), with the greatest increases observed during the spring and winter months.[4]
- Extreme precipitation events (greater than 2 inches in one day) have become more frequent over time.[4]

"Wisconsin's expansive and diverse agricultural productivity means the state is particularly vulnerable to weather and climate variability brought on through a changing climate."

Table 1. Observed changes in Wisconsin's climate based on data from 1979 – 2021.

	Annual (Jan – Dec)		Summer (Jun – Aug)		Fall (Sep – Nov)		Winter (Dec – Feb)		Spring (Mar – May)	
	Average	**Change**	**Average**	**Change**	**Average**	**Change**	**Average**	**Change**	**Average**	**Change**
Temperature	44.0 °F	+1.6 °F	67.6 °F	+1.4 °F	46.3 °F	+2.6 °F	18.2 °F	+1.2 °F	43.7 °F	0.0 °F
Precipitation	33.9"	+4.9"	12.7"	+1.5"	8.7"	-0.8"	3.7"	+1.6"	8.7"	+2.6"
Vapor Pressure Deficit*	4.8 mb	+0.2 mb	8.4 mb	+0.9 mb	4.2 mb	0.0 mb	1.2 mb	0.0 mb	5.3 mb	-0.5 mb
Extreme precipitation (days with 2")	0.5 days	+1.1 days								
Growing Season Length (frost-free days)	148 days	+8.3 days								

*Vapor pressure deficit (VPD) is an important variable for plant physiology. A higher VPD means that plants will lose more water to the air and dry out more rapidly. See page 9 for more information on how VPD relates to changes in relative humidity.

Impacts on Agriculture

- Increased frequency of heat stress on livestock and crops.
- Decreased dairy herd milk production during extreme heat events.[6]
- Rapid shifts between warm and cold periods in the spring that can damage fruit crops and degrade soil health through freeze/thaw cycles (e.g., pore structure, aggregate stability, etc.).[7,8]
- Less reliable winter snow and ice cover causing winter kill of alfalfa and damage to winter cereals (e.g. wheat) and cranberry crops.
- Increased susceptibility to insect pests and pathogens causing increased crop losses, as well as increased pesticide use and reduced pesticide effectiveness.
- Increased weed pressure from natural regeneration of exposed soils following rain events causing increased herbicide use.
- A need to develop and plant crop varieties adapted to longer growing seasons, increased temperatures, and erratic precipitation access.
- Extended the fall planting date and increased the growing season for cover crops.
- Potential to use longer-season crop varieties that have higher input needs.
- Increased risk of drought causing decreased germination and crop loss, especially during fruiting periods.[9]
- Increased use of groundwater sources for irrigation during extreme heat or drought events.
- Increased crop loss due to excessive precipitation, especially during seed germination periods.[10,11]
- Increased frequency of waterlogged soils resulting in delayed or missed planting and harvesting, delayed or missed manure and fertilizer applications, a need for adjustments to nutrient management to account for changes in nutrient cycling in wet soils, and potential for soil compaction and reduced time for animals on pasture.
- Increased frequency of extreme rainfall events which intensifies potential for soil erosion and gully formation; nutrient, sediment, and pathogen runoff to surface waters; and challenges for manure management.

Climate Outlook

Models of future climate indicate that temperatures are projected to warm, precipitation is expected to become more variable and extreme, and the growing season is anticipated to continue to lengthen. The climate projections in this section are based on the average of 17 different climate models.[12] Two possible futures are presented: a moderate emissions scenario in which greenhouse gas emissions peak around mid-century and then slowly decline, and a higher emissions scenario in which emissions continue to rise throughout the 21st century.[13] Careful planning and adaptive action can lower the risks of climate change impacts for producers. There are many ways to adapt to climate change based on the situation and needs of a particular farm, and some examples are presented below.

Image: Soybeans planted into no-tilled corn residue. Source: USDA

Temperature

Wisconsin can expect to see fewer extremely cold nights and more extremely hot days (Table 2). By mid-century (2040-2059) under a higher emissions scenario, **the annual average temperature in Wisconsin is projected to increase by 5.9°F compared to the 1979-2005 baseline.**[12] By late-century (2080-2099), annual temperature increases may exceed 11°F (Figure 1). These scenarios are compared to average observed thresholds during the 1979 – 2005 period.

Table 2. Predicted changes and ranges to days meeting temperature thresholds for Wisconsin compared to the 1979 – 2005 period.

		Temp Lows ≤ 32°F	Temp Lows ≥ 80°F	Temp Highs ≥ 86°F	Temp Highs ≥ 95°F
Mid-Century	**Lower Emissions**	-31.3 days *(-53.7 to -17.4)*	+0.2 days *(+0.01 to +0.3)*	+64.7 days *(+48.1 to +75.7)*	+4.3 days *(+1.0 to +7.1)*
	Higher Emissions	-37.2 days *(-66.5 to -18.2)*	+0.4 days *(+0.03 to +0.9)*	+73.4 days *(+55.9 to +84.2)*	+7.1 days *(+2.1 to +11.4)*
Late Century	**Lower Emissions**	-42.4 days *(-70.3 to -23.0)*	+0.7 days *(+0.01 to +2.9)*	+75.3 days *(+52.1 to +95.7)*	+8.8 days *(+1.6 to +21.4)*
	Higher Emissions	-70.0 days *(-103.0 to -42.5)*	+6.4 days *(+0.4 to +20.9)*	+103.9 days *(+76.6 to +123.9)*	+30.8 days *(+8.1 to +63.0)*

What Does This Mean for Wisconsin Agriculture?

- Increased heat stress severely impacts farmers, farm workers, and animals. Among livestock, high heat can decrease meat and milk quality and quantity, and egg production causing increased water use for animal cooling efforts.[9,14,15,16]
- The frequency of short-term and rapid onset drought during the summer is projected to be higher due to warmer temperatures and increased precipitation variability.[17] Decreased soil moisture affects plant physiology, potentially leading to an increased risk of reduced yields or crop losses, but uncertainty remains.[9,16]
- Increased soil temperatures affect the appropriate timing and efficacy of fertilizer application. With soils remaining above 50°F later into the fall, fields are more prone to nitrogen loss to the atmosphere, leaching to groundwater, and runoff losses to surface water following nitrogen applications.[18]
- Elevated overnight temperatures accelerate phenological development of crops which would negatively impact yields.[16]
- Increased extreme heat events will amplify agricultural drought frequency and duration.
- Increased risk of agricultural drought and heat stress will increase groundwater withdrawals for irrigation and/or animal cooling during extreme heat or drought events. Increased irrigation demand could negatively impact the state's recreation sector and other non-ag water uses.

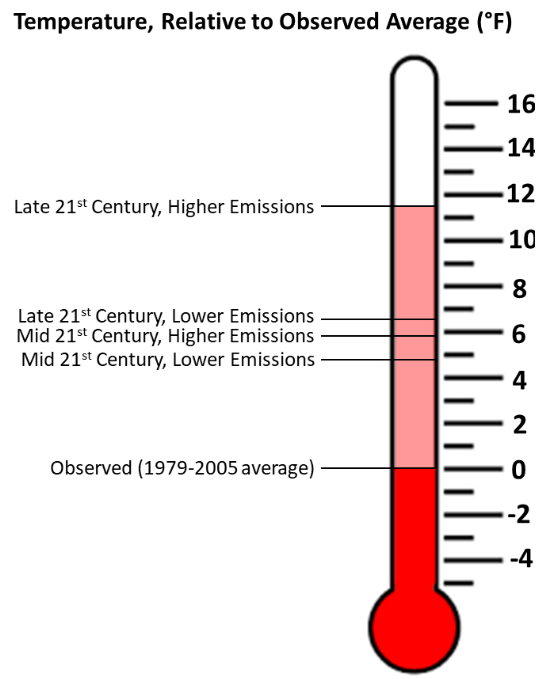


Figure 1. Projected temperature change by scenario, compared to 1979-2005 observed average.

- Erratic and unreliable recharge of groundwater supplies resulting from less snow and higher frequency of sporadic, extreme rain events.
- Higher success rates of cover crop stand development due to longer growing seasons and warmer fall temperatures.
- Crop pests may experience favorable overwintering conditions, causing new pests and diseases to move into the region and become more prevalent, leading to lower yields and increased use of pesticides and herbicides.

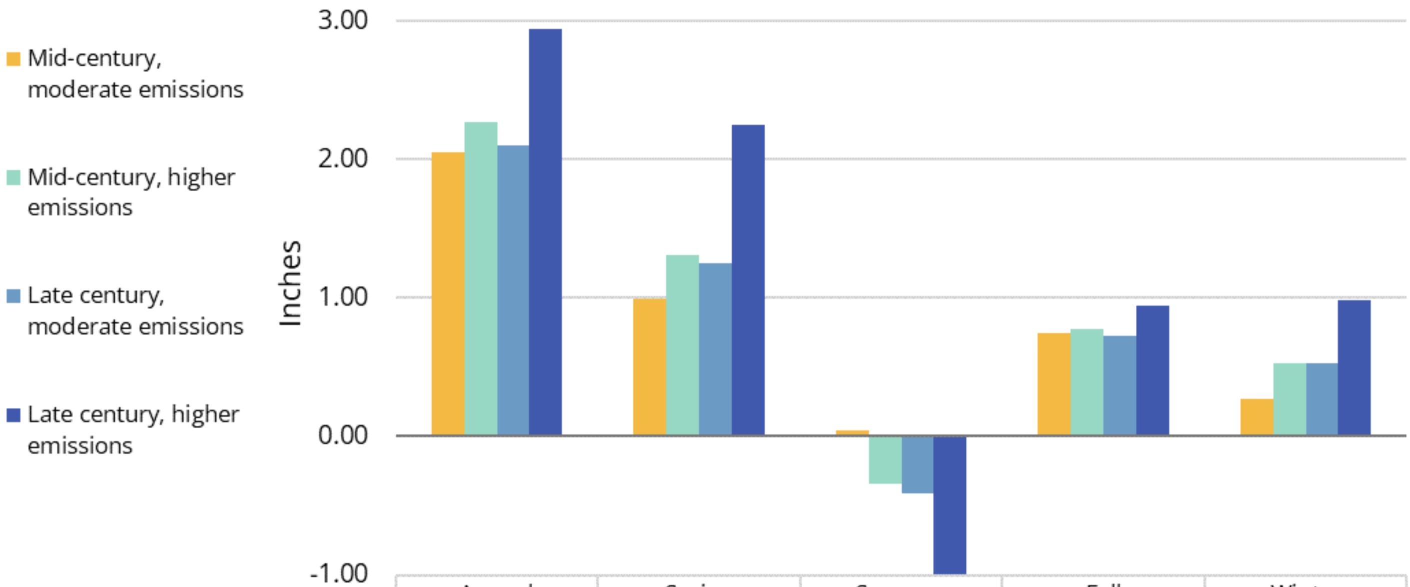
- By 2055, rainfed corn yields in central Wisconsin are projected to decline by 23-34% due to decreased water availability in the summer.[19]

Adaptation Options

- Choose crop species or varieties that are more suited to future conditions (tolerant of heat and water stress), and/or have higher Plant Hardiness Zone ratings. Invest in research and variety development to ensure that there are crops and varieties adapted to future climate conditions in Wisconsin.
- Integrate alternative crop species via conservation crop rotations to maintain or improve soil health.[20]
- Utilize cover crops or reduce tillage to bolster soil health and increase the soil's water-holding capacity.
- Consider on-farm water storage systems to carry water over from excess to deficit moisture conditions.
- Split applications of fertilizer to align with crop need.
- Adjust planting dates to avoid reproductive stages overlapping with high drought risk periods.[20]
- Explore opportunities for perennialization of fields with high-yielding plant species well adapted to both current and future conditions, such as high-value tree crops like hazelnuts, aronia berry, elderberry, Northern Pecans, and perennial grains such as perennial wheatgrass varieties.
- Explore options related to agroforestry practices, such as installing windbreaks and hedgerows with tree crops, alley cropping, intercropping, and silvopasture systems, which provide shade, can access groundwater supplies through deeper root systems, and can buffer crops and livestock from increasing heat.[21]

Precipitation

Annual precipitation is expected to increase, with the largest seasonal increases likely during spring. Decreases in total precipitation and greater variability (based on range of modeled projections) are projected during the summer. These changes are stronger under the higher emissions scenario and for the late 21st century (2080-2099) (Figure 2).



	Annual	Spring	Summer	Fall	Winter
Mid-century, moderate emissions	2.05	0.99	0.04	0.75	0.27
Mid-century, higher emissions	2.27	1.31	-0.34	0.78	0.53
Late century, moderate emissions	2.10	1.25	-0.41	0.73	0.53
Late century, higher emissions	2.94	2.25	-1.23	0.94	0.98

Figure 2. Projected precipitation changes for Wisconsin, annually and seasonally, in inches, compared to the 1979-2005 period average.

What Does This Mean for Wisconsin Agriculture?

- Increased likelihood of leaching and/or runoff of nitrogen and phosphorus from fertilizer and manure applied during spring and fall.
- Winter and spring precipitation increases will prolong field wetness causing further loss of field workdays and impaired root growth and function.[2]
- Wetter pastures, paddocks, and feedlots increase susceptibility to animal foot diseases. Muddy conditions increase the chances of reduced gestational weight in heifers, and therefore increases the need to adjust animal nutrition regimens.[22,23]
- Increased use of groundwater irrigation in summer months to combat drought conditions, especially in course soils, resulting in conflict with recreation due to reduced groundwater recharge of streams and lakes.
- Shorter windows for manure application in the spring and fall will increase the risk of failure to apply and of manure runoff events and water quality impacts.

Adaptation Options

- Diversify crops and crop varieties to plant early-, mid-, and late-season to hedge risks of potential crop failure.
- Diversify crop rotations to hedge against impacts to monocultural crop systems.
- Consider planting earlier in the season, which may be possible due to small increases in field workability days in early spring (late March to early April) and earlier last frost dates.[20]
- Take areas prone to flooding out of crop production. Plant to permanent cover. Increase the conservation benefits by using the areas as filter strips, riparian buffers, and for pollinators and wildlife.[24]
- Utilize conservation crop rotations, cover crops, tillage reduction, and greater use of perennial forage and/or grasslands to improve soil structure, organic matter content, promote water infiltration, increase water-holding capacity, maintain plant-available water during periods of dryness, and otherwise reduce the risk of climate change related impacts and improve productivity.[16]
- Explore opportunities for perennialization of fields using high-yielding species with deep root systems better able to hold soil in place, filter runoff, and uptake excess water, such as high-value tree crops such as hazelnuts, aronia berry, elderberry, Cornellian or Nanking Cherries, and perennial grains such as perennial wheatgrass varieties or Abruzzi rye, which is predicted to perennialize under projected climate changes.
- Explore agroforestry practice options such as installing windbreaks and hedgerows with water-loving trees (such as Aspen, Hackberry, or Swamp Oak) or value-added tree crops (such as elderberry, serviceberry, Cornellian cherries, pawpaw, and chestnuts), alley cropping, intercropping, and silvopasture systems to reduce impact of intense rainfall on soil and filter runoff.

Image: Grasslands under the Conservation Reserve Program. Source: USDA.

Precipitation Intensity

Wisconsin is already experiencing increases in extreme precipitation events (with precipitation greater than 2 inches); these events are likely to be even more frequent in the future.[4]

What Does This Mean for Wisconsin Agriculture?

- The increased frequency of extreme precipitation results in increased soil erosion and nutrient loss from fields, contributing to nonpoint source pollution.

Adaptation Options

- Adjust dates of planting, tillage, and harvest.[9]
- Manage and improve soil health and increase water infiltration by minimizing tillage, managing crop residue, planting cover crops, selecting soil-stabilizing crops, and managing the intensity of grazing.[9]
- Minimize soil erosion by installing grassed waterways and prairie strips, by practicing contour farming, and by switching to perennial crops especially on steeply sloped fields.
- Invest in research on perennial crops, including best management practices, market opportunities and variety development to ensure that perennial crops are viable options for farmers.
- Incorporate trees through alley cropping systems or other agroforestry practices to reduce the rate of soil erosion in crop fields. Living roots in well-managed perennial systems help hold soils in place when heavy rains occur.[21,25]

Growing Season Length

Growing season trends across Wisconsin since 1950 are variable across the state (Figure 3). While many counties have seen an increase of a few days per decade, counties in the central portion of Wisconsin have seen decreasing days over the last six decades. By mid-century however, under a higher emissions scenario, the growing season is expected to increase by an average of 35 days. This is a result of later first frosts in the fall and an earlier onset of frost-free conditions in spring.

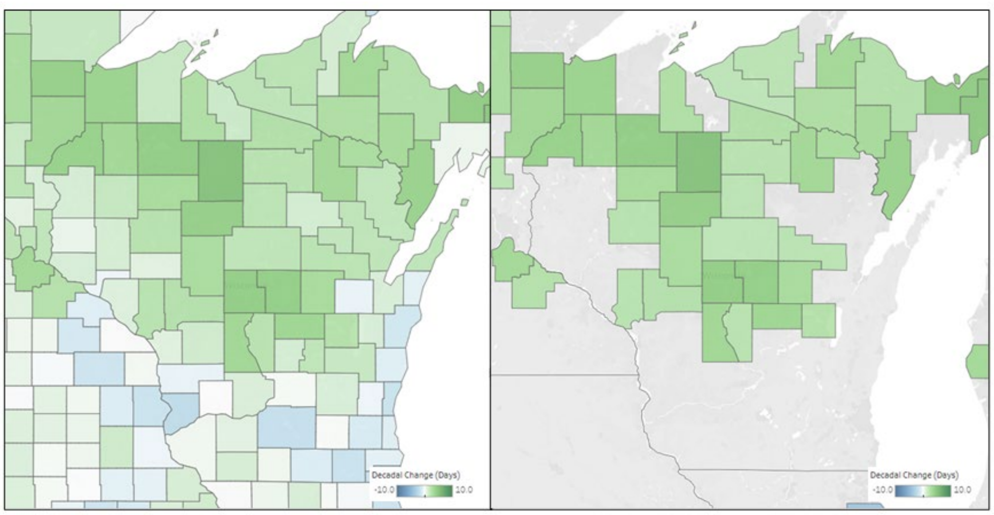


Figure 3. Historical changes in average annual growing season length for Wisconsin counties, 1950-2021 based on gridded ACIS dataset. The right-hand image displays only those counties with a statistically significant trend ($p < 0.05$). Image source: Freeze Date Tool, Midwestern Regional Climate Center, mrcc.purdue.edu/freeze/freezedatetool.html.

What Does this Mean to Agriculture?

- Pests, diseases, and weeds may expand their ranges. Additionally, the number of pest generations per season may increase causing greater negative impacts on crops and livestock.
- Increased need for chemical treatments to address these pest and disease impacts may lead to greater pesticide and herbicide resistance and water quality impacts from chemical use.
- Longer growing seasons may provide farm workers with additional time for fall harvest and other end-of-season crop

and field management activities.

- Cover crops may have better opportunity to germinate and grow after crop harvest and before fall freeze events.
- Warmer winters will accelerate timing of crop buds development and increase the risk of spring freeze injury.
- Warmer winter temperatures may mean that the chill hours needed for productive fruit crops are not met.[16]

Adaptation Options

- Plant earlier in the spring or consider options for double cropping.[24]
- Address pest, weed, and disease issues by diversifying crop rotations, enhancing use of Integrated Pest Management (IPM) techniques, and planting species and varieties that are resistant to pests and disease.[24]
- Consider planting fruit species and varieties which require fewer chilling hours, while keeping in mind the potential risk of trees and shrubs breaking dormancy during late-winter warm spells.
- Incorporate a diversity of species, such as in agroforestry systems, to spread biological and financial risk and create habitat diversity to promote beneficial insects and pollinators.[21]

Relative Humidity

Despite increased water vapor in the atmosphere and precipitation, uncertainty remains in whether current trends of relative humidity will continue. This uncertainty is due to relative humidity's dependence on air temperature and a lack of model consistency of historical trends in temperature. Models indicate that relative humidity is projected to decline annually and across all seasons, with the greatest decreases projected to occur during summer. However, if minimum (nighttime) temperature trends continue to outpace maximum (daytime), vapor pressure deficits will not increase, and relative humidity will stay higher.

What Does this Mean to Agriculture?

- If relative humidity decreases:
  - Plants will be more prone to wilting and stunted growth.
  - Certain animal respiratory viruses may have a longer survival duration.[26]
  - Tree mortality may increase, especially for younger trees.[25]
  - Low relative humidity has a negative impact on corn pollination due to silk desiccation and could impact both field and sweet corn production.
  - Low humidity favors the proliferation of certain arthropod pests such as spider mites in soybeans and vegetable crops.
- If relative humidity increases:
  - Wetness duration may increase leading to enhanced disease potential for crops.[27]
  - Plants will have limited ability to evaporate water (part of the transpiration process) or draw nutrients from the soil.[28]

Adaptation Options

- Plant crop varieties that can thrive in wet years and seasons but are also drought tolerant, if available (including crops, pasture grasses, and tree fruit).[24]
- Invest in research and breeding to develop adapted varieties for future climate conditions.
- Use of mulch, cover crops, no-till, or reduced tillage to retain soil moisture and reduce soil temperatures.[24]
- Where appropriate, establish trees to reduce evaporative water loss from the soil surface. Additionally, soils within agroforestry systems are better able to infiltrate and store water, which will be critically important in climates with warmer, drier summers.[21]

Image: Cover crops can reduce pest pressure, retain soil moisture, reduce soil temperatures, and mitigate nutrient loss. Source USDA

Citations

1. National Agricultural Statistics Service. (2022). 2022 Wisconsin Agricultural Statistics. Retrieved from https://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/Annual_Statistical_Bulletin/2022AgStats-WI.pdf

2. National Agricultural Statistics Service. (2017). Census of Agriculture State Profile: Wisconsin. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Wisconsin/cp99055.pdf

3. National Agricultural Statistics Service. (2021). 2021 State Agriculture Overview: Wisconsin. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=WISCONSIN

4. Frankson, R., K.E. Kunkel, S.M. Champion, and L. Sun, 2022: Wisconsin State Climate Summary 2022. NOAA Technical Report NESDIS 150-WI. NOAA/NESDIS, Silver Spring, MD, 6 pp. https://statesummaries.ncics.org/chapter/wi/

5. Kuchark, C., & Walling, S. (2021). Improving climate change mitigation and resiliency across Wisconsin's agriculture industry. Wisconsin Initiative on Climate Impacts: Agriculture Working Group. https://wicci.wisc.edu/agriculture-working-group/

6. Ferreira, F. C., Gennari, R. S., Dahl, G. E., & De Vries, A. (2016). Economic feasibility of cooling dry cows across the United States. Journal of dairy science, 99(12), 9931-9941.

7. Casson, N. J., Contosta, A. R., Burakowski, E. A., Campbell, J. L., Crandall, M. S., Creed, I. F., et al. (2019). Winter weather whiplash: Impacts of meteorological events misaligned with natural and human Systems in Seasonally Snow-Covered Regions. Earth's Future, 7, 1434-1450. https://doi.org/10.1029/2019EF001224

8. Demchak, K., & Marini, R. (2023). Small Fruit Cold Hardiness – Winter Injury in Brambles. Penn State Extension. https://extension.psu.edu/small-fruit-cold-hardiness-winter-injury-in-brambles

9. Walthall, C., Anderson, C., Takle, E., Baumgard, L., Wright-Morton, L., & et al. (2013). Climate Change and Agriculture in the United States: Effects and Adaptation. USDA Technical Bulletin 1935. https://dr.lib.iastate.edu/entities/publication/8a646593-a172-4e33-a628-f9555c51643d

10. Liu, L., & Basso, B. (2020). Impacts of climate variability and adaptation strategies on crop yields and soil organic carbon in the US Midwest. PLOS ONE, 15(1), e0225433. https://doi.org/10.1371/JOURNAL.PONE.0225433

11. USDA- Risk Management Agency. (2022). Summary of Business Report. Retrieved from https://public-rma.fpac.usda.gov/apps/SummaryOfBusiness

12. Baule, W. (2022). Dataset Description and Methods for Historical and Projected Climate Data for Ag State Summaries. https://www.climatehubs.usda.gov/hubs/midwest/assessing-impacts-climate-change-midwest-agriculture

13. Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A., Velders, G. J. M., & van Vuuren, D. P. P. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change, 109(1), 213–241. https://doi.org/10.1007/S10584-011-0156- Z/TABLES/5

14. Culp, K., & Tonelli, S. (2019). Heat-Related Illness in Midwestern Hispanic Farmworkers: A Descriptive Analysis of Hydration Status and Reported Symptoms. Workplace Health & Safety, 67(4), 168–178. https://doi.org/10.1177/2165079918813380

15. Meierotto, L., & Som Castellano, R. (2020). Food provisioning strategies among Latinx farm workers in southwestern Idaho. Agriculture and Human Values, 37(1), 209–223. https://doi.org/10.1007/S10460-019-09959-6/TABLES/9

16. Walsh, M., Backlund, P., Buja, L., DeGaetano, A., Melnick, R., Prokopy, L., Takle, E., Todey, D., & Ziska, L. (2020). Climate Indicators for Agriculture. USDA Technical Bulletin 1953. United States. Department of Agriculture. Climate Change Program Office. https://doi.org/10.32747/2020.7201760.CH

17. Ford, T. W., Chen, L., & Schoof, J. T. (2021). Variability and Transitions in Precipitation Extremes in the Midwest United States. Journal of Hydrometeorology, 22(3), 533–545. https://doi.org/10.1175/JHM-D-20-0216.1

18. Landau, C. A., Hager, A. G., & Williams, M. M. (2021). Diminishing weed control exacerbates maize yield loss to adverse weather. Global Change Biology, 27(23), 6156–6165. https://doi.org/10.1111/GCB.15857

19. Cai, X., Wang, D., & Laurent, R. (2009). Impact of Climate Change on Crop Yield: A Case Study of Rainfed Corn in Central Illinois. Journal of Applied Meteorology and Climatology, 48(9), 1868–1881. https://doi.org/10.1175/2009JAMC1880.1

20. Tomasek, B. J., Williams, M. M., & Davis, A. S. (2017). Changes in field workability and drought risk from projected climate change drive spatially variable risks in Illinois cropping systems. PLOS ONE, 12(2), e0172301. https://doi.org/10.1371/JOURNAL.PONE.0172301

21. Schoeneberger, M. M., Bentrup, G., & Patel-Weynand, T. (2017). Agroforestry: Enhancing resiliency in U.S. agricultural landscapes under changing conditions. General Technical Report WO-96. In T. Patel-Weynand, G. Bentrup, & M. M. Schoeneberger (Eds.), Gen. Tech. Report WO-96. Washington, DC: U.S. Department of Agriculture, Forest Service (Vol. 96). https://doi.org/10.2737/WO-GTR-96

22. Nickles, K. R., Relling, A. E., Garcia-Guerra, A., Fluharty, F. L., Kieffer, J., & Parker, A. J. (2022). Beef cows housed in mud during late gestation have greater net energy requirements compared with cows housed on wood chip bedding. Translational Animal Science, 6(2).

23. Nickles, K., Relling, A. E., Garcia-Guerra, A., Fluharty, F. L., & Parker, A. J. (2021). 87 Beef Heifers Housed in Muddy Environmental Conditions Lose Body Weight and Body Condition but Meet Gestational Requirements for Fetal Growth. Journal of Animal Science, 99(Supplement_3), 46–46. https://doi.org/10.1093/JAS/SKAB235.081

24. Janowiak, M. K., Dostie, D. N., Wilson, M. A., Kucera, M. J., Skinner, R. H., Hatfield, J. L., Hollinger, D., & Swanston, C. W. (2016). Adaptation Resources for Agriculture: Responding to Climate Variability and Change in the Midwest and Northeast. USDA Technical Bulletin 1944.

25. Angel, J. R., Swanson, C., Boustead, B. M., Conlon, K., Hall, K. R., Jorns, J. L., Kunkel, K. E., Lemos, M. C., Lofgren, B. M., Ontl, T., Posey, J., Stone, K., Takle, E., & Todey, D. (2018). Midwest. In D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, & B. C. Stewart (Eds.), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment: Vol. II (pp. 872–940). U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.CH21

26. Xiong, Y., Mend, Q. shi, Gao, J., Tand, X. fang, & Zhang, H. fu. (2017). Effects of relative humidity on animal health and welfare. Journal of Integrative Agriculture, 16(8), 1653–1658. https://doi.org/10.1016/S2095-3119(16)61532-0

27. Huber, L., & Gillespie, T. J. (1992). Modeling Leaf Wetness in Relation to Plant Disease Epidemiology. Annual Review of Phytophathology, 30, 553–577. https://doi.org/10.1146/ANNUREV.PY.30.090192.003005

28. Fanourakis, D., Aliniaeifard, S., Sellin, A., Giday, H., Körner, O., Rezaei Nejad, A., Delis, C., Bouranis, D., Koubouris, G., Kambourakis, E., Nikoloudakis, N., & Tsaniklidis, G. (2020). Stomatal behavior following mid- or long-term exposure to high relative air humidity: A review. Plant Physiology and Biochemistry, 153, 92–105. https://doi.org/10.1016/J.PLAPHY.2020.05.024