

Appendix B

Scientific synthesis: Anticipated climate impacts on agriculture in Washington state



Introduction

The investigation into climate change impacts on agriculture— including cropland, livestock, and aquaculture systems — is relatively new, with most studies produced in the last 15 years. This document summarizes what is known about the anticipated climate impacts on the agricultural sector in Washington state. The literature is far from comprehensive, with some geographic areas and types of production systems better covered than others. Given the diversity of conditions, agricultural products, and production systems across the state, it is unsurprising — yet noteworthy — that there is significant complexity in the anticipated impacts. Climatic differences east and west of the Cascade Range, in combination with other factors, have led to distinct production systems. The biggest or best-studied climate change impacts are therefore sometimes different east and west (see Figures 1 and 2 in Section 2: Agricultural Climate Risks and Adaptation Opportunities) of the mountains. While some overall patterns can be discerned, there is an ongoing need for research to provide a more complete understanding and to support adaptation.

Changing temperatures, precipitation, and CO₂ levels, and their impacts on crops and animal agriculture

Increased temperatures can accelerate crop growth and maturity, which ultimately reduces crop biomass and therefore potential yields ^{20,21}. However, the carbon dioxide (CO₂) effect — in which increased atmospheric CO₂ increases the rate of photosynthesis and improves crop water use efficiency for many crops — generally improves plant yields ^{20–22}. Combined with potential management adaptations such as changing planting dates or crop varieties, the effect of a warming planet (with increased atmospheric CO₂) is generally positive for potential crop yields in Washington state. Similarly, rangeland net primary productivity is expected to increase through the end of the century ²³. It is important to note that studies cited above are limited in multiple ways. They assume ideal conditions - meaning adequate availability of irrigation water, nutrients, and other factors. They also do not account for impacts from extreme weather, weed and pest pressures, or reductions in crop quality, all of which can reduce actual crop yields or performance.

For the shellfish aquaculture industry, elevated atmospheric levels of CO₂ are more problematic and can cause acidification of the water (i.e., ocean acidification), which reduces the availability of carbonate minerals that are necessary for bivalve shell deposition ^{24,25}. Ocean acidification has been shown to negatively impact shell calcification, early embryonic development, growth, attachment, and survival ^{26–28}. The economic losses contributed to ocean acidification are estimated to be in the billions of dollars annually for the global shellfish industry, and farmers in the state will be impacted by increasingly acidic waters in the coming decades ²⁹.

Changes in precipitation and the resulting agricultural impacts are more difficult to predict ³⁰. Tubiello et al. (2002) reported that simulations with increased precipitation led to higher yields for dryland production systems ³¹. Stöckle et al. (2010) used regional climate projections that indicated increases in both annual and growing season precipitation for multiple dryland sites across Washington state; however, these increases in precipitation were not as impactful on potential yields compared to increases in temperature and CO₂ concentrations ²⁰. Overall, Stöckle et al. (2010) projected potential yield increases for the main agricultural commodities in Eastern Washington through mid- to late-century, primarily due to the positive influence of the CO₂ effect. For irrigated systems, the effect of precipitation is largely dependent on watershed type, which is discussed in *Impacts on Water Supply* below.

Although the CO₂ effect may benefit crop yields and rangeland production, higher CO₂ levels may decrease certain nutrients and proteins in some plants as accelerating maturation affects nutrient accumulation ^{32–35}, which could negatively impact nutrition for both humans ³⁶ and livestock ³⁷.

Elevated temperatures can also change certain phenological processes such as chill accumulation in tree fruit³⁸, which could impact yields. While chill accumulation is expected to decrease in the fruit and berry growing regions of the Southwest^{39,40} and Southeast⁴¹, the Pacific Northwest is, in comparison, more resilient³⁸. Changing crop phenology can also increase the risk of frost and cold damage⁴², especially for varieties that have lower chill requirements. For example, recently introduced blueberry varieties in Washington state have lower chill requirements, but also bloom earlier and are therefore more susceptible to cold damage.

Impacts on water supply

Impacts on water supply for Washington state will be influenced by three main factors: warmer temperatures, reduced precipitation in summer months, and increased precipitation in winter months⁴³. How these changes impact specific areas will largely depend on the watershed type (i.e., snow-dominated, rain-dominant, or mixed rain/snow), the extent to which the watershed is currently experiencing water supply-related issues, the type of agricultural production (dryland versus irrigated, perennial versus annual, etc.), access to water storage infrastructure, and the seniority of the water rights agricultural producers hold.

Streamflow — an important determinant for the surface water supplies that irrigated agriculture relies on — is expected to increase in the fall, winter, and spring, and decrease in the summer⁴⁴. Effects will be most pronounced for mixed rain/snow and warmer snow-dominated watersheds, where small changes in temperatures can substantially impact snow accumulation and melt.

Streamflow reductions in rivers with instream flow rules could prompt more frequent and deeper curtailments (temporary shutoffs of full or partial access to water) for junior rights holders⁴⁵, which could limit irrigation water for these producers. Hall et al. (2024) concluded that in the future, curtailments are more likely to occur, and may occur over a longer timeframe within a given year⁴⁵. Even with increased curtailments, rivers may have insufficient flows to support fish populations and riverine function in affected river basins. In addition, low flows could exacerbate water quality issues, such as by increasing water temperatures or by concentrating nutrients or other pollutants^{46–48}. Enhanced planning at multiple levels (e.g., statewide, basin-wide, on-farm) will be necessary to adequately store and deliver water for irrigated agriculture as the amount and timing of water availability shifts earlier in the growing season, and droughts and floods potentially become more common⁴³.

Dryland agriculture will also be impacted by changes in the amount and timing of precipitation. Effects on soil moisture at seeding time will be especially important for water-limited dryland systems^{49,50}. Increased atmospheric evaporative demands and early season evapotranspiration^{21,51} can also impact the timing and magnitude of soil moisture availability for plant growth during the growing season. In response, growers may have to fallow more land⁵², limiting production. However, there are many site-specific factors and constraints that will determine how individual growers can best respond to changes in precipitation patterns and soil moisture⁵³.

Rangelands will also be impacted by shifting precipitation patterns, coupled with increasing temperatures. Decreased precipitation in the summer months and the potential for increased evapotranspiration pose a risk to forage availability in the later growing season through limited soil water availability⁵⁴, which could pose challenges in maintaining historical stocking rates^{37,55,56}. Water access — and the availability of forage in sufficient proximity to drinking water — may become more limited throughout grazing areas. This could cause an increasing need for additional water infrastructure and greater feed supplementation in the traditional forage grazing season to support animal growth.

Extreme weather

Extreme weather events will continue to cause severe disruptions to agricultural systems. The Northwest chapter of the Fifth National Climate Assessment notes increasing crop insurance loss payments due to extreme events and impacts, an indicator associated with economic disruption of agricultural production⁵⁹⁻⁶¹. The following sections discuss particular types of extreme events that are relevant to Washington state agriculture.

Heat

As temperatures warm, heatwaves are becoming more frequent, more extreme, and longer lasting⁶². The June 2021 Pacific Northwest heatwave reduced yields of many crops, including spring wheat, barley, canola, cherries, grapes, and raspberries, among others, in nearby British Columbia by roughly 20-30 percent compared to expected yields for that year⁶³. Many crops grown in Washington, such as blueberries, apples, and some types of Brassicas, have been shown to suffer quality and yield reductions from various forms of heat damage when temperatures reach certain thresholds⁶⁴⁻⁶⁷. Impacts usually begin occurring around 90°F and include sunburn, sun spotting, shriveling or wrinkling, and cell death. Heatwaves can also affect crop quality by raising nighttime temperatures, as in apples where red color development — a key marketability trait — is lessened when fall night temperatures are too high⁶⁶.

The higher temperatures expected in the Western US under climate change increase the likelihood of reaching the critical heat-humidity thresholds where heat stress impacts animal health and productivity⁶⁸⁻⁷⁰. Vulnerability varies depending on the species, breed, life stage, nutritional status, genetic potential, size, and previous exposure of the animal. However, high-yielding individuals and breeds tend to be more susceptible, with dairy cows among the most vulnerable⁶⁸. Projected changes in heat stress events for dairy cows⁷¹ and cattle on rangelands⁷² are anticipated to be impactful, but are less severe in Washington state compared to other regions of the US.

The cold-water finfish and shellfish aquaculture species cultured in Washington state are particularly vulnerable to elevated water temperatures as they cannot regulate their internal body temperature (i.e., they are ectotherms) and are adapted to the natural cool water of the region. The salmon and trout cultured in river systems across the state are already experiencing summer high water temperatures that can induce stress⁷³. Marine shellfish aquaculture has also experienced severe high mortality events associated with the recent marine heat waves, with June 2021 representing a particularly devastating event^{74,75}. Shellfish are not only vulnerable to elevated water temperatures^{76,77} but can experience mortality events when extreme low tides occur during days with abnormally high air temperatures. This can expose the animals to high air temperatures for an extended period of time⁷⁵.

Droughts and floods

As discussed in the *Water Supply* section, droughts, heavy rainfall, and flooding may become more common in the future. Though relatively understudied, these events are expected to reduce crop yields^{78,79}. Washington state's 2021 drought, for example, reduced access to irrigation water and resulted in yield loss for several crops^{59,80}. Tohver et al. (2014) predict that some rain-dominated and mixed rain/snow basins in the state are expected to experience summer low flows around half of their historical minimum, as early as the 2040s, an indication that future droughts may be more severe⁴³.

Flooding is also likely to increase in frequency and severity across both mixed rain/snow basins, and in warm, rain-dominated basins where peak flows occur in the late fall or winter. Tohver et al. (2014) found that by 2080, shifts in climate in some mixed rain/snow basins are projected to lead to floods that are between 1.5 and 2 times greater in magnitude than the historical baseline⁴³. Flooding can devastate agricultural

operations, as illustrated in the Chehalis basin of Western Washington in 2007, in which 19 out of 30 dairies were flooded ⁸³. Two operations suffered a complete loss of animals, despite being sheltered in barns that were historically safe from flooding.

Changes to hydrology and precipitation patterns, including sea level rise, more winter precipitation, and higher intensity rainfall events, could also exacerbate pre-existing agricultural drainage issues, already prevalent in Western Washington, by overwhelming drainage infrastructure, flooding fields, and increasing runoff from agricultural lands ^{84,85}. Increasing runoff can cause a variety of compounding concerns including topsoil loss ⁸⁶, nutrient and pesticide contamination of water bodies ⁸⁷, and deterioration of salmon spawning habitat ⁸⁸.

To understand the impacts of flooding on shellfish aquaculture, it is important to recognize these animals' influence on water quality. As filter feeders, shellfish have important ecological functions and can improve water quality in enclosed ecosystems. Shellfish aquaculture can reduce the impacts of terrestrial nutrient inputs that can increase eutrophication of the water. However, flooding and the associated runoff from urban or agricultural land can degrade water quality in marine culture environments by promoting harmful algal blooms or introducing wastewater effluents. This may contaminate shellfish with harmful fecal bacteria or result in increased levels of pollutants bioaccumulated in shellfish ⁸⁹⁻⁹¹.

Coastal storms

The increased prevalence and intensity of coastal storms associated with climate change will add additional challenges to shellfish farmers. Storms can damage aquaculture equipment or tidal beds which can result in economic losses and increased labor costs to growers.

Wildfire and wildfire smoke

Wildfires across the Western US, including in Washington state, have become larger, hotter, more severe, and more deadly over the last several decades, due to a suite of factors that includes, but is not limited to, climate change ^{92,93}. Wildfire events pose a threat to animal safety and can have enterprise-threatening impacts on ranchers in the region ⁹⁵. Rangelands and surrounding areas can take 3-15 years to recover after a wildfire depending on weather patterns (especially precipitation) and rangeland vegetation composition ^{96,97}. Resting those lands as they recover takes significant acreage out of production for that period. Finding alternative grazing land or supplemental feed to offset this loss is a significant economic burden. Forage composition can also be permanently altered, as invasive annual grasses can recover from wildfires more effectively than native species ⁹⁸. Invasive grasses — most notably cheatgrass — also become a fuel source for future fires, as their abundance creates a continuous fuel bed and they senesce and dry out earlier than perennial grasses. In this way, invasives and wildfires reinforce each other, creating a positive feedback loop that leads to ongoing losses of productive forage in affected rangelands ^{57,99-101}.

Even for crops and animals not directly in harm's way, indirect impacts from smoke can be consequential. For livestock, smoke inhalation and the stress from confinement or evacuation have not been well studied, but are likely to reduce productivity. Potential impacts include poor weight gain, reduced milk production and milk quality, respiratory illnesses, and negative immune and reproductive impacts ^{94,102,103}. Heat stress compounds these negative effects, which can persist even after air quality improves. Impacts to young animals are particularly concerning given potential for long term impacts ^{103,104}. Wildfire smoke can also impact crops such as wine grapes ¹⁰⁵. Wine made from smoke-tainted grapes will have compromised aroma and flavor, and may require additional processing to restore quality ¹⁰⁶.

Impacts on pests, weeds, and disease

Overall, there is limited information on how pests, weeds, and diseases may impact cropping systems in a climate-changed future. Generally, warmer temperatures increase threats from insect pests¹⁰⁷. For example, Stöckle et al. (2010) and Noorazar et al. (2022) modeled the impact of climate change on codling moths in the Pacific Northwest, concluding that moths will emerge earlier and have the potential for additional generations within each growing season, exerting additional pressures on apple production systems^{20,108}.

Stöckle et al. (2010) also modeled changes in the occurrence of cherry and grape powdery mildew, two common crop diseases in the Pacific Northwest. Results varied by climate model, though most projections predicted no change or only a slight increase in disease incidence²⁰. Though Northwest-specific work is lacking, climate change is likely to lead to changes in some livestock infectious diseases, particularly those with pathogens or vectors whose development or transmission is influenced by climatic factors^{68,109}. Impacts could include changes in spatial distributions, annual and seasonal cycles, disease incidence and severity, and susceptibility of livestock to illness⁶⁸. Changes in climate could cause new or currently uncommon crop or livestock diseases to spread in the region, though this requires further investigation and monitoring.

Elevated water temperatures can increase the susceptibility of cold-water aquaculture species to diseases, as thermal stress has negative impacts on immune function and may promote the growth of some pathogens. More studies are needed to fully understand how aquatic pests and diseases will impact the aquaculture industry. Clear associations between the prevalence of *Vibrio* bacteria and water temperature have been identified in Washington state^{110,111}. *Vibrio* are pathogenic to humans and prevent the harvest of shellfish during outbreaks which, results in economic losses to growers¹¹². Changes in Washington state marine water conditions have also been linked to the increased occurrence of harmful algal blooms that can kill shellfish or make them toxic for human consumption¹¹³⁻¹¹⁵.

Climate change is expected to benefit many weed species. For example, increased temperatures and elevated CO₂ benefit invasive annual grass growth over native grasses in rangeland systems, which could reduce forage quality^{72,98}. Lawrence and Burke (2015) found that climate change impacts on downy brome (i.e. cheatgrass), a common Washington weed in dryland systems, could make current herbicide regimens less effective in the future as herbicide-resistant biotypes spread further and the weed reaches seed maturity earlier in the spring when precipitation is expected to increase¹¹⁶. Climate change is expected to benefit many weed species. For example, increased temperatures and elevated CO₂ benefit invasive annual grass growth over native grasses in rangeland systems, which could reduce forage quality^{72,98}. Lawrence and Burke (2015) found that climate change impacts on downy brome (i.e. cheatgrass), a common Washington weed in dryland systems, could make current herbicide regimens less effective in the future as herbicide-resistant biotypes spread further and the weed reaches seed maturity earlier in the spring when precipitation is expected to increase¹¹⁶.

Impacts on pollinators

Many berry, fruit, and vegetable crops are reliant on managed honeybees and native pollinators. Climate change can alter the species distribution of native pollinators¹¹⁷, create a mismatch between the timing of forage availability and foraging needs^{118,119}, and result in an increased risk of honeybee colony failure¹²⁰. For example, warmer winters cause premature physiological aging in bees that were previously less active in the colder winters. Cold storage for hives may become important in the future¹²⁰.

Washington state's relative position

Though climate impacts will be mixed and differ by location and cropping system, Washington may overall fare better than many other regions of the US^{121,122}. Drought risk may be increasing more for other regions compared

to the Northwest, with the Southwest US experiencing an increasing trend in meteorological drought severity ¹²³.

Other influences beyond climate change are also contributing factors. For example, California's San Joaquin Valley could see as much as a 20 percent reduction in irrigation water supplies by 2040 due to the combination of climate change and changes in policy that drastically reduce groundwater withdrawals and require greater water releases for environmental flows ¹²⁴. Without intervention, these changes could lead to losses of more than 50,000 jobs in the region and reductions in agricultural revenue of more than \$10 billion in a worst-case scenario. Even in the best-case scenario, nearly 500,000 more acres will be fallowed compared to baseline (2003 - 2010) conditions.

Comparatively, most regions in Washington with irrigated agriculture are more surface-water dependent, and not under environmental pressures of the same magnitude (with some notable exceptions). Thus, the state's relatively temperate climate, surface water availability, extensive irrigation systems, and variety of crops bolster its potential to become a more agriculturally important region in a climate changed future. However, there are still many consequential impacts from climate change that will affect Washington state agriculture. Strategic management will be vital to realize potential production increases.

Considerations beyond impacts on crops, livestock, and aquaculture

Impacts on human health

Increasing temperatures under climate change will bring increased exposure of agricultural workers to dangerous levels of heat ¹²⁵ and contribute to negative health outcomes including heat-related illness, kidney injury, adverse pregnancy and birth outcomes, and mental health effects, as well as increased risk for traumatic injury ^{126,127}. In Washington, workers' compensation claims for heat-related illness spike during years with higher average maximum outdoor temperatures ¹²⁸, a trend that is expected to worsen under climate change ¹²⁹ International Classification of Diseases 9/10 codes, and medical review to identify accepted and rejected Washington State (WA). Areas in Eastern Washington such as Yakima, Okanogan, and Benton counties are expected to experience increases in the number of days with a heat index $\geq 90^{\circ}\text{F}$ by mid-century compared to historical (1971 - 2000) conditions ($\sim +35$ days; ClimateToolbox.org), representing a sharp increase in dangerous working conditions.

Increased frequency or severity of wildfires that lead to deteriorating air quality can create additional negative impacts, sometimes occurring concurrently ¹³⁰. Heat and drought can also drive increased rates of wind erosion which can elevate levels of particulate matter in the air ¹³¹, exposure to which has been linked to increased chronic respiratory symptoms and the worsening of lung and heart disease ¹³². Rules and protocols related to agriculture, human health, and workers' exposure to hazards have recently been updated to include requirements for shade, rest, and acclimatization while lowering the temperatures at which some preventive actions must be taken ¹³³. However, there is an ongoing need to support implementation and further adaptation, especially the development and implementation of strategies that do not reduce farm productivity and profits or worker earnings ¹²⁵.

Impacts on environmental quality

Climate change, specifically through its potential to increase floods and droughts, may impact environmental quality by increasing issues with soil erosion. Climate change-driven increases in droughts may lead to increased wind erosion ¹³⁴ and associated reductions in air quality ¹³⁵. Though increased biomass growth due to warmer temperatures and higher CO₂ concentrations could temper water- ¹³⁶ and wind-driven erosion

¹³¹ in the inland Pacific Northwest, Farrell et al. (2007) projected more than a doubling of soil erosion in conventionally tilled dryland systems by mid-century in this region ¹³⁶. Droughts also lead to reductions in crop biomass and corresponding residue inputs to soil, which may translate to declines in soil organic matter and degraded soil structure, negatively affecting crop yields and further increasing rates of erosion ¹³⁷.

Changes in precipitation patterns can also impact manure management needs and strategies for dairy operations ¹³⁸, particularly in Western Washington. Over the last decade or more, dairy farmers in Western Washington and Oregon have anecdotally noticed changes in seasonal rainfall patterns that align with regional climate change projections for increased winter and spring season precipitation ^{30,139}. A preliminary analysis in Whatcom County indicated an increased frequency of large storms that lagoon capacity is not designed for, and therefore, an increased risk of lagoon overflow is likely (Rajagopalan, unpublished results). Understanding these climate change-related impacts is critical, as lagoons are long-term infrastructure investments that can last up to 40-50 years.

Regulatory and market considerations

Although climate change will cause important impacts on agricultural systems, it is just one of many factors that producers must consider and may not be of most concern ¹⁴⁰. In a survey of Pacific Northwest wheat producers, changes in cost of inputs and crop prices were ranked ahead of any climate-related considerations in terms of the risk they posed ¹⁴¹. Furthermore, most producers in this survey perceived climate change-related *policies* as posing a higher risk to their operations than less reliable precipitation, despite the fact that most wheat producers lack irrigation. In a similar vein, supporting processing and other agriculturally associated businesses and infrastructure is likely to be important to ensure the ongoing viability of agriculture in Washington state.

Most agricultural markets are global, and these markets have a substantial impact on the economic outlook of agriculture in Washington. This reinforces the conclusion that impacts on production in Washington state need to be assessed alongside the likely impacts on production elsewhere in the US and world ^{122,142}. This includes impacts that are policy-related, for example, resulting from the impacts of climate-related policy in the state that are different from policies that impact producers elsewhere. Climate change is also likely to impact food consumers in the state and elsewhere, with the potential for increasing food prices; negative impacts on those who rely on hunting, fishing, foraging, and subsistence farming; and adverse impacts on culturally important foods, including but not limited to salmon ^{142,143}.

Meanwhile, some agricultural systems face pressures from consumers and buyers to meet regulatory standards for emissions reductions or otherwise implement environmentally friendly production practices ¹⁴⁴, or, in the case of cropping systems, to move toward production of specialty crops ¹⁴⁵. In some cases, this may complement, and in other cases, this may complicate efforts to adapt systems to address climate impacts. It will be key to recognize these other factors when prescribing policy or promoting programs that seek to support producers' attempts to adapt to projected climate impacts ¹⁴⁶ as new soil carbon initiatives are created by public, private, and philanthropic entities. It has also led to confusion over what is possible or practical to achieve through agricultural management, as soil carbon formation and storage is complex, and its response to management is context-dependent. This can pose challenges to decision makers tasked with creating defensible, science-informed policies and programs for building and protecting soil carbon. Here we summarize the science concerning the potential for agricultural soils to serve as a natural climate solution, in order to frame a discussion of current approaches in United States (US).

Specific challenges for small operations and socially disadvantaged farmers

There is some evidence that smaller farms may be more economically vulnerable to climate change impacts

¹⁴⁰ likely due to their relatively limited financial base and lack of other resources (e.g., irrigation) to help them ameliorate impacts compared to larger farms ¹⁴⁷. This can be expected to extend to other small farm situations, even those that produce livestock, livestock products, or diversified vegetables or fruits. A growing number of small farmers in Washington represent historically underserved and socially disadvantaged populations including women, Latino, Asian, and immigrant farmers, who possess additional vulnerabilities that are likely to make it even harder to adapt to climate change ¹⁴⁸.

Many diversified small farms participate in direct-to-consumer markets with farms typically providing products on a weekly or even more frequent basis to customers. In Western Washington, many of the operations growing vegetables and fruit have traditionally grown cool-season crops such as cabbages, broccoli, kale, and spinach during summer months, as well as other specialty crops like warm-season vegetables, berries, or apples. As the climate warms and heatwaves become more intense, cool-season crops could become less viable ^{65–67} during periods in which they have historically been grown, perhaps necessitating adaptation for these small farms.

There is some evidence that small operations have been able to adapt quickly during previous disruptions, including during the COVID-19 pandemic ¹⁴⁹. However, small, under-resourced, and socially disadvantaged farmers are less likely to qualify for or use government support programs ¹⁵⁰, causing them to bear more of the economic burden of adapting. Farmers with limited literacy or limited English proficiency may also struggle to successfully navigate support programs, even when they are made available. Similar issues arise with many conventional farming education models that are not tailored to farmers with limited access to land, water, and capital, or who lack English proficiency ¹⁴⁸. This underscores the need for governments to keep small and socially disadvantaged farms and farmers in mind when crafting policy to help adapt to climate change.

Additionally, lack of capacity to address climate change impacts may push small farmers to a higher reliance on off-farm income. While this can buffer potential losses ¹⁴⁰, it may also be a concerning symptom of economic distress and reduced economic viability of small-scale agriculture.

Areas for future study and climate adaptation

Climate change impacts on Washington state's agriculture are varied and complex and interact with other existing risks and uncertainties faced by production systems. Simultaneously, some climate-driven changes could result in opportunities.

Key messages from the literature include the need to plan for ongoing shifts in water supply to rangelands, irrigated agriculture, and dryland agriculture. While there is a larger body of work on water supply impacts on irrigated agriculture, knowledge gaps remain, such as understanding the likely additional water demands to supply overhead evaporative cooling used in some cropping systems in response to extreme temperatures. Additional study is also required on impacts on and mitigation strategies for rangeland and dryland systems.

Climate science related to identifying probabilities of exposure to extreme weather events has advanced rapidly over recent years but continues to develop. While this facilitates our ability to better understand likely risks, predicting the exact impacts of extreme weather and ways to adapt remain gaps that warrants further exploration. This includes impact assessments and adaptation studies that are specific to extreme weather-related challenges. Large ensemble datasets and downscaled datasets from regional climate models will support these efforts.

Additional work is also needed to fully understand potential impacts on crop and forage quality, and to pests, weeds, diseases, and beneficial insects including pollinators, given the complexity of interconnected risks. This work must go beyond understanding the impacts of climate change, to identify management strategies to mitigate the deleterious effects.

While climate change presents clear challenges for Washington state's agriculture, there is also the potential that negative impacts may be less severe than elsewhere in the Western US. With successful management of negative impacts, there is the potential that the state could become more important in terms of national agricultural production. There is a strong need for ongoing work that positions agricultural producers at all scales to take advantage of opportunities where they exist, and that proactively identifies and addresses any unintended negative impacts of such strategies.

Adaptive responses to climate impacts across scales

Many climate impacts are unavoidable, and response or recovery efforts are needed alongside climate change mitigation efforts. Unfortunately, robust studies that provide concrete evidence of the effectiveness of climate adaptation solutions for agriculture are scarce. There is a pressing need for additional work evaluating climate adaptation responses, including strategies to prepare for changes in water supply, pest pressures, and in some cases, shifts to novel crops that may be suitable in Washington state's future. Investigation into adaptation should include strategies for state, regional, and local entities as well as for commodity groups and individual farmers and farmworkers.

Some impacts can be avoided or mitigated through implementing farm-scale management practices. Examples of these strategies include adjusting planting dates of dryland crops as growing seasons lengthen ²⁰, or installing shade netting or evaporative cooling for fruit trees to reduce physiological disorders from heat stress ⁶⁶. In some cases, decision-support tools may be key to supporting individual producer adaptation, especially when decisions are complex ⁸³. This may occur through enhancement of existing decision support systems (such as Washington State University's AgWeatherNet or Decision Aid System ¹⁵¹) or the development of new tools (such as StockSmart ^{152,153}). There are also opportunities to implement on-farm practices with multiple co-benefits to producers and the environment. For example, practices that increase soil organic matter can increase the soil's water-holding capacity ^{154,155}, while supporting other essential soil functions and overall resilience. However, it is important to acknowledge the limits of these strategies in terms of their ability to consistently deliver benefits across regions, soil textures, and cropping systems, as well as the barriers to implementing these practices across cultural, social, and economic contexts.

Other adaptation strategies may be most appropriately implemented by people or entities working in support of growers and ranchers. For example, via increased adoption by beekeepers of indoor temperature-controlled hive storage to reduce physiological aging and the consequent increased colony failure risks. Another example is increased education by a variety of agricultural support entities on worker safety requirements (e.g. required acclimatization, rest, shade, and water availability) and strategies (e.g. hydration, light and ventilated clothing), especially in areas that have not historically experienced extremely high temperatures.

Still, other impacts will require solutions that involve shared infrastructure, policy, extensive incentive programs, or other support. These solutions are mostly if not fully outside the decision-space of individual growers and ranchers and would need engagement from a variety of decision-makers. Examples of this type of adaptation include addressing many water supply challenges: aquifer recharge projects, better and earlier drought and seasonal forecasts, supporting effective water markets, shifting the time-of-use rules on water rights, and infrastructure improvements ^{44,78,78,161-165}. Other examples address the need to strengthen institutional responses that prepare for and respond to extreme weather impacts, and to enhance weed, pest, and disease monitoring to respond to changing risks to crops and animals ^{109,166}. Related activity in Washington state includes the establishment of the Agricultural Pest and Disease Response Account that can rapidly distribute funds during an invasive species crisis ¹⁶⁷ and a Drought Preparedness Account to mitigate existing and anticipated drought impacts ¹⁶⁸.

Given the complexity involved, it is important that decision-makers explore the limits of particular adaptation

strategies^{83,156}, as well as the potential unanticipated consequences of the solutions themselves and the trade-offs they pose. For example, Hall et al. (2021, 2024) found that areas with vulnerabilities to changes in surface water supplies frequently coincided with groundwater declines^{44,45}. This convergence suggests that preparing for and mitigating water supply changes must include options beyond switching to alternative water sources.

While climate change is likely to exacerbate existing challenges, it also emphasizes the need for creative, new solutions that holistically support viable, sustainable agricultural systems. Some example areas where new thinking and new solutions are needed include strategies to better manage invasive species on rangelands⁹⁸, or strategies that protect farmworker health without negative impacts on worker earnings, farm profitability, and agricultural viability. In addition, developing adaptation strategies will require enhanced collaboration across entities, and increased research and extension capacity that is production system-specific. Prior stakeholder engagement efforts identified the need for enhanced partnership along the research-extension-practice continuum to explore the economic and environmental costs and benefits of climate change adaptation and mitigation strategies⁸³. Novel methods have been proposed to strengthen extension capacity for supporting local agricultural adaptation planning, such as identifying production practices from other climatic regions to envision Washington's future opportunities and challenges¹⁶⁹. As more examples arise of tried and tested adaptation actions at different scales, and as our understanding of impacts and their relative importance to agriculture continues to improve, entities and individuals in this sector will together make progress toward comprehensively addressing the complex impacts of a changing climate on Washington state's agricultural systems.

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A. Whittemore^a, C.E. Kruger^a, K. Rajagopalan^b, K. Doonan^a, M. Phelps^c, S.A. Hall^a, G. LaHue^d, D.L. Gelardi^e, and G.G. Yorgey^a (2025). Anticipated Climate Impacts on Agriculture in Washington State. In: *Climate Resilience Plan for Washington Agriculture*. D.L. Gelardi^e (Ed.). Washington State Department of Agriculture AGR2-2502-003, pp 89-98 <https://agr.wa.gov/ClimateResilienceWaAg>.

^a Center for Sustaining Agriculture and Natural Resources, Washington State University

^b Department of Biological Systems Engineering, Washington State University

^c Department of Animal Sciences, Washington State University

^d Department of Crop and Soil Sciences, Washington State University



^e Washington State Department of Agriculture. Olympia, WA

