Climate Change Impacts on Ohio Agriculture

Aaron Wilson
Lee Beers
Carrie Brown
Ryan McMichael
Josh Bendorf
William (BJ) Baule
Laurie Nowatzke
Jeff Andresen
Dennis Todey

September 2024

Recommended Citation

Wilson, A. B., Beers, L., Brown, C., McMichael, R., Bendorf, J., Baule, W., Nowatzke, L., Andresen, J., & Todey, D. (2024). Climate Change Impacts on Ohio Agriculture. Ames, Iowa: United States Department of Agriculture Climate Hubs, and Great Lakes Research Integrated Science Assessment.

Methods and Supplementary Materials

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

Contact Information

Laurie Nowatzke

Midwest Climate Hub
Agricultural Research Service
United States Department of Agriculture
1015 N. University Blvd.
Ames, IA 50011
laurie.nowatzke@usda.gov
515-294-0213

Acknowledgements

Contributors

USDA Midwest Climate Hub

Ohio State University

GLISA, the Great Lakes CAP/RISA Team

Northern Institute of Applied Climate Science

USDA Northern Forests Climate Hub

Michigan State University

Grants

This work was partially supported by USDA NIFA Grant 2021-7000635562.

Reviewers

Representatives of the Ohio State University, Ohio Federation of Soil and Water Conservation Districts, and Ohio producers.

Climate Change Impacts On Ohio Agriculture

Agriculture is a critically important aspect of the economy and cultural identity of Ohio. In 2022, Ohio had 76,009 farms with 13.6 million acres.[1] According to the 2022 USDA Census of Agriculture, the estimated market value of agricultural products sold in Ohio totaled more than $15.4 billion, which ranks 11th nationally.[1,2] Ohio has a diverse array of crops produced in the state, as the state ranks 8th nationally in nursery, greenhouse, floriculture, and sod, 8th in grains, 9th in Christmas tree/woody crop production, and 11th in tobacco.[1,2] Livestock comprise 43% of the state's total sales of agricultural goods, with the highest total sales coming from poultry ($2.6 billion), hogs ($1.6 billion), and dairy cattle ($1.3 billion).[1,2] Ohio also has a strong forest products industry with forestry adding $30.4 billion to the economy annually.[3]

Like other regions in the United States, agricultural productivity in Ohio is vulnerable to weather and climate variability. In recent decades, changes in Ohio's climate, including rising temperatures and increased precipitation variability have emerged, with continued changes expected in the future. These climate changes are already impacting the agricultural and forestry sectors, not only in physical and direct impacts to farms and forestlands, but also through indirect impacts to the overall cultural, social, and economic resilience of Ohio's communities. In 2022, Ohio was the 10th largest agricultural exporting state in the country.[4] Therefore, when considering impacts on the agricultural and forestry sectors in Ohio, climate change-driven stressors and disruptions can emerge well outside the geography of the state.

Observed Changes to Ohio's Climate

Observational changes in Ohio's climate are calculated from gridded meteorological data from 1979 to 2021 (period of record for the dataset) by partners at Michigan State University and GLISA, the Great Lakes CAP/RISA Team (GLISA).[5] A summary of the historical, observed changes in Ohio's climate are described as follows.

Temperature

- Average annual temperature increased by 2.2°F between 1979 and 2021 (Table 1). Present day average annual temperature (2002-2021) is 1.6°F warmer than the early 20th century average (1901-1960).[6]
- Seven of the top ten warmest years on record (1895-present) have occurred since 1990.[7]
- All seasons have experienced an increase in average temperature between 1979 and 2021, with the greatest change occurring in the fall months (September – November; Table 1).
- Present day average winter low temperatures (2002-2021) have warmed 2.1°F relative to the early 20th century (1901-1960).[7]
- Although the number of very hot days in summer (≥ 95°F) has been declining in Ohio, the frequency of nights with a low temperature ≥ 70°F has been increasing since the mid-20th century.[6]

Precipitation

- Average annual precipitation (Figure 1) has risen by 7.0" between 1979 and 2021, with the greatest increases observed during the winter (2.9") and spring (1.9") (Table 1). Present day average annual precipitation (2002-2021) is 4.42" greater than the early 20th century average (1901-1960).[7]
- Eight of the top ten wettest years on record (1895-present) have occurred since 1990.[7]
- Extreme precipitation events (greater than 2.0") have become more frequent between 1979 and 2021 (Table 1), with events since 1990 challenging the historical peaks of the early 1910s.[6]
- Droughts have occurred in numerous years since the 1980s (e.g., 1988, 2000, 2002, 2007, and 2012) but the driest multi-year periods in Ohio occurred in 1930-1934 and 1960-1964.[8]

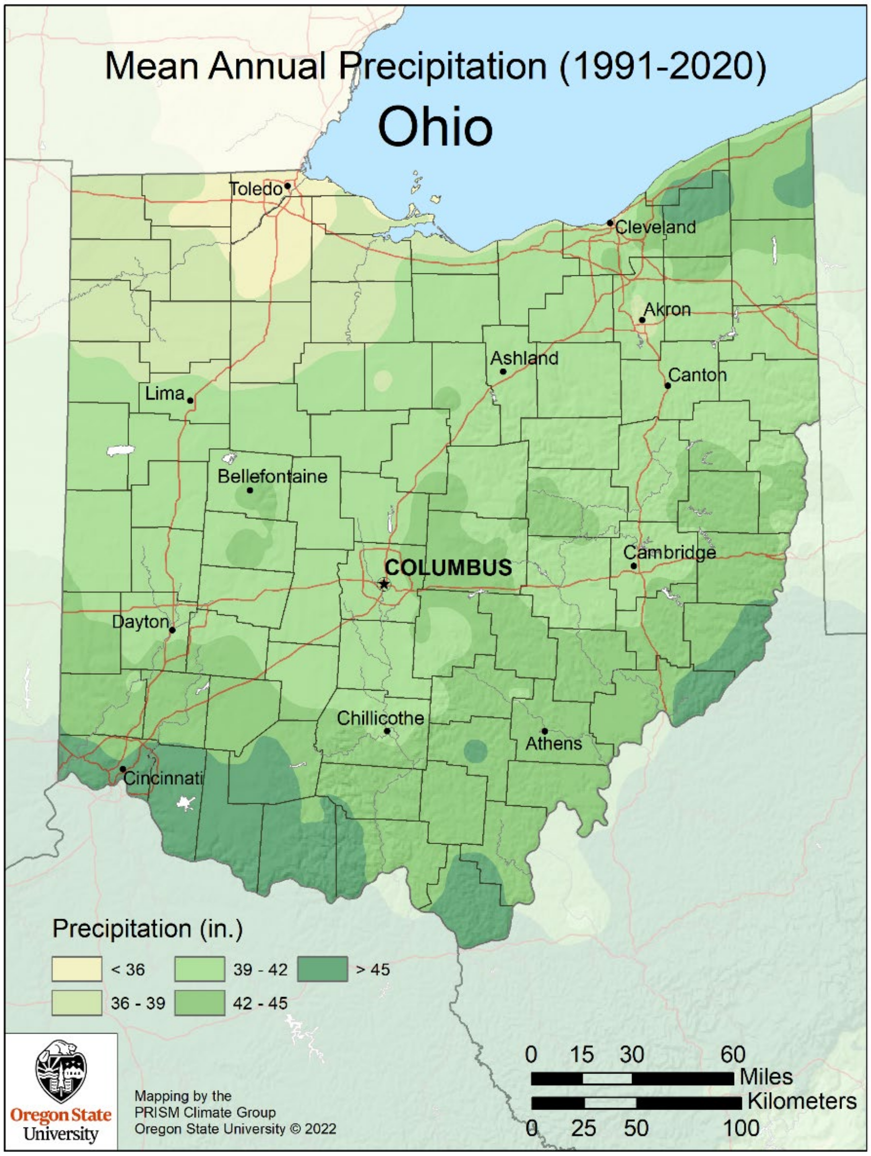


Figure 1. Mean annual precipitation (inches) for the period 1991-2020. Information based on PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu. Copyright 2022. Map generated on 28 March 2024.

Table 1. Observed changes in Ohio's climate based on data from 1979-2021. "Average" refers to the 1979-2021 average, and "Change" refers to change in the value between 1979 and 2021 based on a trend analysis.

	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	51.4 °F	+2.2 °F	71.5 °F	+1.7 °F	53.2 °F	+2.2 °F	29.8 °F	+2.0 °F	50.5 °F	+1.8 °F
Precipitation	41.1"	+7.0"	12.2"	+1.5"	9.4"	+0.8"	8.1"	+2.9"	11.3"	+1.9"
Vapor Pressure Deficit	5.9 mb	+0.6 mb	9.5 mb	+1.2 mb	5.7 mb	0 mb	2.0 mb	0 mb	6.2 mb	+0.1 mb
Extreme precipitation (days with 2")*	0.5 days	+1.0 days								
Growing Season Length (frost-free days)	177.7 days	+13.1 days								

*The average value being less than 1 means that, on average, these events do not happen every year. On average, Ohio observed one of these events every 2 years between 1979 and 2021. The change value represents the slope of the linear regression performed on the extreme precipitation frequency data, showing an increase in the frequency of events.

Observed Impacts on Agriculture and Forestry

Opportunities

- Longer growing seasons and increased temperature provide opportunities to plant alternative varieties of crops and trees.
- Shifting growing zones with Ohio now in Zone 6a to 7a.[9]
- Create new markets around new crops/trees.
- Longer grazing periods for livestock.
- Reduce utility costs though there are tradeoffs between less winter heat but more summer cooling needs.

Challenges

- Greater frequency of heat stress (from heat and humidity) on trees, crops, livestock, and farmworkers.
- Increasing risk of both drought and seasonal flooding events.
- Increasing weed, pest, and disease pressure as well as animal pathogens.[10]
- Disrupting the synchronization of pollinator/pollination cycles.[11]
- More erratic spring freeze/thaw cycles that may damage trees and fruit crops (e.g., Figure 2).
- Changes to species distribution in forested settings.
- Greater production costs and lower yields for some crops.[12,13]
- Wetter soils, resulting in delayed agricultural planting, higher erosion, and nutrient loss.
- Decreasing suitable fieldwork days.[14]

Figure 2. Cold injury damage to an Ouachita thornless blackberry variety in April 2021 in southern Ohio. Photo courtesy of Ryan Slaughter, Ohio State University.

Future Climate Change

Models of future climate indicate that temperatures are projected to continue to warm, precipitation is expected to become more variable and extreme, and the growing season is anticipated to continue to lengthen.[15] The climate projections in this section are based on the average of 17 different regional climate models.[5] Two possible futures are presented: an intermediate scenario in which greenhouse gas emissions peak around mid-century (RCP 4.5) and then slowly decline, and a very high scenario in which emissions continue to rise throughout the 21st century (RCP 8.5).[16] Careful planning and adaptive actions can lower the risks of climate change impacts for producers and the agricultural and forestry sectors more broadly. There are ways to adapt to climate change based on emerging impacts and the needs of a particular farm, crop, or community, and examples are presented below.

Projected Temperature Change

Climate model projections indicate that Ohio can expect to see continued warming throughout the 21st century, with fewer extremely cold nights, more very warm nights, and more very hot days.[15,17] Depending on the scenario, climate models project that annual average temperatures in Ohio will increase over historical baselines by 2.2°F to 6.7°F by mid-century (2040-2059), and by 5.7°F to 10.2°F by late-century (2080-2099).[18]

The models summarized by Michigan State University indicate a significant decrease in the number of days when temperatures fall below freezing, adding 1-2 months onto the growing season length in all scenarios (Table 2). Although these changes are most pronounced at the end of the century and in the very high scenario, even the intermediate, mid-century projections indicate major changes in Ohio's climate that could have important implications for agriculture and forestry.

Table 2. Modeled mean change (compared to the 1979 – 2005 period) in the number of days per year that meet or exceed a specified temperature threshold for Ohio. Values are provided for mid- and late-century and for two future scenarios of projected climate change. Included below the average change is the range of all model projections that make up the modeled mean change.

	Low temp. ≤ 32°F	Low temp. ≥ 80°F	High temp. ≥ 86°F	High temp. ≥ 95°F
Mid-century, intermediate	-32.4 days *(-50.2 to -15.6)*	+0.3 days *(0.0 to +2.6)*	+84.6 days *(+66.8 to +96.9)*	+8.0 days *(+1.9 to +24.1)*
Mid-century, very high	-37.4 days *(-56.1 to -18.3)*	+1.0 days *(0.0 to +8.5)*	+92.1 days *(+73.1 to +107.4)*	+14.0 days *(+3.7 to +39.8)*
Late century, intermediate	-41.8 days *(-58.0 to -22.3)*	+1.4 days *(0.0 to +9.3)*	+93.2 days *(+74.6 to +111.7)*	+14.5 days *(+3.2 to +42.7)*
Late century, very high	-66.9 days *(-86.9 to -43.0)*	+13.4 days *(+0.7 to +50.9)*	+119.3 days *(+96.0 to +134.8)*	+48.5 days *(+15.4 to +95.0)*

What Does This Mean for Agriculture and Forestry?

Heat Stress

- Increased heat stress severely impacts farmers, foresters, and animals. Among livestock, high heat stress can decrease meat and milk quality and quantity, and egg production.[19]
- Higher temperatures during the growing season may also stress cool season crops like broccoli and cabbage.[20]
- Farm workers who work outdoors are also particularly vulnerable to heat-related illness.[21,22,23]

Soil Impacts

- Decreased soil moisture affects agricultural plant physiology, potentially leading to an increased risk of reduced yields or crop losses, but uncertainty about these impacts remains.[12,20]
- Increased soil temperatures affect the appropriate timing and form of fertilizer application. Areas of the state where fall nitrogen applications are effective management will likely shift, particularly with anhydrous ammonia. With soils remaining above 50°F later into the fall season, fields are prone to nitrogen loss and subsequent water quality impacts following nitrogen applications.
- The frequency of short-term and rapid onset drought during the summer is potentially higher due to warmer temperatures and increased precipitation variability.[24]
- Decreased soil moisture may also increase chances for forest wildfire, as well as forest pest or pathogen outbreaks due to water stress.[25]

Growing Conditions

- By mid-century, under a very high scenario, the optimal growing region for corn and soybean is likely to shift both north and west in the Corn Belt, with more suitable growing conditions emerging in Minnesota and the Dakotas.[26] However, while models suggest that yields may increase initially from the changing climate, they may in fact begin to decline by mid-century.[27]
- With more days at or above 86°F projected across all scenarios (Table 2), the risk of yield declines from extreme temperatures increases.[28]
- Warming is expected to increase the severity and frequency of crop and animal diseases.[29]
- Elevated overnight temperatures will continue to affect corn development and vegetable crops, negatively impacting yields.[20]
- Research suggests warm and dry years narrow the area with optimal growing conditions for corn while soy has a higher tolerance for heat.[26]

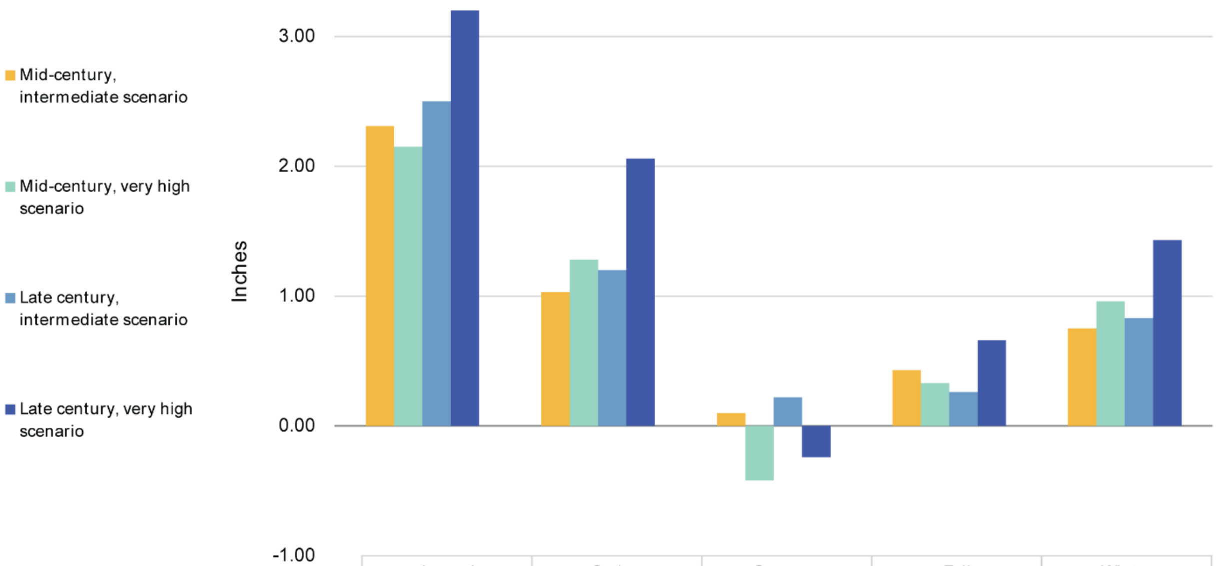
- Maple syrup production is threatened by impacts on sugar maple tree range, sugar content, mineral profiles, and increased susceptibility to root die-back and reduced shoot growth.[30]
- Maple sap seasons can be expected to begin earlier in the year with increasing winter & spring temperatures.[31,32]

Adaptation Options to Changing Temperature

- Integrate alternative crop species via conservation crop rotations to maintain or improve soil health.[33]
- Choose crop species or varieties that are more suited to future conditions including heat tolerance and water stress to limit potential yield losses.
- Consider double cropping systems to take advantage of the longer growing seasons.
- Utilize cover crops or reduce tillage to bolster soil health.
- Utilize high tunnels to help mitigate risk to extreme weather variability, extend the growing season, and protect soils.
- Increase diversity of covers and crops to expand the range of tolerance to different conditions.
- Choose longer maturity corn cultivars to take advantage of longer growing season (potentially increasing yields), or plant shorter maturity corn varieties earlier in the season to avoid reproductive stages happening during worst risk of drought in later summer (likely to give average, but more consistent yields).[33]
- Utilize and re-evaluate ventilation and cooling system for livestock facilities.[34]
- Explore options related to agroforestry practices, such as windbreaks and alley cropping, which provide shade and can buffer crops and livestock from increasing heat.[35]
- Explore tapping different species (e.g., Red maple, Walnut) for new syrup products or markets.[30,31]
- Utilize Climate Change Tree Atlas to help select more resilient species.[36]
- Explore options to reduce forest and farmworkers' exposure to high temperatures like providing shade, improved personal safety equipment, access to drinking water, and alternative working hours.[23]
- Implement active forest management to help keep trees healthy and vigorous, which will help the trees and the forests in which they reside to be more resilient to changes in temperature.

Projected Precipitation Change

Annual precipitation is expected to increase in the future, with the largest seasonal increases likely during winter and spring (Figure 3).[18] Decreases in summer precipitation are projected under a very high scenario (Figure 3). The likelihood for more extreme heavy rainfall events, rapid transitions between wet and dry conditions, and significant changes to seasonal runoff are expected as well.[18,24,27]



	Annual	Spring	Summer	Fall	Winter
Mid-century, intermediate scenario	2.31 (6%)	1.03 (9%)	0.10 (1%)	0.43 (5%)	0.75 (9%)
Mid-century, very high scenario	2.15 (5%)	1.28 (12%)	-0.42 (-4%)	0.33 (4%)	0.96 (12%)
Late century, intermediate scenario	2.50 (6%)	1.20 (11%)	0.22 (2%)	0.26 (3%)	0.83 (10%)
Late century, very high scenario	3.91 (10%)	2.06 (19%)	-0.24 (-2%)	0.66 (7%)	1.43 (18%)

Figure 3. Projected precipitation changes for Ohio, annually and seasonally, in inches (percentage in parentheses in table) based on two different scenarios (intermediate (RCP4.5) and very high (RCP8.5)).

What Does This Mean for Agriculture?

- Winter and spring increases in precipitation will lead to further loss of field and forest workdays, increased replant activity, impaired root growth and function, and prolonged field wetness (Figure 4).[20]
- Wetter pastures and paddocks increase susceptibility to animal foot diseases and may impact livestock nutrition maintenance schedules and gestational weight.[37,38]
- Increases in intense precipitation, especially during early spring, may increase erosion and nitrogen fertilizer leaching.[39]
- Challenges for manure applications and winter storage.
- Decreased soil moisture in summer could lead to greater irrigation demand though uncertainties remain in projected changes to potential evaporation and overall water demand.[40,41]

Figure 4. Flooded field shortly after corn emergence in west central Ohio. Photo courtesy of Aaron Overholser, farmer in Darke County, Ohio.

Adaptation Options to Changing Precipitation

- Consider planting earlier in the season, which may be possible due to small increases in field workability days in late March to early April, coupled with an earlier last frost date.[33]
- Use filter strips or riparian buffers in areas prone to flooding.[42]
- Increase soil health by improving soil structure and organic matter content to be better able to infiltrate precipitation, increase water-holding capacity, and maintain plant-available water during periods of dryness.
- Manage soil health by improving soil structure, organic matter content, and water storage capacity while potentially improving productivity through conservation crop rotations, cover crops, and reduced tillage.[20,43]
- Be prepared with farming strategies that help manage too much soil moisture in the spring (such as cool season cover crops or improved drainage) and not enough soil moisture during late summer (such as high-cover crop residue systems, drainage water recycling, or controlled drainage structures).
- Consider on-farm water storage systems to carry water over from excess to deficit moisture conditions.[44]
- Consider alternative windows for manure applications, follow runoff guidelines, and other agricultural best management practices.[45]
- Incorporate woodland management that includes adaptation for wetter conditions during timber harvest.[46]

Growing Season Length

Trends in growing season length across Ohio since 1950 are variable, but most counties have experienced a statistically significant increase in growing season length (Figure 5). These trends range from one or two days per decade to an increase of a month or longer. This is a result of later first frosts in the fall and an earlier onset of frost-free conditions in spring.

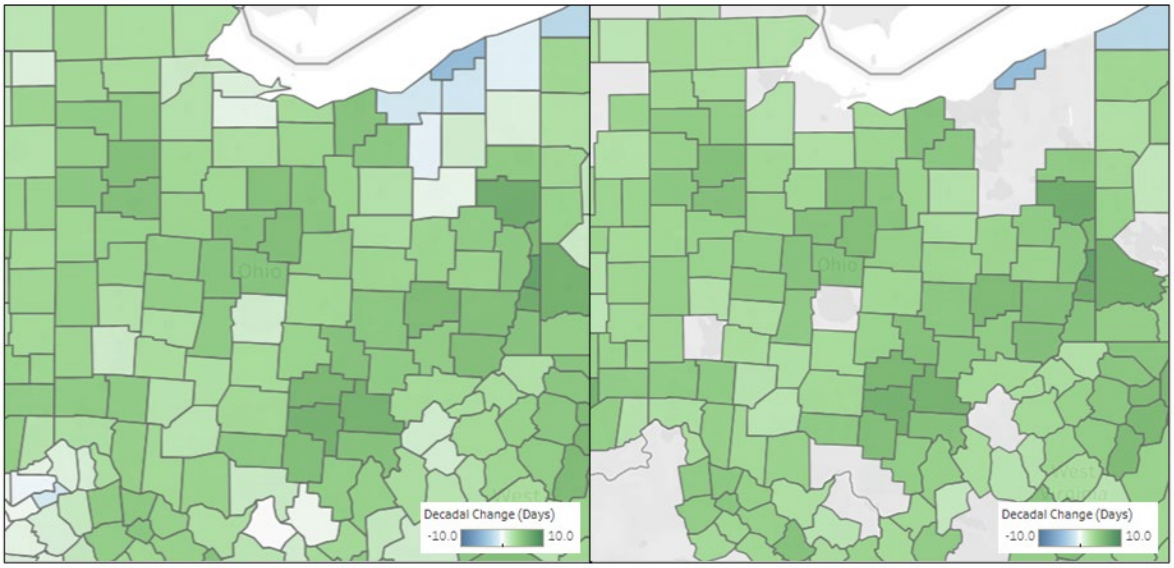


Figure 5. Observed changes in average annual growing season length for Ohio counties, 1950-2023, based on gridded Applied Climate Information System data. The right-hand image displays only those counties with a statistically significant trend ($p<0.05$). Image source: Freeze Date Tool, Midwestern Regional Climate Center.[47] Original data source is https://www.rcc-acis.org/.

What Does this Mean for Agriculture?

- Pests, diseases, and weeds may expand their ranges. Additionally, the number of pest generations per season may increase, resulting in a greater impact on forests, crops, or livestock. An increased need for chemical treatments to address these impacts may lead to greater pesticide and herbicide resistance and greater input costs for farmers. Increased tree loss due to pest damage may increase wildfire risk.[20]
- Provides additional time for agricultural harvest and other end-of-season processes. Also, cover crops may experience increased post-harvest growth. These processes will be heavily influenced by fall soil moisture trends.
- May reduce the winter forestry harvest period, make it more difficult to harvest some species that primarily inhabit wetter habitats, and drive changes in forest composition.[25]
- Forest regeneration after cutting timber can also be negatively impacted by climate change.[48]
- Warmer winters increase risk of spring freeze injury by accelerating development of buds despite increase growing season length.[49]
- Warmer winter temperatures may mean that chill hours for fruit crops are not met.[20]

Adaptation Options

- Plant agricultural crops earlier in the spring or consider options for double cropping.[42]
- 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.[42]
- 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.
- Promote tree species diversity and active forest management to increase the climate change resilience of forests.[48]
- Utilize Growing Degree Day Tools (OSU Phenology Calendar, MRCC Freeze Date Tool).[47,50]

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 both air temperature and absolute moisture content in the air.[41] Larger increases in temperature would decrease relative humidity, while larger increases in absolute moisture content would increase relative humidity. Models indicate that relative humidity is projected to decrease annually and across all seasons in Ohio. 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 for Agriculture?

- If relative humidity decreases:
  - Plants will be more prone to wilting and stunted growth because of excess crop water use.
  - Certain animal respiratory viruses may have a longer survival duration.[51]
  - Tree mortality may increase, especially for younger trees.[25,46,52]
- If relative humidity increases:
  - Wetness duration may increase leading to enhanced disease potential for crops and trees.[53]
  - Plants will have less ability to evaporate water (part of the transpiration process) or take up nutrients dependent on the flow of water from the soil.[54]

Adaptation Options

- Plant varieties adapted to a higher variability of moisture (both wetter and drier climates) if available (including crops, pasture grasses, and tree fruit).[42]
- Use of mulch, cover crops, no-till, or reduced tillage to retain soil moisture and reduce soil temperatures during the summer.[42]
- Where appropriate, establish trees to reduce evaporative water loss from the soil surface. Soils within agroforestry systems are better able to infiltrate and store water, which will be critically important in climates with warmer, drier summers.[35]
  - Active forest management will help keep the trees and the forests in which they reside more vigorous and thus more resilient to climate change (Figure 6).
  - Plant similar tree species from southern seed sources.

Ohio Climate Change Resources and Extension Programs

Ohio universities, government agencies, and partners have a variety of resources and programs available to help agricultural and forestry audiences learn about climate change and its impacts on agricultural and natural resources, find data to support decision-making, and explore resources to help adapt to climate change.

- The **Ohio State University Extension's Agronomic Crops Network** (https://agcrops.osu.edu/) provides weather and climate information via weekly or bi-weekly articles, webinars on weather and climate impacts including interactions with agronomic and specialty crops, diseases, pests, farm management and finances, and holds workshops and conferences that bring together researchers and engagement professionals to discuss climate interactions on a variety of topics.
- **Central State University** is involved in several climate-smart agriculture initiatives (https://www.centralstate.edu/oh-mi-climate-smart-agriculture).
- The **State Climate Office of Ohio** (SCOO; https://climate.osu.edu/) and its OSU partner, the **Byrd Polar and Climate Research Center** (https://byrd.osu.edu/), offer climate data and information, climate education on global to local scales, and a number of climate resources including recent maps, monthly and quarterly summaries, tools for improved application decisions, and other adaptation and mitigation information.
- The **Nature Conservancy of Ohio** (https://www.nature.org/en-us/about-us/where-we-work/united-states/ohio/stories-in-ohio/driving-climate-action/) offers a number of stories from Ohio on climate solutions and sustainable agriculture and forestry practices.
- The **Ohio Natural Resources Conservation Service** (NRCS; https://www.nrcs.usda.gov/conservation-basics/conservation-by-state/ohio) provides information on the growing number of programs that support Ohio farmers and landowners through financial and technical assistance.

Figure 6. Project site of the Ohio Hills Adaptive Silviculture for Climate Change (ASCC) Network, part of southeastern Ohio's Interagency Forestry Team's Collaborative Oak Management Region in Vinton Furnace State Forest.[55] Photo courtesy of Courtney Peterson, Program Manager, AASC Network.

Citations

1. United States Department of Agriculture: National Agricultural Statistics Service (NASS). (2024). 2022 Census of Agriculture. Complete data available at www.nass.usda.gov/AgCensus.
2. United States Department of Agriculture: National Agricultural Statistics Service (NASS). (2024). 2022 Census of Agriculture: State Profile. https://www.nass.usda.gov/Publications/AgCensus/2022/Online_Resources/County_Profiles/Ohio/cp99039.pdf.
3. Reese, J. (2024). Timber Talk: An introduction to Ohio's forest products industry. Ohio Ag Net. https://ocj.com/2024/05/timber-talk-an-introduction-to-ohios-forest-products-industry/.
4. United States Department of Agriculture: Economic Research Service (ERS). (2024). State Agricultural Trade Data. https://www.ers.usda.gov/data-products/state-agricultural-trade-data/
5. Baule, W. (2022). Dataset Description and Methods for Historical and Projected Climate Data for Ag State Summaries. https://www.climatehubs.usda.gov/sites/default/files/Methods%20for%20Historical%20and%20Projected%20Climate%20Data%20for%20Ag%20State%20Summaries_20220809.pdf
6. Frankson, R., K.E. Kunkel, S.M. Champion, and D.R. Easterling. (2022). Ohio State Climate Summary 2022. NOAA Technical Report NESDIS 150-OH. NOAA/NESDIS, Silver Spring, MD, 5 pp. https://statesummaries.ncics.org/chapter/oh/
7. NOAA National Centers for Environmental information, Climate at a Glance: Statewide Time Series, published February 2024, retrieved on February 28, 2024 from https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series
8. NIDIS. Ohio. Retrieved on February 28, 2024, from https://www.drought.gov/states/ohio

9. USDA Plant Hardiness Zone Map (2023). Agricultural Research Service, U.S. Department of Agriculture. Accessed from https://planthardiness.ars.usda.gov/
10. 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
11. McElwee, P.D., Carter, S.L., Hyde K.J.W., West, J.M., Akamani, K., Babson, A.L., Bowser, G., Bradford, J. B., Costanza, J. K., Crimmins, T. M., Goslee, S. C., Hamilton, S. K., Helmuth, B., Hoagland, S., Hoover, F.-A. E., Hunsicker, M.E., Kashuba, R., Moore, S. A., Muñoz, R. C., Shrestha, G., Uriarte, M., & Wilkening, J. L. (2023). Ch. 8. Ecosystems, ecosystem services, and biodiversity. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH8
12. 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
13. 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
14. Kansas State University. K-State Fieldwork Capacity Tool. https://agmanager.info/farm-management/machinery/k-state-fieldwork-capacity-tool
15. USGCRP. (2023). Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023
16. 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
17. Wilson, A.B.; Avila-Diaz, A.; Oliveira, L.F.; Zuluaga, C.F.; Mark, B. (2022). Climate extremes and their impacts on agriculture across the Eastern Corn Belt Region of the U.S. Weather and Climate Extremes, 37, https://doi:10.1016/j.wace.2022.100467
18. Marvel, K., W. Su, R. Delgado, S. Aarons, A. Chatterjee, M.E. Garcia, Z. Hausfather, K. Hayhoe, D.A. Hence, E.B. Jewett, A. Robel, D. Singh, A. Tripati, and R.S. Vose. (2023). Ch. 2. Climate trends. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH2
19. Rojas-Downing, M.M., A.P. Nejadhashemi, T. Harrigan, and S.A. Woznicki. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. Climate Risk Management, 16, 145–163. https://doi.org/10.1016/j.crm.2017.02.001
20. 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. www.doi.org/10.32747/2020.7201760.CH
21. 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
22. 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
23. El Khayat, M., Halwani, D. A., Hneiny, L., Alameddine, I., Haidar, M. A., & Habib, R. R. (2022). Impacts of Climate Change and Heat Stress on Farmworkers' Health: A Scoping Review. Frontiers in public health, 10, 782811. www.doi.org/10.3389/fpubh.2022.782811
24. 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
25. Domke, G.M., C.J. Fettig, A.S. Marsh, M. Baumflek, W.A. Gould, J.E. Halofsky, L.A. Joyce, S.D. LeDuc, D.H. Levinson, J.S. Littell, C.F. Miniat, M.H. Mockrin, D.L. Peterson, J. Prestemon, B.M. Sleeter, and C. Swanston. (2023). Ch. 7.

Forests. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH7
26. Hoffman, A. L., Kemanian, A. R., & Forest, C. E. (2020). The response of maize, sorghum, and soybean yield to growing-phase climate revealed with machine learning. Environmental Research Letters, Volume 15, Number 9. IOP Publishing Ltd. iopscience.iop.org/article/10.1088/1748-9326/ab7b22
27. Wilson, A.B., J.M. Baker, E.A. Ainsworth, J. Andresen, J.A. Austin, J.S. Dukes, E. Gibbons, B.O. Hoppe, O.E. LeDee, J. Noel, H.A. Roop, S.A. Smith, D.P. Todey, R. Wolf, and J.D. Wood. (2023). Ch. 24. Midwest. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH24
28. Schauberger, B., Archontoulis, S., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., ... & Frieler, K. (2017). Consistent negative response of US crops to high temperatures in observations and crop models. Nature communications, 8(1), 13931. https://doi.org/10.1038/ncomms13931
29. Melillo, Jerry M., Terese (T.C.) Richmond, & Yohe, G.W. Yohe, Eds. (2014). Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. www.doi.org/10.7930/J0Z31WJ2
30. Giesting, K. (2020). Maple Syrup. USDA Forest Service Climate Change Resource Center. www.fs.usda.gov/ccrc/topics/maple-syrup
31. Rapp, J.M., Lutz, D.A., Huish, R.D., Dufour, B., Ahmed, S., Morelli, T.L., & Stinson, K.A. (2019). Finding the sweet spot: shifting optimal climate for maple syrup production in North America. Forest Ecology and Management, 448, 187–197. https://doi.org/10.1016/j.foreco.2019.05.045
32. Houle, D., Paquette, A., Côté, B., Logan, T., Power, H., Charron, I., & Duchesne, L. (2015). Impacts of climate change on the timing of the production season of maple syrup in eastern Canada. PLOS One, 10(12), e0144844. https://doi.org/10.1371/journal.pone.0144844
33. 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
34. Gunn, K.M., M.A. Holly, T.L. Veith, A.R. Buda, R. Prasad, C.A. Rotz, K.J. Soder, and A.M.K. Stoner. (2019). Projected heat stress challenges and abatement opportunities for U.S. milk production. PLOS ONE, 14 (3), e0214665. https://doi.org/10.1371/journal.pone.0214665
35. 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). www.doi.org/10.2737/WO-GTR-96
36. USDA Forest Service. (2023). Climate Change Tree Atlas. Available online at https://www.fs.usda.gov/nrs/atlas/tree/.
37. Nickles, K., Relling, A. E., Garcia-Guerra, A., Fluharty, F. L., & Parker, A. J. (2021). 39 Muddy Environmental Conditions Cause Conceptus Free Live Weight Loss but Not a Decrease in Calf Birth Weight When Compared with Cows Housed on Wood Chips. Journal of Animal Science, 99(Supplement_1), 31–31. https://doi.org/10.1093/JAS/SKAB054.054
38. 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
39. Baule, W.J., J.A. Andresen, and J.A. Winkler. (2022). Trends in quality controlled precipitation indicators in the United States Midwest and Great Lakes region. Frontiers in Water, 4, 817342. https://doi.org/10.3389/frwa.2022.817342
40. Nocco, M.A., R.A. Smail, and C.J. Kucharik. (2019). Observation of irrigation-induced climate change in the Midwest United States. Global Change Biology, 25 (10), 3472–3484. https://doi.org/10.1111/gcb.14725
41. Basso, B., Martinez-Feria, R. A., Rill, L., & Ritchie, J. T. (2021). Contrasting long-term temperature trends reveal minor changes in projected potential evapotranspiration in the US Midwest. Nature Communications, 12(1), 1476. https://doi.org/10.1038/s41467-021-21763-7

42. 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. https://doi.org/10.22004/ag.econ.320856
43. Haruna, S. I., Anderson, S. H., Udawatta, R. P., Gantzer, C. J., Phillips, N. C., Cui, S., & Gao, Y. (2020). Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences & Environment, 3(1), e20105. https://doi.org/10.1002/agg2.20105
44. Tagert, M. (2021). On-Farm Water Storage Systems and Surface Water for Irrigation. Mississippi State University Extension. Publication 3202. Retrieved from http://extension.msstate.edu/sites/default/files/publications/publications/P3202_web.pdf
45. Ohio State University Extension – Agriculture and Natural Resources. (2024). AgBMPs. Available online at https://agbmps.osu.edu/bmp.
46. Ohio Department of Natural Resources (2024). BMPs for Erosion Control for Logging & Forestry Practices in Ohio. Available online at https://ohiodnr.gov/business-and-industry/best-management-practices/forest-pollution-prevention/erosion-control-logging.
47. Midwestern Regional Climate Center. (2024). Freeze Date Tool. https://mrcc.purdue.edu/freeze/freezedatetool
48. García, C., Espelta, J. M., & Hampe, A. (2020). Managing forest regeneration and expansion at a time of unprecedented global change. Journal of Applied Ecology, 57(12), 2310-2315.
49. Kistner, E., Kellner, O., Andresen, J., Todey, D., & Morton, L. W. (2018). Vulnerability of specialty crops to short-term climatic variability and adaptation strategies in the Midwestern USA. Climatic change, 146, 145-158. https://doi.org/10.1007/s10584-017-2066-1
50. Ohio State University. (2024). Ohio State Phenology Calendar. https://weather.cfaes.osu.edu/gdd/
51. 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
52. 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. www.doi.org/10.7930/NCA4.2018.CH21
53. 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
54. 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
55. USDA Northern Forests Climate Hub and the Northern Institute of Applied Climate Science. (2022). Ohio Hills: Adaptive Silviculture for Climate Change (ASCC). https://www.adaptivesilviculture.org/node/1109.