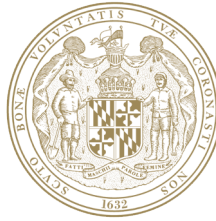


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THE SENATE OF MARYLAND
EDUCATION, ENERGY, AND THE ENVIRONMENT COMMITTEE

Thursday, January 21, 2026

AGENDA

12:30 p.m.

***Briefing on the Maryland Climate-Smart Agriculture Report
(University of Maryland's Harry R. Hughes Center for Agro-Ecology)***

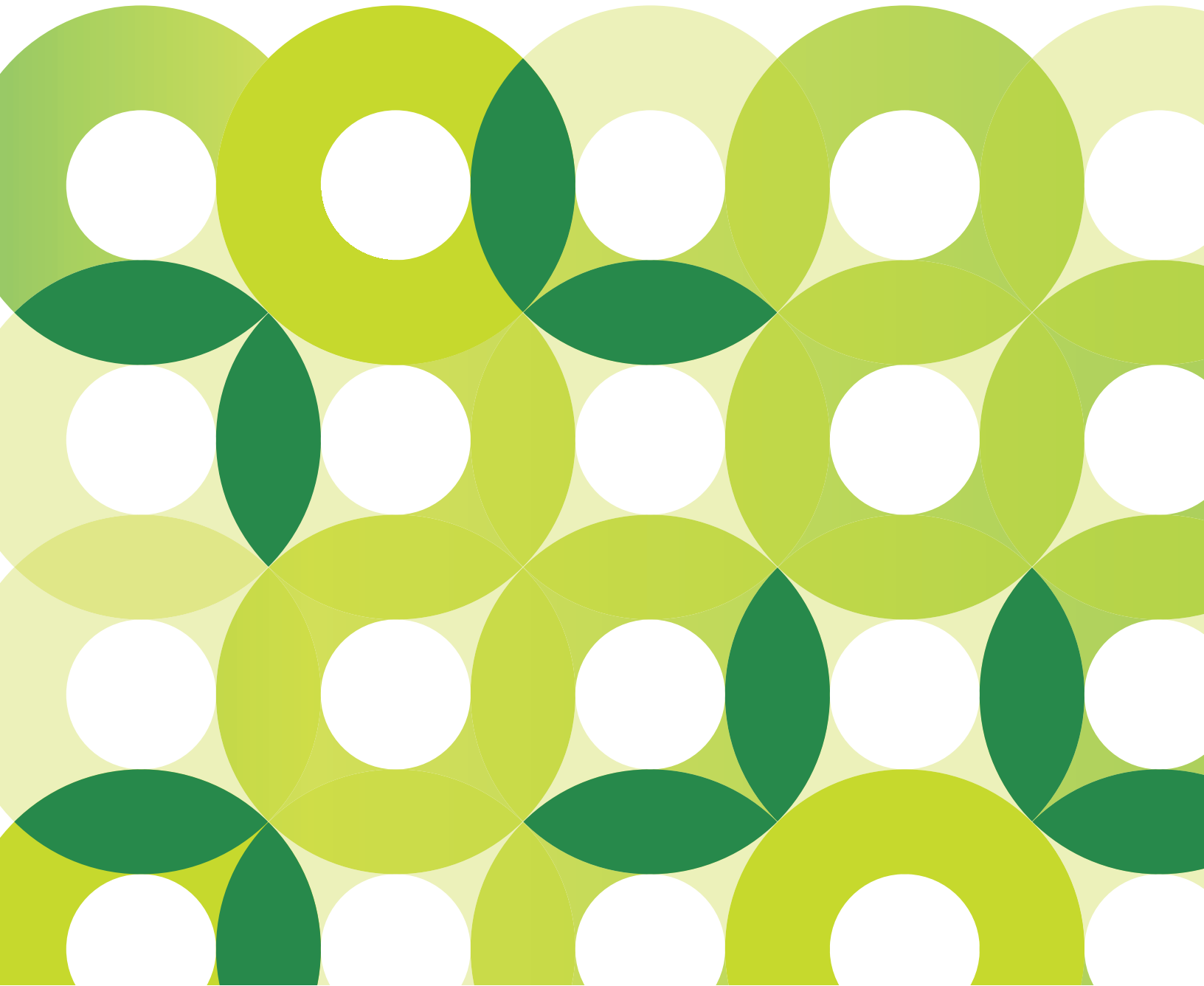
Dr. Puneet Srivastava, *Associate Dean for Research and Associate Director, Maryland
Agricultural Experiment Station*
Ernie Shea, *President, Solutions from the Land and Vice President,
Harry R. Hughes Center for Agro-Ecology*

1:00 p.m.

***Briefing on Federal Policy Implications Affecting Energy and Climate
(Department of Legislative Services)***

Darragh Moriarty, *Senior Policy Analyst, Department of Legislative Services*
Andres Lopez, *Policy Analyst, Department of Legislative Services*

Roadmap to Resilience



COLLEGE OF
AGRICULTURE &
NATURAL RESOURCES



Harry R. Hughes
CENTER FOR AGRO-ECOLOGY



This report was prepared by the Harry R. Hughes Center for Agro-Ecology and the University of Maryland College of Agriculture and Natural Resources (UMD AGNR) with the help of a team of cross-sector partners and was funded by the State of Maryland. Special gratitude goes to the many farmers, technical service providers and trade group representatives who provided feedback along the way.

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List of Acronyms

Best Management Practices (BMPs)	National Agricultural Statistics Service (NASS)
Chesapeake Bay Program (CBP)	National Integrated Drought Information System (NIDIS)
Conservation Reserve Enhancement Program (CREP)	National Oceanic and Atmospheric Administration (NOAA)
Conservation Reserve Program (CRP)	North Central Research and Extension Activity (NCERA)
Conservation Technology Information Center (CTIC)	Northeastern Seaboard Region (NESR)
Corn Disease Working Group (CDWG)	No-till (NT)
Coupled Model Intercomparison Project (CMIP)	Options for Adapting to Rising Seas (OARS)
Cropland Data Layer (CDL)	Project Leadership Team (PLT)
Environmental Protection Agency (EPA)	Shared Socioeconomic Pathway (SSP)
Environmental Quality Incentives Program (EQIP)	Soybean Disease Committee (SDC)
Evapotranspiration (ET)	Standardized Precipitation Evapotranspiration Index (SPEI)
Generalized Logistic (GLO)	Total Maximum Daily Loads (TMDLs)
Integrated Pest Management (IPM)	United Nations Food and Agricultural Organization (UN-FAO)
Leaders in Environmentally Engaged Farming (LEEF)	University of Maryland Center for Environmental Science (UMCES)
Maryland Agricultural and Resource-Based Industry Development Corporation (MARBIDCO)	University of Maryland Eastern Shore (UMES)
Maryland Agricultural Land Preservation Foundation (MALPF)	Wastewater treatment plant (WWTP)
Maryland Agricultural Water Quality Cost Share (MACS) Program	Wetlands Reserve Easements (WRE)
Maryland Commission on Climate Change's Adaptation Resiliency Working Group (MCCC-ARWG)	

Preface

Purpose and Authorization: This report was commissioned by the Maryland State Legislature in 2022 to provide a clearer picture of future climatic conditions and present recommendations to minimize Maryland agriculture's vulnerability and maximize sustainable, resilient, and profitable agricultural production systems in Maryland.

The framework for this report was laid out in a preparatory study commissioned by the Maryland State Legislature in 2021. The Harry R. Hughes Center for Agro-Ecology designed a plan to assess how agriculture in the state of Maryland will be impacted as the climate continues to change. It was conducted in collaboration with a team of climate and agricultural science experts, farmers, and other private stakeholders, state and local agency representatives, and members of land grant and other public universities.

The 2021 study identified six deliverables for the full assessment:

- 01 A science-based description of changes farmers should anticipate** and how projected changes in the state's climate will likely affect soil health and the production of livestock and crops, specifically from temperature, weed, insect, and disease pressure.
- 02 An assessment of policies and programs** that address the impacts of climate change on Maryland's agricultural industries.
- 03 A list of recommendations** to advance new and current state-level public and private sector policies and procedures relevant to agriculture for climate change adaptation and mitigation, including where equity should be evaluated.
- 04 A group of experts created to explore observed and projected climate impacts** on agriculture and generate solutions.
- 05 A plan to communicate ongoing research, programs, and policies** that will help farmers adapt to climate change.
- 06 A system to collect feedback from stakeholders** on their experiences and identify their needs to address climate change impacts.

That 2021 study can be accessed at go.umd.edu/CVAMASStudy.

WHAT THE FUTURE HOLDS IN MARYLAND:

MORE HEAT:

POTENTIAL HEAT STRESS FOR PLANTS AND ANIMALS, SHIFTING PLANT HARDINESS ZONES, NEW INVASIVE PLANTS, AND PESTS.



more days above 86°F by 2026.



Avg annual temp has risen 4–5°F in the last 63 years (5–10°F higher by the end of the century).



Longer, more extreme heat waves.



Declining corn productivity with *more* yield limiting heat days.



28

more nights *above* 68°F means less cooling relief from heat stress to both crops and animals.

DUMP AND DRY CONDITIONS:

DAMAGING STORMS, INCREASED IRRIGATION NEEDS, FAVORABLE CONDITIONS FOR DISEASES AND PESTS.



3.5" more annual rainfall = wet conditions and increased blights, rots, and other diseases.



More intense rainfall and damaging storms, causing erosion and runoff.



More frequent droughts – reducing crop yields and increasing irrigation needs.

SALTWATER INTRUSION:

AGRICULTURAL LAND UNABLE TO SUPPORT CROPS.

31,462 acres affected by 2050 and 43,283 acres by 2070.



Executive Summary

Agriculture is Maryland's largest commercial industry and a cornerstone of both state and national food security.

Beyond producing food, Maryland's agricultural lands deliver vital ecosystem services—from improving soil health and water quality to reducing runoff and supporting biodiversity. Farmers across the state are nationally recognized for their leadership in conservation practices that protect and enhance these natural resources.

However, Maryland's agricultural sector faces mounting challenges. Climate change is altering weather patterns across the state, bringing increased risks of flooding, drought, saltwater intrusion, wildfires and coastal erosion—all of which threaten food production and farm viability. Simultaneously, economic development and population growth are intensifying pressures on land use and natural resource management.

As the breadbasket of the mid-Atlantic, Maryland must rise to meet growing regional and global food demands. But agricultural intensification must be sustainable. This means farming more efficiently, stewarding land and water more effectively, and embracing innovation to adapt to a changing climate. Achieving this will require robust research across diverse agricultural systems to develop adaptive strategies that not only boost yields but also anticipate and mitigate climate impacts over the next 20 to 30 years.

In this evolving federal landscape, Maryland has an opportunity—and a responsibility—to lead. By investing in climate-smart agriculture, the state can continue to set the standard for environmental stewardship and agricultural resilience.

Findings on Climate Change

Climate change is a reality. This report includes a study by a team of multidisciplinary scientists from the University of Maryland (UMD), University of Maryland Eastern Shore (UMES), and University of Maryland Center for Environmental Science (UMCES), who assessed climate change's current and future impacts on agriculture. The Hughes Center also implemented an extensive stakeholder engagement effort and incorporated their on-the-ground perspectives into the recommendations of this report. This report's recommendations result from a combination of those scientific and outreach efforts. This report also recognizes that conditions will continue to change over time due to climate shifts, and practices, programs, and policies discussed within this report will need to be continually analyzed to address the current state.



The Maryland scientists and farmers involved in this study found that currently:

Springs are wetter. Summers are hotter and drier, with more frequent extreme storms followed by droughts. Farmers are contending with flooded fields in spring that threaten livestock and delay plantings, and summer heat that stresses animals and reduces crop yields. False springs have increasingly led to early blooming that negatively impacts fruit production. New pests are migrating from warmer regions, and diseases are finding greater opportunities to thrive under hotter, more humid conditions. Meanwhile, a lack of stress-tolerant varieties of crops and animal breeds limits the ability of farmers to adapt. In addition, some 19,000 acres of farmland on the Eastern Shore are currently threatened by rising sea levels that increase the salinity of soils.



Among numerous other findings, our researchers predict:

- The average annual temperatures across the state will continue to rise, reaching 4°F to 5°F above the last six-decade average by 2060 and 5°F to 10°F by the end of the century.
- Nights will remain warmer, preventing evaporative cooling that can relieve heat-stressed plants and animals.
- Heat waves will grow more extreme and last longer, and over the next 35 years, we will see 37 to 48 more days in which temperatures climb above 86°F, temperatures associated with corn moisture stress.
- Marine heat wave conditions affecting aquaculture are expected to increase more than tenfold by the year 2100 to more than 100 days per year.
- Increasing droughts that result in seasonal water deficits and extreme rainfall events that cause flooding and erosion will also continue to impact water resources and water quality throughout the state.
- On the Eastern Shore, 66% (31,462 acres) more farmland could become threatened by sea level rise over the next three decades, and 128% (43,283 acres) more could be threatened by 2070, relative to 2020 levels.
- Drought conditions increase salinity in tidal systems, increasing the prevalence and intensity of shellfish diseases like MSX and Dermo, while large pulses of freshwater from extreme rainfall can cause mass mortality events.

Climate-Smart Agriculture as a Guiding Principle for Addressing Climate Challenges: What Is Climate-Smart Agriculture?

As Maryland moves forward with new initiatives, we encourage farmers, policymakers, academic institutions, agribusiness partners, non-governmental organizations, and other stakeholders to embrace, enable, and support climate-smart agriculture as it is defined and practiced according to global organizations such as the Food and Agriculture Organization of the United Nations and the World Bank.

Climate-Smart Agriculture is a set of agricultural practices and technologies that work simultaneously to:

- 01** Sustainably increase agricultural productivity and incomes.
- 02** Increase the agricultural sector's resilience in the face of climate-related risks.
- 03** Reduce or offset greenhouse gas emissions and increase carbon sequestration in agricultural lands.

Although climate-smart agriculture is an integration of practices to achieve increased productivity, adaptation, and mitigation of climate change, this farmer-led report focuses on the first two pillars of climate-smart agriculture: productivity and adaptation.

The climate-smart agriculture approach incorporates many of the tools, techniques, practices, and programs that are already employed in the state's existing efforts to address climate change. However, climate-smart agriculture is unique in that it continually considers the best available science to continue meeting productivity, adaptation, and mitigation demands as climate continues to change. It is focused on farmers' abilities to thrive in the face of climate change. Climate-smart agriculture acknowledges the socioeconomic outcomes and benefits for farmers. It also increases the focus on adaptation of existing practices and development of new technologies, like changing planting time recommendations for cover crops, development of climate-resilient crop varieties, identification of crops that grow on salt-intruded lands and precision agriculture, to name a few examples.

Support for best management practices, policies, and programs that help farmers of all scales adapt to and mitigate the effects of climate change must be expanded to ensure the agricultural community continues to thrive. Major issues to be addressed are data gaps, water needs, infrastructure, and resilient crop varieties.

As we work to answer these needs across agricultural sectors, **significant data gaps must be addressed to understand, at the fine scale, what future climate**

conditions will be and how different agricultural systems will respond. For example, more intense rainfall events that result in rapid runoff will make accurate assessments of water availability challenging. At the same time, needs for irrigation are likely to increase, and agricultural water withdrawals from groundwater and surface water resources are likely to become more frequent. Our confined aquifer systems are already being stressed in Maryland due to heavy withdrawals to meet the needs of agricultural irrigation and municipal use. Effective water management will require more accurate assessments of water availability, groundwater use, and the interplay between these factors.

Importantly, the impacts of climate change will vary among communities, as will the downstream effects of various mitigation strategies. It is critical that the state engage with all relevant stakeholders and evaluate the impacts of climate change policies and programs at all levels and across the state, particularly among historically underserved communities that have been left out of such discussions and whose needs have often been bypassed by past policy initiatives. We must ensure that all stakeholders of the agricultural sector have the tools, resources, and voice to influence policies that affect their livelihoods and health.

The challenges ahead will require integrated planning across sectors. The State of Maryland has set ambitious goals for climate pollution reduction, clean waterways, coastal resilience, social justice, and aggressive expansion of renewable energy. An integrated, climate-smart agriculture system builds upon many of the environmental initiatives already being championed by the State of Maryland, including the Governor's Executive Order on Climate, signed in June 2024, which initiated a whole-of-government approach to achieve climate goals while addressing impacts by utilizing all the state's assets, including natural and working lands. This is also evident through the recent initiative under the Governor's Intergovernmental Commission on Agriculture and the Executive Order "Valuing Opportunity Inclusion, and Community Equity" relating to a whole-of-government approach to advance environmental justice and climate action. Supporting climate-smart agricultural practices must be integrated into statewide plans that address all needs to ensure economic prosperity, food security, and environmental sustainability for generations to come.



Overview of Recommendations Based on Science and Stakeholder Feedback:

This report identifies 13 actionable recommendations that should be implemented to help Maryland's agricultural sector sustainably intensify production and mitigate risks.

These recommendations derive from a combination of an extensive feedback process from farmers and stakeholders, and a comprehensive, scientific review of current literature on the impacts of climate change on agriculture. The report details the necessary actions or provides examples of actions that need to be taken to achieve each recommendation and identifies the appropriate responsible parties. Collectively, these recommendations build upon and expand the strategies and actions put forth in the State of Maryland, including through the Maryland Commission on Climate Change Adaptation and Resiliency Working Group Plan and Governor Wes Moore's executive order in June 2025 expanding the Governor's Intergovernmental Commission on Agriculture.

- 01** Adopt Climate-Smart Agriculture and Agroforestry Statewide
- 02** Evaluate and Support Adaptive Management to Achieve Climate-Smart Agriculture
- 03** Integrate the Agricultural Sector into State Preparedness and Response Strategies
- 04** Build an Early Warning System of Climate Impacts on Agriculture
- 05** Create a One-Stop Shop of Climate Adaptation Information for Farmers
- 06** Evaluate and Expand Targeted Climate-Smart Agricultural Education/ Outreach Strategies
- 07** Prioritize and Invest in Academic and Unbiased Scientific Research to Target Information Gaps
- 08** Evaluate and Update Agricultural Best Management Practices to Strengthen Capacity for Adaptation
- 09** Strengthen Monitoring to Track Outcomes, Inform Data Collection, and Address Gaps
- 10** Evaluate, Update, and Fund Conservation Programs that Support Agriculture
- 11** Evaluate Supply Chain and Infrastructure Adaptations Needed to Increase Production
- 12** Conserve Agricultural Land for Agricultural Uses
- 13** Research and Identify Opportunities to Strengthen Farmer Insurance to Protect Against Future Climate Conditions

Introduction

Agriculture is one of the strongest foundational pillars of Maryland's economic and environmental stability.

As the largest commercial industry in the state, agriculture provides approximately \$8.5 billion annually and employs some 350,000 people. Encompassing 32% of the state's total land area, farmland plays a substantial role in the preservation of green space and provides important ecosystem services.

For the health of the economy and food security across the state, the agricultural sector must remain strong, profitable, and sustainable. This means growers will need the support of rigorous science and robust policies, programs, and resources to help them adapt to the conditions on the horizon. In order to adapt to future climate conditions and continue to thrive, Maryland farmers, policymakers, resource managers, and organizations that support agriculture must understand the climate-related changes that are coming and the impacts they will have on agriculture. It is critical to identify gaps in research, outreach, and policy, and to begin to fill these gaps in order to shore up the agricultural sector in Maryland for the benefit of all.

Maryland farmers have proven to be important stewards of our state's natural resources. They lead the nation in conservation practices such as cover cropping and conservation tillage, which involve planting off-season crops and reducing the amount of soil disturbance to control erosion and runoff and improve the health of the soil for later crops. These conservation practices, along with proper nutrient management, the planting of buffers alongside streams, and other farming best management practices, support numerous ecosystem services such as providing habitat for migratory and resident wildlife, enhancing biodiversity and protecting water quality across Maryland. By reducing nutrient and sediment loads into local waterways, agricultural conservation practices contribute to the state's efforts to reach the U.S. Environmental Protection Agency's Total Maximum Daily Load for runoff into the Chesapeake Bay.

The significant achievements of Maryland farmers in leading conservation practices, preserving the state's rural heritage, and underpinning economic prosperity have been made with support from federal and state government, academic institutions, and nonprofit organizations through policy, funding, research, outreach, and education—all built around rigorous science-based recommendations. It is with this same tapestry of players, coordination, and support that the Maryland agricultural sector will advance successfully into the future. Through the findings of this report, farmers will be provided with new options aimed at increasing agricultural resilience in the face of climate change while contributing to climate mitigation. Here, we synthesize findings of scientific studies into more than a dozen key areas, from anticipated climatic conditions to their impacts on specific commodities and with surveys and listening sessions of multiple stakeholders and sector partners to understand what their needs will be and how those needs can be met.

Challenges Ahead: Anticipated Climate Impacts

The research team supporting this study examined the future impacts of climate change on weather and water availability, crop response to heat and drought, animal health from increasing heat and humidity, and potential strategies to reduce stress to poultry and cattle, emergence of new pests and diseases, saltwater intrusion, land subsidence and sea level rise in coastal areas of Maryland, and integrated impacts on Maryland's forests.

This study highlights the urgent need for more data across the board, especially as it relates to understanding and predicting local temperature, rainfall and humidity, crop yield, surface and groundwater availability, and changes in insect pests and diseases, among other key influencing factors.



Weather and Water Availability

Statewide, the number of days with temperatures suitable for growing crops will increase, and so will the number of hot and dry days that stress crops and livestock. In addition, we will see between 28 and 35 more warm nights annually where temperatures do not dip below 68°F, which provides much-needed relief from heat stress to both crops and animals. As conditions vary throughout the state, researchers are challenged to predict where and when these changes will be felt most acutely without finer-scale, local-level data. Some of this data will be provided by the newly initiated Maryland Mesonet program, which is installing 70 networked weather monitoring stations throughout the state.

Additionally, we identified critical gaps in data on rainfall, groundwater, and soil conditions—information that supports irrigation management and decisions on the infrastructure needed to maintain crop yields and water quality.



Crops

Wet conditions were identified as significant drivers of increased diseases in soybean, corn, and wheat—Maryland's three most important row crops. Support for the development of resistant varieties will be crucial to helping farmers mitigate the effects of more frequent rainfall events. In addition, investing in research on automated drainage water management as a conservation practice will allow farmers to better manage their tile drainage systems and conserve water while limiting nutrient loss, protecting local

water quality and the Chesapeake Bay. Extreme and changing weather conditions will bring additional forms of stress to crops, such as heat, drought, early-season cold, and pest pressure. Among all crops studied, there was a lack of robust stress-resistant varieties, which resulted in significant yield declines due to climate stressors. Reduced yields lead to increases in commodity prices and present challenges to dairy, cattle, and poultry producers who rely on Maryland grain for feed. New, stress-resistant varieties are needed to address these concerns.



Poultry and Dairy

In the dairy and poultry industries, adapting to higher temperatures and humidity will require more research into dietary strategies and the development of new heat- and drought-tolerant breeds, as well as education about best management practices for cooling herds and flocks.



Invasives and Pests

Monitoring data on invasive species and changing conditions related to pest pressure is urgently needed. This report identifies temperature as a key factor facilitating the spread and persistence of pests and invasive species, and while integrated pest management is the best method of managing crops, here again, significant gaps in data and monitoring hinder efforts to guide farmers in their pest prevention and management strategies.



Protecting Soil Protects the Farm

Bryan Racine wasn't intentionally building resilience to climate change when he introduced no-till practices and cover cropping to his family farm in Cecil County, Maryland. But, five years later, he says that's precisely what he's done.

"I'm less stressed about the weather," he said. "I feel like I'm adding a little bit of a buffer because my soil is protected. I'm not 100% protected, but I'm not going to lose as much if things get bad." A third-generation farmer, Racine grows corn and soy in rotation and plants a cover crop of rye, rapeseed, and clover in the off-seasons. The cover crop protects the soil from erosion, and the roots help draw rainwater down and nutrients up where his next crop can use them. Racine also leaves crop residue like corn stalks on his fields after harvest, which keeps the sun from drying out his soil and helps rainwater percolate into the ground.

"Bare soil just dries up and washes away," Racine said. "My soil is covered 230 days a year, and all that moisture doesn't just run off. It's there in the soil as a reserve when we get those dry springs." Despite noticeable changes in conditions, like longer hot, dry spells in late summer, fewer long, steady showers, and more heavy, potentially damaging deluges that come after harvest, Racine sees less water damage on his farm today than he did when the family practiced conventional methods. He remembers spending his winters as a boy filling in ditches—some neck deep—where rainwater carved into the fields. Today, he does very little filling in of swales and said he has very little erosion on his farm.

"I don't have the gullies and the washouts like I used to, and I'm not burning as much diesel working the ground. And there's just a lot more variety of birds and bugs and all."

The additional soil moisture has bumped up his productivity, and he also saves money on herbicides because the crop residue and cover crops keep weeds down.

For Racine, preparing Maryland farmers to thrive in the future will require a bigger shift to cover cropping and no-till practices. He would like to see more support for education and assistance in those areas. "Lots of people who have been doing things a certain way for a long time may not change," he said, "but if you can get the young people coming up and new people coming in, that's going to make a difference."



Stress on Water Resources

Increased temperatures will increase evapotranspiration from croplands, thus necessitating more frequent irrigation and heavy groundwater withdrawals from already stressed confined aquifers. This will exacerbate the decline in groundwater levels and will threaten the future sustainability of freshwater in Maryland.



Saltwater Intrusion

On Maryland's Eastern Shore, 18,996 acres of farmland are currently affected by flooding, periodic saltwater inundation or sustained saltwater intrusion due to land subsidence, and sea level rise. These conditions decrease crop yield, and in many cases, have already forced the conversion of cropland into other uses. Our researchers predict that affected farmland will expand to 31,462 acres by 2050 and 43,283 acres by 2070. Substantial research is needed to predict the timing and location of future saltwater intrusion and to develop plans to support farm owners through these changes.



Forests

Maryland's forests and woodlands provide a variety of ecosystem services, including the important role they play in sequestering carbon, filtering and storing water, and enhancing biodiversity. Climate change is already causing declines in forest health as evidenced by the species substitutions that are occurring and the growing negative impacts that invasive species are having across the state.

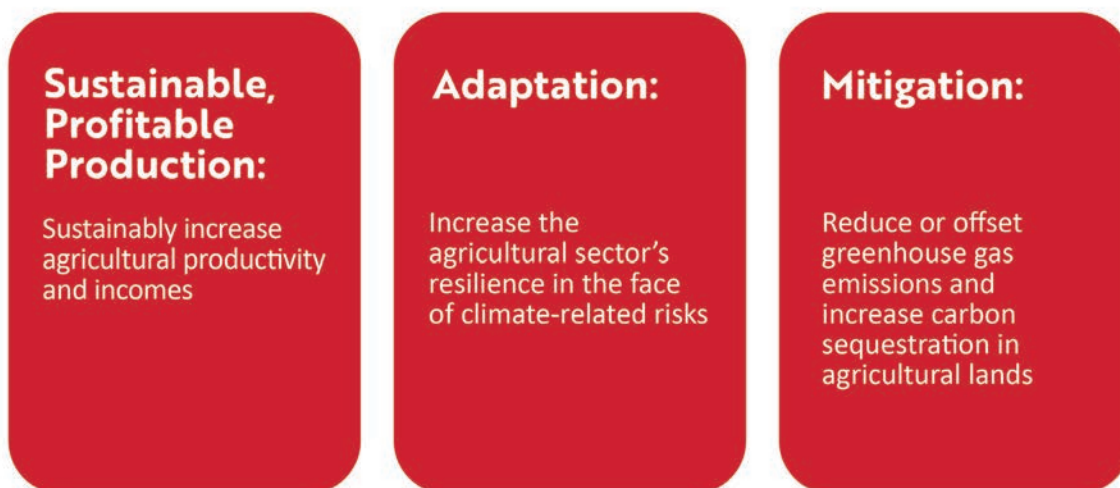
The scope and magnitude of the challenges facing Maryland agriculture are enormous. Prior approaches that address these challenges with siloed response strategies will not be adequate to address the complex and integrated challenges that climate change will create. A path forward informed by science is needed, where climate-smart agricultural approaches are deployed at scale to concurrently achieve multiple outcomes.



An Informed Way Forward

This report is a call to the State of Maryland to embrace the three pillars of climate-smart agriculture and commit to its goals. The specific recommendations in this report serve as a roadmap to achieve this and provide a path toward a more sustainable, climate-resilient future.

Climate-smart agriculture is an integrated approach to managing landscapes—from croplands and livestock operations to forests and fisheries—that addresses the interlinked challenges of food security and climate change. Globally, climate-smart agriculture is recognized as an important strategy for achieving a sustainable future. The approach encompasses a range of practices and technologies that work in synchrony to achieve three goals that can be thought of as the pillars of climate-smart agriculture:



This approach recognizes the complexities of climate stressors and leverages the socioeconomic and ecosystem benefits of a suite of best management practices and climate-smart practices, such as the adoption of heat/stress-resistant crop varieties, precision farming, water management, improved livestock management, and conservation techniques that increase soil moisture, reduce heat and drought stress on crops, and improve soil health.

Current Climate Response Measures

There is much to be proud of in Maryland's response to climate change, especially with regard to reducing pollution.

By 2020, Maryland had reduced greenhouse gas emissions by 30% compared to 2006 levels, and it has since set an aggressive and ambitious goal to further reduce emissions to 60% of 2006 levels by 2031. In 2024, the governor issued an executive order requiring every state agency to create a climate implementation plan and describe how each agency can help achieve the state's climate pollution goals. These initiatives are focused primarily on mitigation of carbon emissions, but the state is also making progress with respect to adaptation and resiliency.

In 2023, the governor established the Maryland Office of Resilience and charged it with developing a statewide resiliency plan and strategy. The Office of Resilience is currently gathering data and input from a broad range of stakeholders, including those in the agricultural sector. In addition, the Maryland Commission on Climate Change's Adaptation Resiliency Working Group (MCCC-ARWG) has developed two important reports to frame the state's actions on climate change.

01

The Climate Adaptation and Resilience Framework Recommendations: 2021-2030 offers a comprehensive list of adaptation strategies and activities to guide the state's efforts across multiple sectors. This Framework lists five goals for Working Lands and Natural Resources-Based Economies: land preservation and restoration, economic development, climate resilient practices, food security, and education and outreach. Within these goals, many of the specific strategies and recommendations incorporate practices that overlap with the recommendations in this report. In fact, the first strategy under Goal 3: Climate Resilient Practices specifically calls on the state to "adopt climate-smart agriculture and forestry statewide." In addition, Goal 4: Food Security calls for implementing "climate smart practices for agricultural and forest lands and working waters, reducing inequity in food supply and distribution chains and expanding technical assistance and support to farmers, foresters, and watermen."

02

The Next Generation Adaptation Plan released in 2024 takes the recommendations from the Framework and lays out a 10-year roadmap with prioritized recommendations and specific timelines for increasing Maryland's resilience to climate change. This report calls for MDA and MDNR to “adopt Climate Smart agriculture and agroforestry statewide by utilizing ecosystem marketplaces where appropriate” and makes important recommendations such as the charge for MDA and MDNR to “encourage innovation and adoption of new technologies to enable farmers, foresters, landowners and watermen to increase sustainability, profitability and resiliency of operations.”

Both of these documents represent a significant step in helping agriculture in our state become resilient and profitable in the face of climate change. Although many of the goals and strategies they call for are important components of climate-smart agriculture, this report provides additional recommendations based on an extensive scientific analysis of climate impacts on Maryland's agricultural sectors and a deep engagement with farmers and agricultural stakeholders to understand their needs and perspectives.

Effectively embracing the globally recognized climate-smart agriculture approach requires a holistic strategy that integrates a full suite of practices. This includes leveraging multiple best management practices and recognizing the important ripple effects and co-benefits that they provide. For example, sustainable farming practices and new technologies that increase productivity and resilience can also result in greater efficiencies that reduce greenhouse gas emissions and help soils retain more carbon and water. In turn, the healthier soils that develop as a result support more diverse ecosystems and increase productivity.

This report supports the State of Maryland's focus on reducing greenhouse gas emissions in the supply chain, developing and supporting healthy soils, and adapting to saltwater intrusion. These complexities must be directly accounted for in the State's efforts to achieve a resilient, climate-smart agricultural sector. While reducing greenhouse gases is an important goal, this farmer-centric report focuses on agriculture remaining sustainable and productive, which will be accomplished through the adaptation of practices that provide resilience to climate change.



Overview of Stakeholder Input

The needs of farmers, farm organizations, and agricultural stakeholders are at the very core of this report.

Over two years, our team conducted listening sessions and interviews with a full range of stakeholders from across the state. We gathered feedback from farmers and 36 partner organizations, including commodity boards and associations, state agencies, nonprofit organizations, and trade partners. Many of the issues that emerged through these sessions echo the concerns identified by the scientific studies, especially with respect to data gaps and coordination of resources, farmer education, and financial support for adaptive measures.

Farmers and stakeholder organizations recognize that the weather is changing and feel frustrated that there is not more data available to predict future conditions at the county and local level. Most are interested in making needed changes to adapt to climate change, but face challenges from multiple fronts.

One of the most important challenges they face is a lack of information about which strategies will work in addressing future climate conditions while also maintaining profitability. Farmers are willing to adopt best management practices (BMPs) that protect the environment and conserve natural resources such as healthy soils and clean water. However, they are concerned about the difficulties of maintaining yields as temperatures continue to rise and extreme events increase. They are eager for more information on the effectiveness of current BMPs under future weather conditions and are looking for guidance and adaptations to BMPs as those conditions change. While they did not express it directly, farmers' concerns about the impact of climate on BMP practices highlight their desire to adopt climate-smart agriculture.

Stakeholders also expressed concern over inadequate assurances of sustained financial and educational support for BMPs and for programs that assist farmers and farm owners in taking new, current, or future adaptive measures. These concerns are magnified by the changing landscape for federal support.

In addition, farmers frequently pointed to a landscape of regulations, assistance programs, and resources that is confusing, uncoordinated, and difficult to navigate. They expressed a strong interest in having a "one-stop shop" solution that would organize and coordinate information from the different technical assistance providers and make accessing available data, financing, and technical support less time-consuming and applications much easier.

Growing Food and the Community with Urban Farming

Urban farmers play a critical role in Maryland's food system. The goals of many of the state's urban farms are rooted in response to community needs and an endeavor to enable societal growth in areas where access to healthy food is often limited.

For the farmers at Plantation Park Heights Urban Farm, the relationship between providing access to food and improving the community has been visible over the decade the nonprofit farm has been operating.

In 2014, Richard Francis, better known as "Farmer Chippy," started farming in his home's yard in the Park Heights area of Baltimore City. Francis is a native of Trinidad and Tobago who, after moving to the U.S., worked as a biomedical field service engineer before landing in his true passion, farming, a profession he's always wanted to pursue.

In Park Heights, Francis looked around and saw hungry and struggling neighbors, vacant lots that sat unused, and communities of people often forgotten in the margins of society regarding education and economic fortitude. As a vegetarian and a man who prefers Caribbean food, with its exotic herbs, peppers, greens, and other vegetables that can be hard to find in the U.S., Francis also looked around and saw that others in his neighborhood were having the same issue of not being able to get the food he was accustomed to, nor did they have reasonable access to healthy food in general.

So, he started growing the food he was accustomed to. Then others in the neighborhood wanted some, too, "so we started giving it away," Francis said.

"We never had the intention to sell the food. I grew up in a community where people care for each other," he said.



Plantation Park Heights Urban Farm was registered as a nonprofit organization in 2017. Over the years, Francis expanded into the vacant lots near his home. More and more community members wanted food, so in exchange, he gave many of them "jobs" on the farm to volunteer and assist in some of the legwork it takes to grow food. It "gave people ownership" of the farm and helped establish a sense of community in the immediate neighborhood.

The farm focuses its efforts on educating not only the adults in its neighborhood who are unfamiliar with agriculture or farming but also the children of the community, who he hopes will grow and start their own farms, providing another pathway and opportunities for city kids from low-income families to be leaders in their own communities.

"It's a three-part project—training children, growing food and growing the community," Francis said. "We want to create an environment that creates work and entrepreneurship opportunities and higher education opportunities for everyone."

Francis now has a team of farmers and people who help with the farm's day-to-day operations and long-term management. They often partner with institutions or grant providers to make the nonprofit operation viable. His farm is involved in several university-level studies, from scientific experiments on rainwater harvesting and biochar to pursuing initiatives like a training institute for prospective urban farmers. "As urban dwellers, urban advocates, we must be involved," he said.

Our team identified a significant need for technical support, new technologies, and resource education among historically underserved populations, especially urban farmers who can help the state build food resiliency and Latinx farmers who represent an important constituency among the Maryland farm community. Among urban growers and farmers, changing weather has not gone unnoticed, but concerns were more often associated with issues related to land access and interactions with landowners and neighbors. It will be important to ensure these producers have access to information and that their voices are represented in decisions about changes to land use and agricultural production practices.

Examples of Current Climate Change Impacts Observed by Farmer Stakeholders:

Among the changing conditions that are already affecting agricultural operations across the state, more frequent heavy downpours are a major concern. Erosion and standing water are significant problems for crops and livestock. Wet conditions, for example, lead to delays in spring planting among soybean and watermelon farmers.

Heat stress impacts all sectors in one way or another. Farm workers require more breaks and greater attention to hydration during heat waves. Among livestock operations, cattle and horse farmers are shifting feeding and grazing schedules to keep animals out of the heat, and sheep farmers are seeing delayed fertility in their herds. Poultry growers are contending with higher humidity and expending more energy to cool poultry houses, especially older structures that may not be adequate to keep poultry cool during hotter summers. Marine heat wave conditions affecting aquaculture are expected to increase to more than 100 days per year, representing a tenfold increase, by the year 2100.

Planting dates for many crops are shifting, and pressure from certain pests and fungal, bacterial and viral pathogens will likely increase. In some cases, as with planting dates, these changes can affect a farmer's eligibility for insurance and assistance programs. For example, the state offers a cost-sharing program for farmers who plant cover crops by a certain deadline. If heavy rains or other conditions delay planting, a farmer will miss out on the payment. Farmers would like flexibility for variable conditions to be built into new programs and regulations that govern farm practices.

Producers and growers are eager to have new varieties of crops and livestock that are more tolerant of heat and resistant to diseases, pests, parasites, and other conditions expected to emerge with hotter temperatures and increasing floods and droughts. Providing these new varieties will require better monitoring to anticipate threats and research and development to produce crops and livestock with the right adaptive qualities.

Report Recommendations Based on Science and Stakeholder Feedback:

1. Adopt Climate-Smart Agriculture and Agroforestry Statewide

The Maryland State government, led by the MDA, along with all agricultural stakeholders and relevant state agencies, must adopt a climate-smart agriculture approach to farming and agroforestry. This approach should be an integral component of Maryland's climate implementation plans from relevant state agencies, as well as a guiding principle in the state's climate resiliency plan and strategy.

That approach prioritizes systems and programs that simultaneously address three outcomes:

- ✓ Sustainably increase agricultural productivity and incomes
- ✓ Increase the agricultural sector's resilience in the face of climate-related risks
- ✓ Reduce or offset greenhouse gas emissions and increase carbon sequestration in agricultural lands

The State of Maryland has prioritized the adoption of climate-smart agricultural and agroforestry practices in its Next Generation Adaptation Plan, which calls for MDA and DNR to utilize ecosystem marketplaces, where appropriate.

As stated earlier in this report, a climate-smart agriculture approach incorporates many of the tools, techniques, practices, and programs that are already employed in the state's existing efforts to address climate change. However, climate-smart agriculture is unique in that it continually considers the best available science to continue meeting productivity, adaptation, and mitigation demands as climate continues to change.

Agroforestry:

Defined as the intentional integration of trees and shrubs into crop and animal farming systems to create productive and sustainable land use practices.

Who could partner in this effort?

Ultimately, the MDA will be the driving force that leads the state to embrace comprehensive climate-smart agricultural approaches. These approaches should be an integral component of Maryland's climate implementation plans from relevant state agencies, as well as a guiding principle in the state's climate resiliency plan and strategy. The Maryland Commission on Climate Change Adaptation and Resiliency Working Group, which has called for the state to implement climate-smart agricultural practices, should more fully embrace the globally recognized definition of climate-smart agriculture, broadening their recommendations to incorporate the full suite of tools and strategies that comprise it, increasing emphasis on supporting farm productivity and profitability, and building resilience in farm operations.

In addition, farmers, nonprofit organizations, research and educational institutions, private agribusinesses, and other stakeholders should prioritize the holistic, integrated approach employed by climate-smart agricultural practices wherever possible.

2. Evaluate and Support Adaptive Management to Achieve Climate-Smart Agriculture

The state and farmers should support crop diversification, incorporate ecosystem services, and encourage and support practices that increase resilience to extreme events such as soil conservation, crop rotation, infrastructure improvements, and whole-landscape and water management practices. Diversification of agricultural products is a powerful tool to manage the risks of loss due to climate conditions. Farmers should be considering new species and new products adapted to future climate conditions and exploring new opportunities for generating on-farm income, such as direct-to-consumer and agritourism or polyculture such as co-production of shellfish and algae.

Researchers, state agencies, and non-governmental organizations should develop crop varieties that are drought and heat-tolerant as well as resistant to emerging diseases and pests. In addition, rapid-growing aquaculture strains that resist disease and tolerate low salinity should be promoted. Although recommended in other sections of this report, it is important to note here that many climate-smart agricultural practices, such as extending crop rotation of corn and soybeans to include wheat and cover crops, are also important components of risk management strategies as they improve soil health and water retention, both of which contribute to a farm's resilience to extreme weather. Diversifying production systems to incorporate ecosystem services such as shade and erosion protection from cover crops and streamside tree plantings can transform the landscape and protect producer incomes in the face of significant changes in climate.

Who could partner in this effort?

MDA, in partnership with industry members and organizations should (as also recommended by the Next Generation Adaptation Plan) develop markets for new agricultural products that are appropriate for current and future climate conditions. This recommendation aligns with efforts by MDA to explore and expand value-added agricultural products.

MDA and other relevant agencies should reduce or remove regulatory and legal bottlenecks for bringing on new agricultural products.

MDA should also support adaptive strategies, such as crop rotations. As also recommended by the Next General Adaptation Plan, state agencies can support the adoption of new technologies through innovative financing or pilot programs that allow opportunities for farmers to access them.

Additionally, this effort could greatly benefit from advancements made in research and adaptive management practices in the private sector.

3. Integrate the Agricultural Sector into State Preparedness and Response Strategies

As state agencies develop their agency-specific climate implementation plans, they should work together with support from MDP to create a statewide plan that integrates Maryland's goals for climate, land use, energy, water, agricultural production, and food systems in a strategic manner that accounts for the impacts and benefits, as well as potential unintended consequences to all communities.

MDA should work closely with the appropriate state agencies and entities to improve the agriculture system's resilience and emergency response, and also relief from climate impacts for agriculture producers. Additionally, the state should develop regional climate action plans to address individual counties' agricultural sector vulnerabilities to climate change and their specific needs.

In order for the state to successfully position itself to adapt to climate change, energy goals, and other issues, state policymakers, agencies, and stakeholders must work together to ensure that policies and programs are compatible. Changes to existing policies and programs may result in the implementation of successful climate adaptation methods. One example would be providing farmers the opportunity to plant orchard trees and therefore take advantage of the financial incentives provided under the state's program to plant 5 million trees by 2031. This change could result in increasing the number of trees planted under the program and provide financial opportunities for farmers.

Preserving Farmland and Building Resilience

Judy Gifford's journey began on a small dairy farm in Connecticut, where her love for cows and agriculture was cultivated. After earning degrees in animal science and public administration, she worked for over 16 years in the public sector, starting as a 4-H Agent, then at the National Institutes of Health and finally on Capitol Hill as staff to a member of Congress and then a lobbyist for the National Milk Producers Federation. As fate would have it, Judy met her husband while working part-time on a dairy farm while employed at NIH. When they had the opportunity to purchase a dairy farm, she gladly left the political world behind to realize her lifelong dream. Judy and her husband, Robert Fry, a bovine veterinarian, purchased 62 acres in Kent County on Maryland's Eastern Shore and established St. Brigid's Farm, aptly named after the patron saint of dairymaids and scholars.

St. Brigid's Farm is home to a purebred herd of Jersey cattle, a breed renowned for its sustainability due to their smaller frame and high milk yield. The farm sells its milk through Land O' Lakes Cooperative, direct markets grass-fed beef, and sells surplus breeding animals to farmers from Pennsylvania to Wisconsin. While many dairy farms have scaled up, Gifford has prioritized sustainable practices that are economically viable and ecologically sound.

"I've always loved the land. I can't stand to be indoors, and I just respect nature," Gifford explains. Her deep connection to the land drives her commitment to preserving Maryland's agricultural resources, which she believes are threatened by large-scale solar energy projects and data centers, warehouses, and distribution centers. "We take our land for granted," Gifford warns. "Once you put concrete in the ground and compact it under solar panels, that farmland is not coming back."

As a Kent Conservation and Preservation Alliance Board of Directors member, Gifford emphasizes that Maryland's fertile land is



invaluable. The state's favorable climate, flat terrain, and proximity to markets make it uniquely positioned to support agriculture, especially as other regions face challenges from climate change. Severe droughts, floods, and saltwater intrusion are reducing agricultural productivity in areas like California and the Midwest. Gifford believes the mid-Atlantic could become America's next "breadbasket" if its farmland is preserved.

To mitigate climate challenges, St. Brigid's Farm employs adaptive grazing, where animals are moved in a manner that best supports the soil food web and plant health. The farm's best management practices (permanent pastures, minimum tillage, buffer strips, fencing off waterways, planting trees, and pollinator habitat) enhance soil and water quality and reduce erosion. Additional sustainable practices include several manure storage facilities managing nutrient levels and irrigating pastures during droughts. Gifford also stores six months' worth of feed as a buffer against extreme weather events.

"The weather has always been fickle," Gifford says. "But it's getting harder to mitigate, and you need more tools. That's where reports and research come in—to give farmers the tools to adapt."

However, Gifford argues that farmers cannot tackle these challenges alone. She highlights a potential rise in the cost of land due to solar leasing, which offers significantly higher lease payments per acre than traditional farming. This drives up rental rates, making it difficult for small-scale farmers to compete.

"Farmers are already on the edge most of the time," Gifford said. "Increasing land costs because of Maryland's solar preference is really scary. If one farm loses its rental land, it creates a ripple effect, driving up costs for everyone else. The farming economy could collapse under this pressure."

Gifford fears that short-term profits from solar development could result in long-term consequences for Maryland's agricultural sector. She calls for a more balanced approach to land use, which values farmland as a critical resource for food security and environmental sustainability.

We commend the commitment of the state agencies and leadership for proposing policies and programs to address the state's agriculture, environment, energy, land use, and water resources issues. To make best use of the state's human and budgetary resources, we suggest the implementation of cross-departmental scans of proposed policies and programs and the engagement of stakeholders during the process. This holistic approach will potentially identify and eliminate conflicts early in the process.

Who could partner in this effort?

In addition to MDA, MDE, and DNR, MDEM and MDP should be leaders at the table for the broad integration effort as part of their charge to develop a "whole of government" strategy and provide state and local governments with tools to plan for and address conjoined and interconnected challenges.

The Maryland Climate Adaptation and Resilience Framework Recommendations and the Next Generation Adaptation Plan both call for the state government to integrate the agriculture sector into state preparedness and planning. Specifically, the Next Generation Adaptation Plan calls for DNR to form "a plan for addressing land retention and aquatic habitat changes that is equitable, inclusive of interests and addresses issues of all affected farmers, foresters, landowners and watermen in the state." It also calls for the plan to "Build on existing climate adaptation and natural resource planning initiatives and programs, and expand partnerships with social services and economic development interests." We encourage the agricultural sector to be involved in creating this plan and help integrate it into the broader state plans managed by various agencies.

As the MCCC-ARWG continues to advise on the state's climate adaptation and resilience strategies, we urge them to fully engage their MDA representative and ensure that this report is integrated into their work. The ARWG should consider drafting a recommendation regarding agriculture for inclusion in the MCCC annual report that is reflective of any ongoing discussions.

4. Build an Early Warning System of Climate Impacts on Agriculture

Maryland State agencies should design and develop a climate early warning program to alert producers to conditions that will compromise or disrupt agricultural productivity. Ensure that existing data is available to stakeholders in relevant and understandable formats and in a user-friendly data portal.

Such a system will require establishing a network of state and regional climatologists and stakeholders from various commodity sectors and developing an official channel for regular communication about the state of key climate threat indicators for Maryland agriculture, such as drought, heat, severe flooding, saltwater inundation, etc. An early warning system will require a public-facing tool, such as a website and perhaps a digital app, to disseminate important climate and weather information to agricultural stakeholders and the community at county-level scales and in timeframes that are

relevant and actionable. For example, an actional item could be the use of real-time data dissemination tools and advice on when to trigger irrigation if drought is predicted to be the problem. Outreach and education campaigns will also be required to inform stakeholders of the new tool and how to use it.

Local data at the appropriate county and smaller levels is needed to develop spatially targeted projections on these key indicators and other climate change impacts. Data scales necessary for agricultural decision-makers must be determined, and where such data are missing, avenues for obtaining them must be explored (see recommendation 6).

Utilize socioeconomic and climate vulnerability mapping tools to identify and prioritize support for the most impacted communities. This can help focus investments and resources on areas with lower incomes, higher unemployment and greater exposure to environmental risks. An example includes the MDE's Climate Vulnerability Score Tool, found at bit.ly/MDclimatescoretool.

In addition to our findings, the MCCC-ARWG also notes in their Adaptation and Resilience Framework the need for a greater understanding of the weather on a local level and an early warning system to notify producers about the impending weather situation. The Maryland Mesonet, a network of more than 70 observation towers currently being built throughout the state, will be instrumental to these efforts. The towers gather real-time weather data for better detection and forecasting of “meso-scale” events such as tornadoes and flash floods, as well as providing data for seasonal climate shifts and longer-term climate changes. Mesonet data can also help forecast needed water resources for the sustainability of agricultural production systems in Maryland and beyond, thus helping the overall resource management.

In addition to MDA, the Maryland Office of Resilience is an appropriate office to help lead and coordinate this effort. The state climatologist and multiple Maryland state agencies will need to be engaged, as well as regional state agencies. The National Integrated Drought Information System's (NIDIS) regional drought early warning systems (DEWS; drought.gov/about/drought-early-warning) can serve as an example for such an effort.

Also, MDA and UMD Extension agents could work in conjunction with the Maryland Office of Resilience to communicate the information to their farmer stakeholders.

5.

Create a One-Stop Shop of Climate Adaptation Information for Farmers

State agencies should work together to create a “one-stop shop” for farmers seeking information about local, state, and federal climate-smart agriculture, conservation programs, financing and data resources to reduce confusion and aid in decision-making. When necessary, these efforts can be supported by nonprofits or in public-private partnerships.

This effort should include the development of a catalog of existing programs and services (e.g., CREP, EQIP, resilience easements, outside opportunities such as Montgomery County Food Council's farmer grant program, etc.) and other opportunities where available. The catalog should identify resources that can support underserved agricultural communities and farmers affected by specific emerging circumstances, such as sea level rise. The "one-stop shop" for farmers should also inform agricultural sectors on the multiple benefits of existing conservation programs, such as addressing soil health, improving biodiversity, and climate adaptation.

One effort currently in development proposes just such a one-stop shop for a subset of the agricultural community. The University of Maryland-funded project titled Options for Adapting to Rising Seas (OARS) is developing a database comparing state, federal, and nongovernmental organization incentive programs available to coastal farmlands and their applicability to farmers impacted by rising sea level, land subsidence, and saltwater intrusion.

The concept of coordinating resources into a one-stop shop has also emerged across multiple state-driven initiatives, including the MCCC-ARWG's Climate Adaptation and Resilience Framework, which recommends the development of an Online Adaptation Hub that provides curated tools and resources to support action and decision-making. With developments in AI and Large Language Models, an AI-driven chatbot feature could make this tool easily accessible to all users. For those with unreliable internet, presentations, extension programs, and other outreach should be made available.

Examples of such a resource that can serve as a model may include Maryland's online hub for licenses, certifications, permits, etc. (onestop.md.gov/) and USDA's farmer incident recovery resource (farmers.gov/protection-recovery).

Who could partner in this effort?

This effort could be owned and operated by MDA through an innovative public-private partnership. One such partnership that may provide useful examples for some elements of a one-stop shop for Maryland agriculture is Wisconsin's water quality trading clearinghouse (wiclearinghouse.org), which aims to reduce pollutants entering waterways by connecting landowners and farmers with potential buyers of water quality credits such as municipal wastewater treatment/stormwater facilities and private industries.

6. Evaluate and Expand Targeted Climate-Smart Agricultural Education/Outreach Strategies

Climate-smart agriculture education and outreach programs should be developed for a variety of communities and audiences, including the subsections of Maryland agriculture to raise awareness and understanding of the benefits of climate-smart practices and to increase support for policy and adoption of these strategies and practices among relevant stakeholders.

Maryland farmland owners and operators are very diverse, including non-operating landlords, multi-generation farmland owners/operators, new and beginning farmers, and historically underserved producers. With the understanding that some communities will be impacted by climate change and by various mitigation measures more than others, targeted outreach to these varied audiences will be important for climate-smart agriculture policy support and adoption of recommended climate-smart practices. All outreach efforts should consider relevant languages and format (digital, print, etc.).

For example, ensure historically underserved members of the agricultural community are protected from the impacts of climate change, such as extreme heat, and have a voice in decisions related to changes on agricultural farmland, including water use policies and solar energy projects.

Many farm workers in Maryland are from under-resourced populations. Ensure that all farm workers have access to safe working conditions, especially in increasing temperatures, and protective regulations against climate impacts. Enforce occupational safety and health standards to protect workers from unsafe working environments related to extreme weather.

LEEF Program:

MDA has established a new tiered incentive program that highlights the conservation and community efforts of Maryland farmers, formed under the Chesapeake Bay Legacy Act called the Leaders in Environmentally Engaged Farming (LEEF) program. This program is an opportunity for information sharing and education about climate-smart practices amongst producers.

Who could partner in this effort?

Targeted outreach and education must be a priority for all entities leading climate-smart agriculture initiatives, including those addressed in all recommendations of this report. Farmer and agriculture representative organizations, along with UMD and UMES Extension, and nonprofits engaged with farmers and agricultural communities should assist agencies in effectively reaching farmers, including those who live in historically underserved communities. The State of Maryland in the MCCC-ARWG's Next Generation Adaptation Plan has also called for MDA and DNR to work with farmers across the state to increase their adoption of soil health and conservation practices.



Prioritize and Invest in Academic and Unbiased Scientific Research to Target Information Gaps

Continue to invest in and conduct research on climate change and the response of agricultural systems. Invest in long-term research and development on climate-smart adaptive measures to ensure agricultural productivity into the future.

It is imperative that Maryland prioritize the continuation and expansion of research that ensures our agricultural systems can continue to support the state's nutritional, environmental, and economic needs. This research should recognize historically underserved agricultural constituencies.

Examples of scientific priorities that were cited in the scientific research report (Appendix 1), include:

- ✔ Develop research that evaluates the overall benefits of climate-smart agriculture to Maryland, including economic and ecosystem service co-benefits that agriculture and individual practices provide, and consumers' views on products produced on farms that have adopted climate-friendly practices.
- ✔ Research and inform farmers about climate adaptability in animal production systems, including dietary alternatives and supplementation to improve yield and increase resistance to pathogens and climate stressors, heat-tolerant breeds, and adaptive cooling technologies and strategies. Support coordinated data gathering around on-farm energy use.
- ✔ Research and inform farmers about climate adaptability in crop production systems, including incorporating crop varieties that are resistant to heat, disease and drought, integrated pest management, methods to improve soil health and carbon sequestration, etc. Support crop breeding for the development of cultivars for dormancy, stress, and drought tolerance.
- ✔ Research practices that reduce pest and physiological stress from changing weather conditions that will occur as the climate changes.
- ✔ Continue research on water management, soil health, and the use of renewable energy in agricultural production.
- ✔ Research silvopasture systems and other agroforestry practices that provide ecosystem services benefits and outcomes and enhance economic sustainability on some farm operations.
- ✔ Support evaluation of silvopasture and agroforestry as BMPs through the Chesapeake Bay Program.
- ✔ Support and improve programs that monitor and remove invasive species from Maryland forests.
- ✔ Support research to evaluate the short- and long-term consequences of alternative adaptation strategies to saltwater intrusion, including how costs, benefits, and environmental outcomes vary depending on location.

- ✓ Develop research on saltwater intrusion's impact on agricultural easements and modify policy to address impacted easements.
- ✓ Research distributed energy production for agricultural and agroforestry operations to assist in the clean energy transition.
- ✓ Research and identify rapid-growing aquaculture strains that resist disease and tolerate low salinity.
- ✓ Research and develop data-driven water resources management for sustainable agriculture considering climate-induced high temperatures that necessitate frequent irrigation events, thus exerting significant stress to freshwater sources in the confined aquifers.

Who could partner in this effort?

In addition to general support for investments in research at the state government level and within MDA, academic institutions, as well as nonprofit organizations and private companies, should also prioritize investments in research.

8. Evaluate and Update Agricultural Best Management Practices to Strengthen Capacity for Adaptation

The following enhancements to BMPs are necessary to move beyond the status quo and embrace a climate-smart agriculture approach. Continue to support and strengthen cost-share programs for best management practices (BMPs) and invest in research to ensure BMPs are appropriate and effective for future conditions. Build flexibility into policies to allow for science-based updates, and support and expand existing training and information programs on BMPs, climate-resilient farming, and sustainable practices.

Given the expected changes in climate and increasing extreme weather events, the feasibility and effectiveness of some current BMPs may change. Pathways for science-based adjustments to existing BMPs and the introduction of new scientifically verified BMPs must be established.

For example, there should be a scientific assessment of the potential impacts of shifting seasonal weather patterns on farming practices such as planting and harvesting dates, which affect cover-cropping programs. An assessment of the impacts of changing precipitation frequency, intensity, and duration on nutrient and sediment loss from agricultural landscapes is also needed to ensure the effectiveness of the BMPs surrounding those issues. BMPs are envisioned to provide multidimensional benefits. For example, cover crops planting between growing seasons helps increase infiltration, reduce runoff and erosion, and simultaneously help enhance the soil health. Research may be needed to determine a mix of soil amendments (e.g., organic

**Spotlight
Butler
Orchard**

Diversification and Adaptation Keep Butler Orchard Growing

“We have absolutely seen climate change,” said Tyler Butler, general manager of Butler Orchard, whose family has been operating in Germantown, Maryland, since 1950. “It’s not about it being super hot; it’s about drastic changes in temperature at different times. The strawberries come sooner than ever, and frost in the spring after a warm spell can ruin the whole crop.”

That’s why it’s been important for the Butlers to lean into diversification; if the strawberries fail, right behind them, he has blueberries and then sour cherries. Come summer, he has flowers, tomatoes, and herbs. There are apples and pumpkins in the fall and Christmas trees in December.

And yet, despite all that variety, their produce only provides 20% of the farm’s revenue. The rest comes from an on-farm market that sells produce, baked goods, and décor (35%) and agrotainment, which includes a festival for every season and on-farm events (45%).

Butler’s grandfather founded the farm with 25 acres of peaches and quickly realized that relying on one source of income was a risk he didn’t want to take. He moved into strawberries, then shifted from wholesale to retail, opening a farm market and adding pick-your-own. And while the Butlers have watched as hundreds of surrounding farms have dwindled to just a few, their operations have ballooned by more than tenfold to encompass over 300 acres of land that produces more than 25 different crops.

They’ve been nimble and adaptive not only to new sources of income, but to new methods and best practices, adopting cover crops and no-till, and working with extension agents to incorporate the latest research findings. And Butler said they are always looking for what’s coming next as the climate changes.



“We have a capital improvements sheet that has a column for sustainability, and right now, we’re looking ahead to future water needs,” he said. “We would love to have a pressurized water system to pinpoint irrigation for efficiency.”

Soil health and increasing soil carbon are also on their radar, so they’ve partnered with a composting program that brings compost to the farm from private individuals who pay to remove it. It may not cover a lot of acreage, but it’s free to Butler, and he feels it’s just another boost to his operation. That kind of innovative, open-minded thinking has been part of the Butler family’s success from the beginning.

As they look ahead to the future, Butler said farmers will need support for things like precision agriculture and other new technologies combined with common-sense regulations.

“One area of question is solar,” he said. “We’re considering it on rooftops, but not on sustainable soil. And I worry about a lot of farmers working land they don’t own. If it becomes more profitable for the landowner to install solar than to grow row crops, we will lose all that production in the State of Maryland.”

He also believes the state needs to grow more table crops, but it can’t be done at the expense of grain production. “We can’t just convert all ag land to table crops, and you can’t tell a conventional farmer he has to switch to lettuce and broccoli suddenly. When making big shifts, we must be smart about these decisions and bring everyone to the table. Maryland farmers have done a great job adapting in the past. We want to be profitable, and usually we’ll make the changes needed if it makes good business sense. “We want to stay in business. We want to be out here working the land. For me and my family, it’s about living the good, green life,” he said.

“We want to stay in business. We want to be out here working the land. For me and my family, it’s about living the good, green life,” he said.

fertilizer and possibly gypsum) that can reduce soil compaction and increase infiltration by establishing soil texture, especially in fine-textured soils. Such practices can not only enhance the soil health but also help to manage water resources while reducing greenhouse gas emissions such as N₂O.

Crop production: Promote cover cropping, no-till or reduced-till farming practices, alfalfa and perennial grass production, crop rotation and diversification, and the development and use of new heat stress, pathogen, and pest-resistant crop varieties as strategies to continue improvements in soil health and farm resilience. Improved BMPs could reduce climate change impacts and greenhouse gas emissions. If improved BMPs are capturing those benefits, then farmers could potentially be paid through conservation finance for practices that provide multiple benefits beyond nitrogen and phosphorus reductions.

Forest management: Invest in enhancements to programs that monitor forest health, increase public and private forest management, and increase private landowner training in forest health management. Healthy forests are an important part of climate solutions pathways because they sequester carbon and mitigate runoff, making proper forest management critical to the state's efforts to address climate change.

New Best Management Practices: Invest in climate-smart agriculture practices at demonstration sites at higher education institutions and state-agency-owned land or research and education centers throughout the state that are open to public outreach.

Who could partner in this effort?

The Chesapeake Bay Program should take up a systematic review of current BMPs to assess their effectiveness under current and anticipated future climate stressors. CBP should also speed up the process for approving new BMPs to reflect climate change and current science. MDA and DNR should allow and encourage testing of innovative new BMP technologies and maintain or increase funding for programming to support BMP adoption. Where CPB approval is required, the organization should prioritize swift and efficient review and approval as recommended above.

DNR, the state's largest landowner, could pilot programs on its land. In addition, the agricultural pilot project sites funded through Maryland's Whole Watershed Act grant program should provide valuable information on the effectiveness of best practices.

USDA National Resource Conservation Service (NRCS), University research and Extension programs, county governments, Soil Conservation Districts, nongovernmental organizations, relevant state agencies, and farmers should collaborate on research to evaluate and update BMPs and promote dissemination of information and increased adoption of BMPs.

9.

Strengthen Monitoring to Track Outcomes, Inform Data Collection, and Address Gaps

Support existing data collection, monitoring, and predictive modeling tools, and develop new ones to fill in data and monitoring gaps and ensure that data is available to stakeholders in relevant and understandable formats.

Accurate, robust data on climate change and agriculture is critical to decision-making at every level from the farm field to the policy desk. Prior to recent reductions in federal support for data collection and sharing, there was a significant need for more data on factors related to climate change and agriculture. Under current federal cuts and restrictions, state agencies, universities, and nonprofit organizations will need to step in to ensure data collection, monitoring, and sharing is maintained for wise and accurate decision-making. Issues that could exacerbate climate-related impacts on the agroecosystem include, but are not limited to, crop diseases, invasive and emerging pests and weeds, soil carbon levels, fertilizer applications, groundwater levels, aquifer withdrawals, etc. Our research report revealed many gaps in data related to these issues that hinder efforts to develop predictive models on the impacts of climate change.

For example, there is inadequate data on groundwater availability, usage, and depletion, and on the impacts of changes in precipitation patterns, drought frequency, and seasonal water distribution on water supply for crop irrigation and livestock needs. Limited USGS data presented by the research team indicate that groundwater levels have declined significantly, ranging from 14 to 72 feet in some aquifers like Aquia, thus necessitating our immediate attention. More data is needed to model the potential impacts of irrigation on groundwater level and sustainability. This gap is also reflected in the MCCC-ARWG Next Generation Adaptation Plan, which calls for an interagency task force to identify and pursue funding for climate-related monitoring and analytical support and long-term water resource planning and adaptation measures. Predictive mapping tools must be developed to address these issues and other regional vulnerabilities. Cornell University's MARISA Climate Data Tools offer some excellent predictive mapping tools, and more are needed to address such things as saltwater intrusion, sea level rise, weather changes, heat stress for crops and livestock, etc.

Furthermore, climate simulations and projections at finer resolutions are needed to accurately capture Maryland's diverse physiographic features.

Data gaps exist throughout the state's agricultural production system. In the poultry industry, for example, Maryland's largest agricultural revenue producer, warmer temperatures could require increases in electricity use for cooling poultry houses and preventing heat stress in birds. In order to identify and monitor the impacts of climate change on poultry production, a comprehensive pooled data system is needed to track electricity and propane use per pound of chicken meat produced in the state.

Proactive management and planning for climate change will require a concerted effort to support and expand a multitude of resources to collect currently unavailable data. For example, N₂O is produced predominantly in fertilized croplands, with additional emissions from manure management, thus gathering data and developing diverse soil amendment data under varying climate conditions suitable for soil health at different scales is a must. Collecting integrated management data useful for climate adaptation and reduction of greenhouse gas emissions under diverse agricultural management practices should be on the state's agenda. Having such data and making it available to those who need it will require strong partnerships between state and federal agencies, research institutions, and private entities. Such partnerships already form the foundations of significant data and monitoring efforts, but they must be strengthened, and new ones will likely be needed. Data collected in this collaborative manner can then be used to make management decisions at field, watershed, and regional scales by developing and using models in concert with the measured data.

Federal and state partnerships support initiatives that states are not well suited to support on their own, such as conducting research, setting minimum standards across state lines, and identifying and tracking pest and pathogen outbreaks. For example, the Chesapeake Bay Program assists in tree assessments in the region using data provided by the EPA, and Maryland's Conservation Buffer Initiative provides incentives for the installation of forest buffers on watercourses through a partnership with the EPA.

In addition to finding new partnerships to fill data gaps, existing partnerships and data gathering efforts must be continued and strengthened. Inflation and stagnant funding levels have already cut into important programs such as the National Plant Diagnostic Center, which was forced to end the "First Detector" program, which trained volunteers in recognizing and reporting invasive pests and diseases. The program helped alert regions to new confirmed sightings of pests and diseases.

Private entities and nongovernmental organizations should also be recognized as a potential resource for data and monitoring support and should be encouraged to participate in private/public partnerships. When not in conflict with USDA protections on business and private information, this data could be shared with academic institutions and scientific researchers to advance climate resilience. To make the collected data useful for all partners in a timely and efficient manner, a state-level data portal should be structured and kept up to date for downloads and synthesis by the partners (state, federal, nonprofits, and stakeholders at large).

Who could partner in this effort?

State agencies such as MDE, MDA, and DNR, in collaboration with the MCCC-ARWG, the state climatologist and state-level academic institutions could, with financial support from the state and federal legislatures, coordinate an effort to ensure comprehensive gathering and monitoring of critical agriculture and climate-related data. The MCCC should factor how agriculture fits into the state's resiliency plan and in its annual report to the state legislature. The state legislature should support the expansion of existing data collection, monitoring and predictive modeling efforts, and the development of new ones. Efforts to fill the data gaps outlined in the research section of this report should be

prioritized. For instance, the agricultural sector and UMD Extension could work together to track and monitor data, then share vulnerabilities with state agencies to assess and prioritize risks adequately.

Maryland Department of Agriculture, University of Maryland-College Park, University of Maryland Eastern Shore, state legislators, farm organizations, nongovernmental organizations, and businesses should advocate for continued and strengthened federal funding for programs, such as the National Plant Diagnostic Network, that provide advanced warning of pathogens and pest outbreaks to farmers and foresters.

As indicated in Recommendation 5, funding should be continued for the Maryland Mesonet, which provides fine-scale climate and weather data throughout the state.

Multiple agencies, research centers, nonprofits, and private entities will be required to contribute to these efforts through data gathering and sharing, data synthesis and model development.

10. Evaluate, Update, and Fund Conservation Programs that Support Agriculture

Maintain and improve funding for current conservation programs and the technical services to support them. Provide grants, low-interest loans, and technical assistance to vulnerable farm operations of all sizes, ensuring they can adapt to sustainable practices without bearing undue financial burdens. Continuously evaluate and improve these conservation programs to ensure they advance conservation strategy goals based on current science and BMPs. Develop new programs to address emerging needs as climate change stresses farm profitability. Analyze the effectiveness of specific conservation programs as climatic conditions continue to shift.

Maryland's support for conservation programs minimizes the financial burdens for farmers who must adapt their practices to thrive in a changing climate, but they also help Maryland meet broader conservation strategy goals. Examples include the Maryland Agricultural Water Quality Cost Share (MACS) Program, which targets water quality improvements to meet the Chesapeake Bay Total Maximum Daily Loads (TMDLs); the Healthy Soils Competitive Fund, which targets the wide range of benefits reaped through improved soil health, such as carbon capture, reduced runoff, increased yields, and improved ecosystem health; and MARBIDCO's shellfish aquaculture financing fund, which provides loans to support commercial aquaculture in Maryland. Climate-specific adaptation and resilience benefits vary among conservation programs, and we recommend that those programs with a climate-related benefit be prioritized.

As the state faces a potential rise in agricultural irrigation demands due to climate change, conservation programs can develop and promote the adoption of climate-resilient water management strategies, such as storage and precision irrigation technologies,

New Old Ways to Build Resilience

For Ron Holter, water management is one key to thriving amid a changing climate. For him, that has meant building up his soil health over the last 20 years. Holter operates Holterholm dairy farm, which has been operating in Jefferson, Maryland, since 1889.

He has seen firsthand how his management practices have buffered him from the impact of drier conditions and extreme rainfall events. "With dryer summers, I'm needing to buy more hay because my cows are 100% grass-fed; they don't get grain," he said. "But the rotational grazing I've been doing over the past two decades has made a huge difference in my land and my bottom line."

In the 1990s, before Holter switched to rotational grazing and regenerative farming methods, dry summers meant his fields were brown and dead. When it rained, water ran off the rolling hillsides. Back then, his family grew Holsteins in a conventional operation, housing his cows in buildings and growing corn to feed them. He switched to rotational grazing in 1996, converting corn fields to pasture, and since then, the organic matter that has built up enables the soil to hold about 40,000 gallons more water per acre. "I've now got grass through the dry season," he said. "It doesn't grow as tall or fast during extreme dry spells, and I may have to supplement to keep the cows productive, but my pastures are still green." The additional organic matter also helps keep water from running off during wet seasons.

Holter also finds his cows seem better adapted to weather conditions and more resilient to the climate shifts he sees on the farm. "It hasn't felt hotter, but the hot spells have been longer. My cows live outside year-round, and we switched from Holstein to Jersey cows, which are smaller, and the heat hasn't been an issue for them so



far." If increasing temperatures become an issue, Holter said he expects to use adaptive measures such as shade mobiles to move around the fields.

For Maryland to build resilience now and into the future, Holter believes new and young dairy farmers and beef producers should be supported with education and training in proper rotational grazing to help them build the kind of healthy, resilient soils that keep productivity high.

"These things are going to really help their bottom line as conditions become more extreme," he said. "We need to inspire, teach, and model how to graze properly, and show that it can be financially and environmentally better."

Any transition involves costs, and rotational grazing requires labor and infrastructure, such as electric fencing, and adaptation to new practices. Still, Holter said that once these practices are established, farmers can cut their costs dramatically by buying half as much grass. It took Holterholm Farm four or five years to see productivity rise after switching to regenerative practices, but today, he feels his farm is healthier, more productive, and more resilient than ever before.

or the reuse of wastewater treatment plant discharges for irrigation. Preliminary research by the scientists and engineers at the UMD, College Park, strongly recommend assessing the adoption of treated water from wastewater treatment plants (WWTP) and consideration of cost-sharing for its adoption. Adoption of practices like the inclusion of the reclaimed water in irrigating nonfood crops can help reduce stress on our already stressed freshwater resources and help Maryland to be water sustainable in the future.

Conservation practices that are more resilient to climate change should be investigated and developed, including new programs that assist landowners with the initial costs of establishing a newly planted forest bank as recommended by the 2022 Technical Study on Changes in Forest Cover and Tree Canopy in Maryland. At the same time, existing programs should be evaluated to ensure maximum effectiveness as BMPs evolve.

Who could partner in this effort?

Federal, state, and local governments; nonprofit organizations; and public or private partners that currently provide and administer conservation programs should ensure they are fully funded and consider strengthening, expanding, or reprioritizing them.

11. Evaluate Supply Chain and Infrastructure Adaptations Needed to Increase Production

Invest in infrastructure needed to sustainably increase and diversify production, such as cold storage, grain elevators, meat processing facilities, irrigation water, and waste management infrastructure.

Increasing agricultural productivity and diversifying into new markets to meet the needs of a growing population while facing the impacts of climate change will require investments in infrastructure beyond what can be supplied by conservation programs and to an extent that will be cost-prohibitive to producers.

Increases in production must come with equivalent increases in infrastructure and services to support that production. For example, significant increases in grain production under climate change may require large investments in irrigation equipment and water management systems.

Likewise, to diversify farm production and income streams to improve farm resilience may require cold storage along with more meat processing facilities. These changes will likely need support from state and federal programs as well as private industry investments. Diversification will mean exploring value-added products and creating new markets, initiatives MDA is embracing.

Who could partner in this effort?

The Maryland congressional delegation should prioritize federal support for infrastructure investments. MDA is the appropriate agency to drive infrastructure and

supply chain adaptations. The agency is currently working to develop statewide guidance for value-added points along the supply chain to increase farmer productivity and profit, and the recommendations in this report support this continued effort and encourage a focus on climate change adaptation.

Industry, private businesses, and local jurisdictions must also commit to investments and policies that ensure infrastructure supports increasing production and is resilient to future climate conditions.

12. Conserve Agricultural Land for Agricultural Uses

There is no climate-smart agriculture without agricultural land. Productive farmland is not only the foundation of our food system—it underpins the health of rural economies, supporting local jobs, small businesses, and community stability across the state. Once farmland is converted to non-production land, it's an irreversible decision that often leads to more development. The American Farmland Trust, in its 2022 report "Farms Under Threat 2040: Choosing an Abundant Future," recognizes Maryland as one of the top 10 states nationwide at risk of losing the highest proportion of its farmland. "Maryland is also among the top 10 states facing farmland loss due to rising sea levels and due to salinization of soils and groundwater which jeopardize many more acres, even before the land is inundated," the report also states. Also, the MCCC-ARWG's Next Generation Adaptation Plan calls for a landscape approach to maintaining agricultural lands, with management actions that support resource-based industries, with a key emphasis on working with community partners.

To date, Maryland has been a national leader in preserving farms and open space conservation. Increased pressure on agricultural lands comes from many development sectors including solar installations, data centers, and housing units. The conversion of farmland to other purposes, such as solar installations, often leads to increases in land lease prices that in turn, force land-leasing, beginning, and long-term tenant farmers out of the marketplaces.

A healthy, resilient agricultural system requires intentional land preservation for agricultural production. Prioritizing land use policies that support farmland preservation and conservation is critical not just for the farmers who rely on land to make a living, but also for the security of the regional and local food system, the environment, and the state economy as a whole. To accomplish this, agricultural leaders or representatives must be included in discussions of research, policy, economics, land use, environmental, and any other on-the-ground implications to ensure that the concerns and perspectives of those who will actually be impacted and who understand the implications have a voice in the long-term viability of our agricultural economy.

Stable, long-term funding for preservation programs such as the Maryland Agricultural Land Preservation Foundation (MALPF), Rural Legacy, and other Program Open Space

funds must be secured and maintained while implementation of land preservation actions move forward. These investments are especially critical for protecting prime farm soils—the most fertile and productive lands that are irreplaceable once lost. (Agricultural lands store carbon in soils and vegetation, buffer against flooding, and provide opportunities to expand adoption of climate-smart practices that reduce greenhouse gas emissions.)

State, county, and local entities should work to keep agricultural lands in production by developing opportunities to expand access to farmland, including urban farmland and farm ownership, over the following decades. Local government and planning offices could also prioritize agricultural preservation at the comprehensive plan level. The State of Maryland should continue funding programs that expand farmland access. There will be some aspects of changing climatic conditions that can reduce agricultural production, like saltwater intrusion in coastal areas of Maryland. Emphasis in such cases should be focused on solutions to maintain agricultural production if an increase is unlikely.

Who could partner in this effort?

The Maryland Department of Agriculture is well positioned to lead this work in partnership with farmers, farm business entities, and nonprofit organizations. The governor's office and the state lawmakers should continue to support and fund agriculture preservation programs and champion them on the state and national stages as a measure to protect Maryland's economy and natural resources. Other state agencies like DNR, MDE, and MDP can play a role in identifying ways to protect agricultural land. UMD and UMES Extension should be ready to work with state agencies to implement educational programs that foster these policies at the community and farm level.

Together, these partners can ensure that farmland preservation is supported, our agricultural economy remains strong and profitable, and our rural landscape is valued.

13. Research and Identify Opportunities to Strengthen Farmer Insurance to Protect Against Future Climate Conditions

Ensure that farmers of all production types are adequately protected against losses due to extreme weather events, including producers of specialty crops and livestock, and, especially, small, underrepresented, and historically underserved farmers.

Evaluate and research crop insurance programs to compensate farmers for losing land to saltwater intrusion and to support interim measures such as shoreline restoration.

The USDA crop insurance programs provide subsidies that make the programs affordable to most farmers. To avoid unnecessarily contributing to the rejection of farmer insurance claims, USDA must update planting dates to reflect changes to the USDA Plant Hardiness Zone Map, as these dates factor into crop insurance policies. Failure to adjust them could impact a farmer's eligibility to receive coverage for losses.

In addition, with increasing extreme weather events, there is concern that insurance costs will become unaffordable to farmers. There is also concern that premium rates for property coverage, especially for infrastructure, will become cost-prohibitive, or that some property insurance providers will refuse to insure, due to extreme climate-related weather impacts. This is emphasized by a new report from the Maryland Insurance Administration, which found that homeowner insurance companies are increasingly refusing to renew policies statewide.

For aquaculture, USDA's shellfish crop insurance is only available for four types of perils, only available in certain counties in certain states, and is limited to containerized stock (so it cannot be used to insure on-bottom aquaculture, which is the majority of leases in Maryland).

Who could partner in this effort?

The state should monitor farm insurance availability and consider subsidizing insurance programs to ensure adequate coverage for all types of farmers, and not only those who grow major commodity crops. The USDA, with support from Maryland's congressional delegation, could help lead efforts at the federal level to strengthen farmer insurance.

Recently introduced state programs that may serve as examples include:

- ✓ **The Delaware Agricultural Production Insurance Assistance Program:**
bit.ly/boostfederalcropinsurance
- ✓ **The North Carolina Disaster Crop Fund:** ncagr.gov



Epilogue

In developing this climate-smart agriculture action plan for Maryland, we intentionally placed farmers at the center of our discussions and decisions.

Rather than taking a traditional government-centric, top-down approach where experts assessed the challenges and developed recommended response strategies, we invited farmers, farm and conservation organizations, and their value chain partners to join us as collaborators and co-creators. Stakeholder input was gathered from farmers, farm organizations, and industry partners representing the full scope of agriculture in the state. The research studies within this report focused on the state's major agricultural commodities. This study's probe into the published literature disclosed an acute lack of scientific data on smaller commodities such as aquaculture, equine, beef, sheep, fruits, vegetables, forestry, honey, and nursery products. Estimated economic impacts of near-future climate changes on Maryland agriculture, including aquaculture, could not be addressed due to resource limitations. Additional efforts should be made to estimate these.

We also made a commitment to everyone who joined this novel, cross-boundary collaborative that our effort extended beyond just writing a report. We have built a multi-stakeholder alliance composed of public and private sector entities that will continue to work together to widely socialize and earn policy and decision maker support for the climate-smart agriculture response strategies developed through these efforts. The Harry R. Hughes Center for Agro-Ecology will remain the focal point and a resource for this collaborative effort. Please join us in our ongoing work to strengthen our state's sustainable farming operations, improve resilience, and revalue the full range of goods and ecosystem services that Maryland agricultural lands deliver.

Climate change will impact all farms indiscriminately. Some will face greater challenges than others, but all will be touched. The good news is that while the climate change challenges we face will be significant, they are not insurmountable. The key to overcoming them is to work together over a long-time horizon, continually adjusting and adapting to changing conditions. Maryland's agricultural history dates back to pre-colonial days, and it has been continually evolving and reinventing itself, harnessing innovation, technology, and entrepreneurial ingenuity to meet the needs of the day.

Maryland farmers have long been at the forefront of change toward better, more inclusive, sustainable stewardship of the land. Our farmers have led the country in adopting conservation practices, and our scientists have driven the technologies to support them. The transition to fully embracing Climate-Smart Agriculture will not require a ground-up rebuilding, but rather a refocusing, and a continuation of the hard work and adaptation our state has been engaged in for decades.

Preparing for climate change, mitigating its effects, and adapting to what's to come is the next step to ensuring that Maryland's environment, natural resources, and economy will continue to thrive with the help of current and future generations of farmers.



Scope & Limitations

This report was based on:

- 01 A series of scientific research reviews** of existing literature on the impacts of climate change on Maryland agriculture and an assessment of the current research projects designed to address these challenges.
- 02 Multi-stakeholder interviews, surveys, and listening sessions** with farmers, aquaculturists, industry organizations and associations, conservation organizations, nonprofits and others, with a broad representation across Maryland counties and agricultural sectors.
- 03 Workshop sessions and meetings of the Project Leadership Team**, with representatives from the Maryland Department of Agriculture, Maryland Department of Natural Resources, Maryland Department of the Environment, Maryland Department of Planning, Maryland Department of Emergency Management, U.S. Department of Agriculture Climate Hub, the University of Maryland-College Park and the University of Maryland Eastern Shore, the University of Maryland Center for Environmental Sciences, agricultural producers, aquaculture representatives, and the nonprofit sector.

Carbon emissions and carbon sequestration, which affect atmospheric greenhouse gas concentrations and are the primary driving forces behind climate change, were excluded from this report. While mitigation is one pillar of a climate-smart agriculture approach, this study focuses more on the other two objectives of a climate-smart agriculture approach: sustainably increased production and adaptation. There are many research teams and organizations investigating ways to reduce carbon emissions through innovative agricultural practices. This report is intended to inform a statewide response to the climatic changes farmers are already seeing today and can expect to see over the coming decades. However, many of the recommendations made here to increase resilience will also contribute to climate change mitigation and produce other ecosystem service benefits, such as improvements to soil health, water conservation, and reductions in agricultural runoff.

The Project Leadership Team guided the direction of the report and synthesis of stakeholder outreach to create the final recommendations. This report represents the most comprehensive, cross-cutting, collaborative effort to date to gather and synthesize an enormous body of understanding on a very broad range of topics. As society tackles the challenge of slowing climate change, this report provides guidance to help the agricultural sector in Maryland adapt, thrive, and increase resiliency amid the changes that have already begun.

Appendix 1: Technical Research Report

Science- and Technology-Based Approach to Minimize Climate Vulnerability and Achieve Sustainable and Resilient Food Production Systems in Maryland

Introduction

The research section of this report presents a comprehensive assessment of historical climate data and future projections, along with assessments and predictions of how these climatic changes will impact land, water, and energy resources, ultimately affecting agricultural productivity and economics.

This report comprises 12 research studies and one stakeholder survey, presented here in four broad categories based on the following research objectives:

Climate and Agriculture Research Objective: Assemble historical and future high-resolution temporal and geospatial climate data (temperature, precipitation, drought, extreme events) for Maryland using a combination of observational data and CMIP6* climate model predictions.

Sector-Specific Impacts Research Objective: Conduct a comprehensive review of the impacts of relevant climate conditions on land, water, and energy resources, and assess their effects on agricultural productivity and economics. Specific topics addressed include carbon sequestration, dairy and poultry production, crop yields under climate stressors, crop diseases and insect pests, stress on water resources, sea level rise and saltwater intrusion, impacts of future climate on corn, and legal considerations of the impacts of climate change on agriculture.

Modeling Vulnerabilities and Opportunities Research Objective: Combine ensemble climate projections with machine learning and regression-based models of agricultural impacts to project future climate vulnerabilities and opportunities for Maryland agriculture.

Stakeholder Engagement Research Objective: Develop stakeholder needs assessments using community-based stakeholder participatory approaches and multi-pronged assessment strategies (e.g., workshops, listening sessions, surveys) developed with the assistance of the Hughes Center Project Coordinator.

**CMIP6: The Coupled Model Intercomparison Project (6th phase) is an international effort overseen by the World Climate Research Programme Working Group for the development and review of coupled climate models aimed at understanding natural climate variability and predictability on decadal to centennial time scales, and predicting the response of the climate system to changes in natural and anthropogenic forcing.*

Summary Findings & Technical Recommendations

The following presents a broad overview of the research findings with specific recommendations made by the research team in each category and sector. These findings and recommendations presented by the individual researchers who conducted each study informed the Project Leadership Team and align with the broader recommendations made in the overall report.

CLIMATE AND AGRICULTURE

Projections for 2031-2060 indicate an increase in annual mean temperatures by approximately 4-5°F and a rise in annual accumulated precipitation by around 3.5 inches compared to the 20th century (1951-2000). These changes will likely extend the growing season and vegetation period, alter growing degree days for row crops, and increase the frequency of hot days, warm nights, heat waves, and extreme precipitation events.

Specific Recommendations:

- **Humidity Data:** Establish consistent humidity-related data to assess its trends and better evaluate the combined impact of humidity and heat on human health and the agroecosystem.
- **Maryland Mesonet:** Support the development of the Maryland Mesonet to provide real-time weather data across the state, including essential parameters like wind speed, humidity, air temperature, barometric pressure, solar radiation, precipitation, and soil moisture, etc. The goal is to have three weather stations per county, with farmers recruited as potential hosts for these stations.
- **Enhanced Climate Simulations:** Obtain climate simulations and projections at finer resolutions to accurately capture Maryland's diverse physiographic features.

SECTOR-SPECIFIC IMPACTS

Carbon Sequestration

Maryland's Climate Pollution Reduction Plan aims to increase soil carbon sequestration in agriculture. While the goals appear achievable, they face significant challenges due to climate change impacts on crop yields, which directly influence soil carbon stocks. Climate-induced changes, including drought, heat waves, and storms, may reduce yields and counteract gains from adopting best practices like no-till and cover crops. Additionally, the loss of agricultural land from urban development and sea-level rise could further reduce soil carbon stocks, exacerbating the issue.

Specific Recommendations:

- **Adaptive Management:** Encourage and support adaptive practices in agriculture to maintain crop productivity, focusing on sustaining high residue inputs to soil, which are crucial for soil carbon stocks.
- **Best Practices:** Incentivize continued adoption of best practices such as cover cropping and conservation tillage, which enhance soil carbon and mitigate losses.

Dairy Production

Ambient temperatures in Maryland have increased by 1-3°F above the historical average since 1971, impacting dairy cow productivity, welfare, and health. High-producing dairy cows are especially vulnerable to heat stress during summer, as they generate significant metabolic heat. Without interventions, productivity losses in Maryland are expected to rise with future temperature increases.

Specific Recommendations:

- **Heat Abatement:** Dairy producers should fully adopt and effectively implement existing heat abatement technologies, including shade, water cooling, and air movement, to improve cow welfare and productivity during hot months.
- **Diet:** Explore and adopt emerging dietary strategies (e.g., Vitamin D3, omega-3 fatty acids, and dietary protein adjustments) to further mitigate the effects of heat stress.

Poultry Production

As Maryland's leading agricultural revenue generator, the poultry industry has implemented technologies to manage optimal temperatures in broiler houses. However, challenges remain in tracking energy use per pound of meat produced and understanding the full impact of temperature changes on poultry health.

Specific Recommendations:

- **Diet:** Add prebiotics and probiotics to broiler diets to increase beneficial gut microorganisms, which can reduce stress, and promote growth under heat stress. Increased levels of amino acids like tryptophan and glutamine in diets may help mitigate the impact of temperature changes on broiler health and performance.
- **Energy Expenditure Data:** Establish a comprehensive pooled data system to track electricity and propane use per pound of chicken meat produced over time in Maryland.

Crop Yield (Abiotic/Climate)

Row crop yields (corn, soybean, wheat, etc.) have increased from 1974 to 2023, while fruit crops (peaches and apples) have declined in both yield and acreage. Despite gains in row crops, the absence of varieties that are tolerant to climate-related stressors has resulted in reduced yields for all crops during periods of drought and extreme temperature. Fruit crops are particularly affected by false springs, which lead to flower drop and yield losses. Maryland's reliance on rainfed agriculture increases vulnerability, underscoring the need for adaptive measures to ensure food security and economic stability.

Specific Recommendations:

- **Breeding:** Invest in breeding programs for drought, heat, and false spring-resistant crop varieties.
- **Irrigation:** Expand and fund efficient irrigation infrastructure, especially in drought-prone areas.
- **Best Practices:** Promote crop rotation, diversification, cover cropping, and no-till or reduced till farming to enhance soil health, structure, and moisture.
- **Farmer Training:** Train farmers in climate-resilient practices, including the use of stress-resistant crop varieties.

- **Financial Support:** Provide financial incentives, insurance schemes, and subsidies for climate-smart agriculture and irrigation systems.
- **Policy:** Advocate for supportive policies and funding at state and federal levels for agricultural adaptation.
- **Monitoring:** Enhance monitoring systems to track climate effects on yields and identify emerging trends.

Crop Damage (Insects)

Maryland's changing climate—characterized by warmer temperatures, altered precipitation, and extreme weather—will likely lead to expanded ranges, increased generations, and more frequent outbreaks of insect pests. Southern insect species are expected to move northward, while milder winters and faster growing seasons will allow some pests to increase in number. However, extreme weather may create mismatches between pests and plant hosts, affecting pest dynamics. Heat stress may benefit certain pests if they are better adapted to it than their natural enemies.

Specific Recommendations:

- **Pest Data/Monitoring:** Establish a consistent, widespread pest monitoring program to track changes in pest phenology and abundance under shifting climate conditions.
- **Integrated Pest Management:** Encourage Maryland farmers to adopt integrated pest management (IPM) and conservation biological control strategies to foster resilience against changing pest pressures.

Crop Diseases (Pathogens)

Maryland's major crops—soybean, corn, and winter wheat—are increasingly affected by crop diseases as temperatures rise and precipitation patterns shift. Recent years have seen the emergence of new diseases and resistant pathogen strains. For instance, tar spot disease, first observed in the Midwest in 2015, was reported in Maryland in 2022 and continues to spread, while new races of soybean cyst nematodes are overcoming resistance genes. Wheat Fusarium Head Blight remains a serious threat, reducing yields and contaminating grains. As climate change intensifies, these diseases are likely to evolve and worsen, emphasizing the need for effective management strategies.

Specific Recommendations:

- **Genetic Resistance:** Adopt genetically resistant crop varieties, the most effective and sustainable method for combating crop diseases.
- **Best Practices/Crop Rotation:** Implement crop rotation, particularly alternating non-host crops with corn and wheat to control Fusarium species and reduce disease risk.

Water Resources and Extreme Events

Maryland's agricultural water use has risen substantially from 1980 to 2022 due to expanding irrigation needs, with a peak of 3.1 billion gallons withdrawn from the Aquia Aquifer in 2019. Simultaneously, extreme precipitation events have become more frequent, causing rapid runoff that challenges accurate water availability assessments. Rising temperatures and evapotranspiration (ET) rates are expected to increase water deficits, underscoring the need for robust water management practices such as efficient irrigation and enhanced monitoring to manage these challenges effectively.

Specific Recommendations:

- **Irrigation & New Varieties:** Invest in efficient irrigation systems, promote water conservation, and develop drought-resistant crop varieties. Use alternate sources of water (e.g., treated wastewater from wastewater treatment plants for irrigation and non-food crops).
- **Seek Cost-Sharing Programs for Adaptive Management Practices:** Seek appropriate sources of funds and devise state-level policy on cost-sharing options for the adoption of alternate sources of water for irrigating non-food crops in Maryland.
- **Groundwater Data/Monitoring:** Address data gaps and enhance water monitoring by developing a regional groundwater model, expanding monitoring networks, and improving data accessibility, particularly for smaller withdrawals and water quality data.

Sea Level Rise, Land Subsidence, and Saltwater Intrusion

Maryland is experiencing rising sea levels and land subsidence that threaten agricultural lands with inundation and saltwater intrusion, particularly on the Eastern Shore, where approximately 19,000 acres are currently at risk. Projections indicate that this figure will increase to 31,462 acres by 2050 and 43,283 acres by 2070. This will reduce the profitability of traditional crops like corn and soy, prompting the exploration of salt-tolerant alternatives and, in some cases, transitioning out of agricultural use.

Specific Recommendations:

- **Research:** Support research on adaptation strategies, evaluating their costs, benefits, and environmental impacts.
- **Resource Catalog:** Develop a catalog of current and future conservation programs (e.g., CREP, EQIP) to aid farmers with saltwater-affected lands.
- **Management Tools:** Improve prediction and mapping tools for proactive management and planning.

Climate Impacts on Corn

The objective was to apply state-of-the-art econometric modeling to examine how Maryland agriculture has been affected by climate since 1950 and to use the models to estimate future impacts based on climate projections from the Coupled Model Intercomparison Project (CMIP). Our modeling projects that all Maryland counties will experience declining corn productivity growth by 2050, particularly on the Eastern Shore, where some counties (Dorchester, Queen Anne's, Somerset, and Worcester) may see reduced yields by mid-century. These declines are driven by increases in corn killing degree days, leading to negative productivity growth by the century's end.

Specific Recommendations:

- **Corn Varieties:** Create corn varieties with greater tolerance to extreme heat to mitigate the impacts of increased heat stress.
- **Irrigation:** Implement careful and efficient irrigation practices to reduce vapor pressure deficits, especially during critical growth stages like silking.
- **Crop Data:** Enhance robust data collection and sharing for important agro-economic crops throughout the state.

Legal Considerations of Climate Impacts on Agriculture

Crucial aspects of agriculture are being harmed by climate change in ways that are difficult to redress in the traditional legal sense. These harms include changes to heat index and weather patterns, groundwater salinization, physical damages from storms, growing zone change, and many other extensive issues. Although there are laws on the books to address those who contribute to environmental harms, a person or entity who has been harmed must have legal standing to bring a case before a court. Current requirements to establish legal standing present many challenges to climate change cases, partly because the traditional standing doctrine was created with a focus on individualized harm and direct causation. However, causation can be difficult to prove, and the impacts of climate change are often felt by all equally and not just by one party individually. Our objective was to review ways to improve the standing of agriculture in these areas to allow for litigation related to the impacts that they will experience.

Specific Recommendations:

- **Redefine Environmental Injury:** Broaden the concept of “harm” to encompass widespread ecological and environmental harms such as loss of biodiversity, disruptions in ecosystems, and degradation of natural resources.
- **Clarify Causation:** Develop a robust evidentiary framework to establish a direct connection between specific human actions, particularly the emission of greenhouse gases, and the broader climatic consequences.
- **Injunctive Emissions Reductions Remedies:** Rather than merely seeking compensation for past harms, the emphasis should be on implementing measures to curtail future emissions and mitigate ongoing environmental degradation.

MODELING VULNERABILITIES AND OPPORTUNITIES

This study aimed to develop predictive models linking historical climate data to agricultural outcomes in Maryland and to use the models to project agricultural outcomes into the future under three SSP (Shared Socioeconomic Pathway) scenarios (low, medium, and high carbon emissions). Predictive models were developed using various machine learning techniques, including Random Forest, Lasso, and Ridge regression, on data collected from 1980 to 2022.

Crop Yield Predictions: The models revealed a strong correlation between precipitation and the yields of corn and soybeans, while temperature was more influential on wheat yields.

Water Withdrawal Predictions: An ANN-Random Forest model was created to predict water withdrawals during the growing season, with key predictors being evapotranspiration (ET) and temperature.

Future Projections: The models forecast varying impacts on crop yields and water withdrawals under various future climate scenarios (SSP126, SSP245, and SSP585), which are critical for adapting agricultural practices to climate change. Results obtained in this project indicated high emission scenarios (SSP585) having the most impact on both crop yield and water resources.

Specific Recommendations:

- **Data:** There is a need for improved data collection, management, and sharing mechanisms to support long-term agricultural research.
- **Collaboration and Funding:** State agencies should collaborate with academic institutions and seek financial support from state legislatures to develop a systematic effort for collecting and managing agroecosystem data and storing data in an accessible and user-friendly format.

STAKEHOLDER ENGAGEMENT

A Qualtrics survey was administered to 229 volunteer stakeholders in the agricultural sector, aimed at understanding their perceptions of current and future climate conditions, adaptive management practices, concerns, barriers to adoption, and perceived opportunities. The survey included a diverse group of respondents from all Maryland counties but was not designed for random sampling or research purposes, meaning the results reflect only the views of those who volunteered.

The survey found that respondents were generally proactive, changing production practices to manage climate-related risks, but the main barriers to adaptation included cost and risk. Common concerns included pests, diseases, and inconsistent growth, with a variety of issues impacting different stakeholders. Potential new opportunities cited by respondents included a longer production season, more cost-share programs, and new market opportunities.

Specific Recommendations:

- **Technical and Financial Assistance:** Providing support to reduce risk and upfront costs could facilitate the implementation of adaptive practices and strategies.
- **Stakeholder Engagement:** Better engagement could yield more reliable information regarding stakeholder needs and attitudes.

Conclusions & Discussions

The findings of the studies presented above underscore the intricate relationship between climate change and agriculture in Maryland. They highlight the urgency of developing adaptive strategies to address the multifaceted challenges posed by climate impacts, while also presenting opportunities for continued innovation and improvement in agricultural practices. Continued research, data collection, and stakeholder engagement are essential for ensuring the resilience and sustainability of Maryland's agricultural sector in the face of changing climate conditions.

Implementation of the recommendations offered under each technical report may help agroecosystem components become resilient to the impacts of climate change now and into the future. In addition, best management practices (BMPs) may need to be evaluated and their strategic outcomes assessed to make food production systems resilient and sustainable under future climate conditions.

For example, current state and federal cost-shared BMPs designed for water quality improvements to meet Chesapeake Bay TMDLs (Total Maximum Daily Loads) will also help with adapting to and mitigating the effects of climate change and reducing global greenhouse gas emissions (Chesapeake Bay Program Science, Restoration, Partnership, 2022/2024, Pickford and Hanson, 2024). These BMPs include practices such as proper crop rotations, nutrient management programs, cover crops, vegetated buffers, riparian zones, and animal waste management practices.

However, previous research by this research team's co-principal investigator, Shirmohammadi, and his collaborators, found that BMPs designed to remediate water quality problems under current climate conditions were insufficient to meet water quality requirements for TMDLs under future climate scenarios (Renkenberger et al. 2017). Their research found that increased annual rainfall and storm intensity will increase the proportion of watershed area needing BMPs, and current hotspots will generate excess amounts of nutrient constituents that will require redesign of existing BMPs. They also pointed out that community-based participatory strategies will likely be required to foster BMP adoption and sustain water quality gains in the Chesapeake Bay region.

In addition, principal investigators Negahban-Azar and Shirmohammadi have been looking at the adoption of treated wastewater from wastewater treatment plants for irrigating non-food crops in Maryland, thus maintaining fresh groundwater for future purposes. This work comes in light of stress in Maryland's confined aquifers since 1985, primarily due to climate stress and the need for irrigation (Paul et al. 2021; Rahaman et al. 2024). A similar approach to rethinking BMPs for all other aspects of agroecosystems may be necessary.

The research team suggests that the State of Maryland, through its legislative agenda, allocate resources to meet the challenges related to data collection, storage, analysis, and management, as well as relevant modeling work to address the knowledge gaps related to the climate impacts on Maryland's agricultural sectors.

REFERENCES

- Paul, M., M. Negahban-Azar, A. Shirmohammadi, and H. Montas. 2021. Developing a Multicriteria Decision Analysis Framework to Evaluate Reclaimed Wastewater Use for agricultural Irrigation: The Case Study of Maryland. *Hydrology* 8(4):18p.
- Pickford, J, and J. Hanson. 2024. Quick Reference Guide for Best Management Practices: Nonpoint Source BMPs to reduce nitrogen, phosphorus, and sediment loads to Chesapeake Bay and its local waters. Chesapeake Bay Program Science, Restoration, and Collaboration Guidance Report, second edition. 184p. (https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/BMP-Guide_Full.pdf).
- Rahman, A., M. Negahban-Azar, A. Shirmohammadi, and Ritesh Karki. 2024. Evaluating the potential of recycled water use for irrigation in southern Maryland: impact on groundwater conservation and crop yield. *Water Supply* Vol 00 No 0, 1 doi: 10.2166/ws.2024.137. IWA Publishing, London, UK.
- Renkenberger, J., H. Montas, P.T. Leishnam, V. Chanse, A. Shirmohammadi, A. Sadeghi, K. Brubaker, A.K. Rockler, T. Hutson, D. Lansing. 2017. Effectiveness of best management practices with changing climate in a Maryland watershed. *Transactions of the American Society of Agricultural and Biological Engineers (ASABE)* 60(3): 769-789. (doi: 10.13031/trans.11691).

Objective I: Climate and Agriculture

CLIMATE CHANGE

Alfredo Ruiz-Barradas

SUMMARY

Agriculture is Maryland's number-one industry; however, it is also one of the main sectors vulnerable to climate change. This collaboration provided the raw climate data for the larger project and an analysis of the climate models' ability to simulate statewide climate-oriented agricultural indices and their projections into the twenty-first century. Future emission pathways indicate that the climatology for the period 2031-2060 will show increased annual mean temperatures by approximately 4-5°F and annual accumulated precipitation by about 3.5 inches above their twentieth century (1951-2000) climatological values of 54.1°F and 42.73 inches. These changes will be reflected in increases in the length of the growing season, vegetation period, modified corn growing degree days, and stress degree days; the number of hot days and warm nights; a slight increase in the number of heat waves and warm night spells (with more night spells than heat waves), and their duration and temperatures; and a slight increase in the number of days with extreme precipitation.

INTRODUCTION

Research on the impacts of global climate change in Maryland is increasingly important as global temperatures continue to set records. Climate change challenges human health, economic growth, and quality of life everywhere. This research, conducted under the umbrella of the Maryland State Climatologist Office, aims to elucidate some of the impacts of climate change that drive local agriculture in Maryland.

The range in Maryland's weather and climatic conditions arises from the state's diverse physiographic features, its eastern placement within the expansive North American continent, the cradling of the Chesapeake Bay with its brackish waters, and its closeness to the Atlantic Ocean. An inherent part of the weather and climate we experience is due to its variability in time and space; this variability, which is the result of the natural interaction in the climate system, is evident through phenomena such as localized thunderstorms, hurricanes, droughts, and global multi-year, multi-decadal, or even multi-century events that might induce, for instance, abnormally wet, dry, hot, or cold seasons or multi-year/decade droughts. And because our planet is not an isolated and inert entity, its climate also has the potential to experience long-term changes in temperatures and weather patterns due to natural changes in solar activity, Earth's orbit, or emissions from volcanic eruptions. Notably, these climatic changes occur very slowly over thousands or millions of years.

However, since the mid-1800s, human activities have been the primary driver of a rapid change in climate due to land-surface alterations and the burning of fossil fuels such as coal, oil, and gas (IPCC, 2023). Increasingly warmer global mean temperatures typically track this change in climate.

Global temperatures are expected to surpass the 1.5-2°C (2.7-3.6°F) warming range by the end of the century unless there are immediate, rapid, and large-scale reductions in greenhouse gas emissions (IPCC, 2023). Regionally, seasonal mean temperatures in Maryland (Figure 1) show warming trends everywhere in the state in every season, with the largest trends over Baltimore City, Piedmont, and Eastern Shore counties. Precipitation trends (Figure 1) are not uniform, with spring and fall largely becoming wetter across the state, while winter and summer show wet trends over portions of the Piedmont, southern coastal plains, and the westernmost part of the state, along with large areas of drying trends over the rest of the state.

The consensus is that climate change's impact will continue to increase in Maryland, affecting all sectors (Boicourt and Johnson 2011). Humans, animals, and plants are sensitive to extreme heat; crops without irrigation and populations without air conditioning are vulnerable to heat waves and warm spells—particularly pregnant women, children, the elderly, and the sick. Prolonged periods without rain and extreme precipitation events are important risks for crops and the general population. Recognizing the scope and scale of these impacts helps us better understand how climate change affects the state.

Maryland's agriculture is the leading industry in the state (USDA 2023) and is one of the main sectors vulnerable to anomalous climate conditions. The observed trends in temperature and precipitation are projected to continue in the twenty-first century (Runkle et al. 2022), with an increased number of hot days and higher temperatures during heat waves (Boesch 2008; MDE 2016), and a small increase in the projected annual precipitation (MDE 2016). However, little is known about relevant physical indicators (Walsh et al. 2020) and climate-oriented agricultural indices in the state, except that the length of the growing season is increasing, beginning earlier and ending later (EPA 2023). A better understanding of the agriculture-climate relationship is only possible with high temporal and spatial resolution climate data.

This collaboration is significant as it provides an initial assessment of the climate models' ability to simulate and project climate-oriented agricultural indices for Maryland statewide into the twenty-first century.

DATA AND METHODS

Given the scale of the state, only a few suitable datasets from observations and climate models were readily available when this research was conducted.

Historical Observed Data

The primary observed data was obtained from NOAA's National Centers for Environmental Information daily dataset, nClimGrid-Daily (Durre et al. 2022), which contains gridded fields of daily maximum, minimum, and mean air temperatures and daily total precipitation amount for the Contiguous United States over a 1/24-degree (~5km×4km) grid from January 1, 1951, to the present. The data also includes consistent statewide and county area averages of the same parameters. The data is designed for climate monitoring and other applications that place event-specific meteorological patterns into a long-term historical context.

Climate Model Data

This data comes from NASA's downscaled climate simulations and projections from Phase 6 of the Coupled Model Intercomparison Project (CMIP6): NASA's Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)(Thrasher et al. 2021, 2022). The data was downloaded for

a domain slightly larger than Maryland (37.125°–39.875° N, 79.875°–74.125° W) on a 0.25° × 0.25° (~28 km×21 km) horizontal grid at daily resolution. This dataset was produced to provide a set of global, high-resolution, bias-corrected climate change projections that can be used to evaluate climate change impacts on processes sensitive to finer-scale climate gradients and the effects of local topography on climate conditions. The downscaled CMIP6 archive includes 35 climate models and Earth system models (ESM) from which the following seven ESMs from leading international research centers were downloaded:

- ACCESS-ESM1-5, Australia
- CanESM5, Canada
- CNRM-ESM2-1, France
- MPI-ESM1-2-HR, Germany
- MRI-ESM2-0, Japan
- NorESM2-MM, Norway
- GFDL-ESM4, USA

This type of model tries to incorporate the interactions of the atmosphere, ocean, land, ice, and biosphere to simulate regional and global climates, including representations of the global carbon cycle, dynamic vegetation, atmospheric chemistry, ocean biogeochemistry and their climate feedbacks (e.g., Heavens et al. 2013).

The experiments obtained from each model were:

- Historical simulations of the twentieth century from 1950 to 2014, where models were forced with observed solar radiation, aerosols, and gases from volcanic eruptions and anthropogenic carbon dioxide concentrations.
- Projections for the twenty-first century from 2015 to 2100 under the following Shared Socioeconomic Pathways (SSPs):
 - > SSP126 scenario. This scenario simulates development under low CO₂ emissions compatible with the 2°C target at the end of the century, assuming climate protection measures are being taken and sustainable development is pursued.
 - > SSP245 scenario. This represents a middle-of-the-road scenario that extrapolates the past and current global development into the future.
 - > SSP585 scenario. This represents the upper boundary of scenarios with high CO₂ emissions from fossil-fuel-driven development.

The daily variables acquired for each model and experiment were:

- Total precipitation
- Maximum surface air temperature
- Minimum surface air temperature
- Mean surface air temperature
- Relative humidity
- Wind speed
- Downwelling solar radiation at the surface

Data Analysis

Only area averages at the state level were used since the resolution of the downscaled CMIP6 models was not enough to properly capture the effects of the western topography and the Bay at county levels. Statewide, area averages of the meteorological variables were calculated with the help of shapefiles from the USGS's USA County Boundaries (USGS 2021). Climate-oriented indices were calculated from the statewide daily data from observations, models' simulations of the twentieth century climate, and climate projections into the twenty-first century for the three Shared Socioeconomic Pathways (SSPs) from the seven models, using 365-day years (the leap day was omitted). The indices and their definitions are as follows:

- **Growing Season Length (EPA, 2023):** The period between the last frost of spring and the first frost of fall, when the minimum air temperature drops below the freezing point of 32°F.
- **Vegetation Period (Tschurr et al. 2020):** The period between the first occurrence of a six-day period with daily mean temperatures above 41°F and the first occurrence of a six-day period with daily mean temperatures below 41°F after the first of July. If no such period occurs after July 1, the vegetation period ends on December 31.
- **Consecutive Dry Days in the Vegetation Period (Tschurr et al. 2020):** The longest yearly period with daily precipitation below 0.04 inches.
- **Growing Degree Days:** The yearly sum of the daily mean temperature above a base temperature (e.g., 50°F).
 - › Modified Growing Degree Days: Maximum and minimum temperatures are modified before calculating the mean temperature of the day; if the maximum temperature is above 86°F, it is reset to 86°F; if the minimum is below 50°F, it is reset to 50°F.
 - › Stress Degree Days: The yearly sum of the daily maximum temperature above a base temperature of 86°F.
- **Hot Days:** The yearly number of days with maximum temperatures above 86°F.
 - › Heat Waves: Two or more consecutive days with maximum temperatures above 86°F. The mean duration and temperature of each heat wave are calculated; these values are used to obtain the mean and maximum durations and temperatures of the heat waves.
- **Tropical Nights:** The yearly number of days with minimum temperatures above 68°F.
 - › Spells of Tropical Nights: Two or more consecutive days with minimum temperature above 68°F. The mean duration and temperature of each warm spell are calculated; these values are used to obtain the mean and maximum durations and temperatures of the warm spells.
- **Extreme Precipitation:** The yearly number of days with precipitation equal to or greater than the 95th percentile of Maryland statewide daily total precipitation. The 95th percentile was obtained for observations and historical model simulations in the period 1951-2000; these values, in inches, are 0.64 for observations, 0.53 for the Australian model, 0.48 for the Canadian model, 0.55 for the French model, 0.57 for the American model, 0.55 for the German model, 0.56 for the Japanese model, and 0.58 for the Norwegian model.

A multi-model mean was calculated for the historical simulations and the three SSP projections, which is considered to represent the most plausible future. Their evolution from 1950 to 2100 is presented next. It must be noted that this analysis focuses on contrasting the results from the low-emission SSP126 pathway with the high-emission SSP585 pathway of the mid-century climatology (2031-2060), where results for the middle-of-the-road SSP245 emissions pathway are similar to the SSP126 pathway.

RESULTS

Analysis of Maryland statewide temperatures and precipitation from the downscaled CMIP6 historical simulations shows warm and season-dependent wet and dry biases (Appendix A). Despite the biases, the observed warming trends are reasonably simulated in the 1951-2014 period, while the observed wetting trends are underestimated by the multi-model mean. The future pathways (SSP126-SSP585) indicate that the climatological annual temperatures in mid-century (2031-2060) will warm by ~4-5°F and at the end of the century (2071-2100) by ~5-10°F above the twentieth century average (1951-2000). Similarly, the climatological annual precipitation will increase by ~3.6 inches in mid-century (2031-2060) and ~4-5 inches at the end of the century (2071-2100) above the twentieth century average.

Under these conditions, the Maryland statewide climate-oriented agricultural indices are presented in figures showing them as departures from the 1951-2000 climatology for the whole 1951-2100 period. The departures from climatology in observations are contained within the envelope of the departures from climatology in the models' historical simulations, although a better display of the uncertainty or model spread would be the 5th-95th percentile. The uncertainty in the projections is assessed from the inter-model standard deviation relative to the multi-model mean (i.e., coefficient of variation; Vavrus et al. 2015).

The Growing Season

Observations from 1951 to 2014 (Table 1) indicate that the average growing season lasts ~205 days, starting on April 8 and ending on October 30. The growing season lasts less in the multi-model mean (~189 days) than in observations, starting later and ending earlier in the year (Table 1). The projected warming indicates that the duration of the climatological (2031-2060) growing season will increase by starting earlier and ending later in the year. On average, it will increase by ~26 days for the low SSP126 pathway and ~32 days for the high SSP585 pathway (Figure 2). Inter-model variability in the duration of the growing season is ~20 and ~19 days for the low- and high-emission pathways (Table 10) indicating approximately 9% uncertainty in the projected changes from both pathways. It should be noted that as the length of the growing season increases, so does the number of frost-free days (Table 10).

The Vegetation Period

Observations from 1951 to 2014 (Table 2) indicate that the average vegetation period lasts ~278 days, starting on February 28 and ending on December 1. The vegetation period lasts more in the multi-model mean (~289 days) than in observations, starting earlier and ending later in the year (Table 2). As in the case of the growing season, which is also temperature-dependent, the projected warming indicates the climatological (2031-2060) vegetation period will also increase on average by starting earlier and ending later in the year. On average, it will increase by ~31 days for the low SSP126 pathway and ~37 days for the high SSP585 pathway (Figure 3). Inter-model variability in the duration of the vegetation period of ~23 and ~25 days for the low- and high-emissions pathways (Table 11) suggests approximately 8% uncertainty in the projected changes.

Dry Spells in the Vegetation Period

Observations from 1951 to 2014 (Table 3) indicate that the average number of dry spells during the vegetation period is ~36, with a mean duration of ~5 days and a maximum duration of ~16 consecutive days. The features of the dry spells in the multi-model mean are very similar to those in observations, with ~36 spells, a mean duration of ~4 days, and a maximum duration of ~13 consecutive days (Table 3).

The climatological (2031-2060) number of dry spells for the three pathways will increase, on average, by ~3 spells; the maximum duration of the dry spells will increase by ~1 day, and their mean duration will not increase (Figure 4). Inter-model variability in the number of dry spells of ~4-5 spells and in the maximum duration of the spells of ~1 day for these pathways (Table 12) indicates approximately 12% and 11% uncertainties in their projected changes.

Growing Degree Days

Observations from 1951 to 2014 (Table 4) show that, on average, the annual modified degree days (GDDF) and stress degree days (SDDF) are ~3843 GDDF and ~148 SDDF. The modified degree days and stress degree days are larger in the multi-model mean (~4260 GDDF, ~252 SDDF) than in observations. The projected warming indicates that the climatological (2031-2060) modified degree days and stress degree days will increase. On average, the modified degree days will increase by ~825 GDDF for the low SSP126 pathway and ~1025 GDDF for the high emissions SSP585 pathway; similarly, stress degree days will augment by ~276 SDDF for the low emission pathway and ~398 SDDF for the high emission pathway (Figure 5). The inter-model variability of ~252 GDDF and ~134 SDDF for the low-emissions SSP126 pathway (Table 13) indicate approximately 5% and 27% uncertainties in their projected changes, while inter-model variability of ~257 GDD and ~147 SDDF for the high-emissions SSP585 pathway suggest roughly 5% and 24% uncertainties in the projected changes.

Hot Days and Heat Waves

Observations from 1951 to 2014 (Table 5) indicate that, on average, the number of hot days is ~42, the number of heat waves is ~9, the first wave starts on May 29, and the last heat wave starts on September 3. Observations (Table 6) also show that, on average, the mean duration of a heat wave is ~4 days, the longest heat wave lasts ~10 days, the mean temperature of a heat wave is ~89.0°F, and the hottest heat wave is ~91.6°F. The projected warming shows that the climatological (2031-2060) number of hot days and heat waves will increase; the heat waves will start early in the year and end later in the year; these heat waves will increase in the number of days they last and in their temperatures. On average, and under the low-emission SSP126 pathway, the number of hot days will increase by ~37 days, the number of heat waves by ~2; the first heat wave in the year will start ~12 days earlier, and the last heat wave will start ~15 days later than they do in the twentieth century climatology (Figure 6); the mean duration and temperature of the heat waves will increase by ~3 days and ~0.7°F, and their maximum duration and temperature will increase by ~14 days and ~1.3°F (Figure 7). Under the high-emission SSP585 pathway, the number of hot days will increase by ~48 days, the number of heat waves by ~1; the first heat wave in the year will start ~16 days earlier, and the last heat wave will start ~19 days later than they do in the twentieth century climatology (Figure 6); the mean duration and temperature of the heat waves will increase by ~5 days and ~0.9°F, and their maximum duration and temperature will increase by ~23 days and ~1.4°F (Figure 7).

It is worth noting that the projections for the end-of-century climatology (2071-2100) indicate that under the high-emission SSP585 pathway, the number of heat waves will be reduced by ~1; however, their mean and maximum durations will increase by ~13 and ~75 days, and their mean and maximum temperatures will increase by ~1.5°F and 3.2°F. The low-emission SSP126 pathway limits the impact of the projected mean and maximum temperatures of the heat waves to 0.9°F and 1.6°F, while the middle-of-the-road SSP245 pathway is close by with increases of 1.1°F and 1.9°F in the mean and maximum temperatures of the heat waves.

The inter-model variability in hot days of ~11 days, heat waves of ~2 waves, maximum duration of the heat waves of ~12 days, and maximum temperature of the heat waves of ~1.6°F for the low-emission SSP126 pathway (Tables 14 and 15) suggest ~13%, ~20%, ~45%, and ~2% respective uncertainties in their projected changes. Similarly, the inter-model variability in hot days of ~12 days, heat waves of ~2 waves, maximum duration of the heat waves of ~16 days, and maximum temperature of the heat waves of ~1.5°F for the high-emission SSP585 pathway (Tables 14 and 15) suggest approximately 13%, 22%, 46%, and 2% respective uncertainties in their projected changes.

Warm Nights and Warm Spells

Observations from 1951 to 2014 (Table 7) show that, on average, the number of warm nights is ~20, the number of warm spells is ~4, the first spell starts on June 29, and the last spell starts on August 16. Observations (Table 8) also indicate that, on average, the mean duration of a warm spell is ~4 nights, the longest warm spell lasts ~6 nights, the mean temperature of a warm spell is ~69.8°F, and the warmest warm spell is ~70.7°F. The projected warming shows that the climatological (2031-2060) number of warm nights and warm spells will increase; the warm spells will start early in the year and end later in the year; these warm spells will increase in the number of days they last and in their mean temperatures. On average, and under the low emission SSP126 pathway, the number of warm nights will increase by ~28 nights, the number of warm spells by ~3; the first warm spell in the year will start ~16 nights earlier, and the last warm spell will start ~19 nights later than they do in the twentieth century climatology (Figure 8); the mean duration and temperature of the warm spells will increase by ~1 night and ~1.4°F, and their maximum duration and temperature will increase by ~7 nights and ~2.4°F. Under the high-emission SSP585 pathway, the number of warm nights will increase by ~35 nights, the number of warm spells by ~4; the first warm spell in the year will start ~17 nights earlier, and the last warm spell will start ~20 nights later than they do in the twentieth century climatology; the mean duration and temperature of the warm spells will increase by ~2 nights and ~1.5°F, and their maximum duration and temperature will increase by ~9 nights and ~2.7°F. (Figure 9)

It is also worth noting that the projected change in the number of warm spells stays relatively the same, in the 3-4 range, through the century in the three pathways. However, the projected change in the climatology at the end of the century (2071-2100) of the mean and maximum durations of the warm spells will increase by ~6 and ~31 nights, and their mean and maximum temperatures will increase by ~2.6°F and 4.7°F under the high-emission SSP585 pathway. The low-emission SSP126 pathway limits the impact of the warm spells' projected mean and maximum temperatures to 1.5°F and 2.6°F, while the middle-of-the-road SSP245 pathway is close by with increases of 1.7°F and 3.0°F in the mean and maximum temperatures of the warm night spells.

The inter-model variability in warm nights of ~12 nights, warm night spells of ~2 spells, the maximum duration of the spells of ~7 nights, and the maximum temperature of the warm spells of ~1.7°F for the low-emission SSP126 pathway (Tables 16 and 17) suggest ~18%, ~18%, ~47%, and ~2% respective uncertainties in their projected changes. Similarly, the inter-model variability in warm nights of ~10 nights, warm night spells of ~2 spells, the maximum duration of the warm spells of ~7 nights, and the maximum temperature of the warm spells of ~1.8°F for the high-emissions SSP585 pathway (Tables 16 and 17) suggest ~14%, ~18%, ~38%, and ~2% respective uncertainties in their projected changes.

Extreme Precipitation

Observations from 1951 to 2014 (Table 9) indicate that the average number of days in a year with extreme precipitation is ~18, with a mean precipitation of ~1.02 inches and a maximum of ~2.16 inches. The multi-model mean has one more day of extreme precipitation, with ~19 days, with a mean precipitation of ~0.83 inches and a maximum of ~1.56 inches. The mean and maximum precipitation of extreme events are smaller in the models than in the observations.

The climatological (2031-2060) number of days with extreme precipitation (Figure 10) will increase by ~3 days for the three pathways, and the maximum precipitation will increase by ~0.16 inches and ~0.22 inches (or 10% and 14% of the 1951 to 2000 climatology ~1.54 inches) under the low- and high-emissions pathways.

The inter-model variability in days with extreme precipitation of ~5 days and maximum precipitation of ~0.40 inches for the low-emissions SSP126 pathway (Tables 18) indicate ~21% and ~24% respective uncertainties in their projected changes. Similarly, the inter-model variability in days with extreme precipitation of ~5 days and maximum precipitation of ~0.38 inches for the high-emission SSP585 pathway (Tables 18) suggests approximately 21% and 21% respective uncertainties in their projected changes.

CONCLUSIONS

This component of the research, as designed for the larger Climate Vulnerability project, had two main objectives: (1) assembling historical and future high-resolution temporal and spatial climate data for Maryland using a combination of observational data and downscaled CMIP6 climate model simulations and projections; (2) generating climate-oriented agricultural indices important in tracking the impact of climate change.

Climate-related Agricultural Indices

The Earth system climate models performed reasonably well in reproducing the observed magnitude of the departures from the climatology in the 1951-2014 period. That is, the observed departures were largely within the envelope of options simulated by the models given by the intra-model variability. It would be unreasonable to expect more than that because the global models are run at spatial resolutions that lack the details to properly simulate the topographic and sea-land effects characteristic of Maryland; along this line, the spatial resolution of the statistical downscaling process was not fine enough for the physiographic needs of the state.

The future pathways indicate that climatological annual temperatures in mid-century (2031-2060) will warm by ~4-5°F and at the end of the century (2071-2100) by ~5-10°F above the twentieth century average. Similarly, climatological annual precipitation in mid-century (2031-2060) will increase by ~3.5 inches and at the end of the century (2071-2100) by ~4-5 inches above the twentieth-century average (1951 to 2000). Under these circumstances, we found the following when comparing the projected climatology for the 2031-2060 period against the twentieth century (1951 to 2000) climatology of the models:

- The growing season in observations lasts ~205 days, starting on April 8 and ending on October 30 (1951 to 2014). The duration of the growing season will increase by ~26 to 32 days under the SSP126–SSP585 pathways by mid-century (2031 to 2060). Uncertainties are approximately 9%.
- The vegetation period in observations lasts ~278 days, starting on February 28, and ending on December 1 (1951-2014). The duration of the growing season will increase by ~31-37 days under the SSP126–SSP585 pathways by mid-century (2031-2060). Uncertainties are approximately 8%.

- The dry spells within the vegetation period in observations are ~36, with a mean duration of ~5 days and a maximum duration of ~16 days. The number of dry spells will increase by ~3 spells, and their maximum duration will increase by ~1 day under all pathways by mid-century (2031-2060). Uncertainties are approximately 12% for the number of dry spells and approximately 11% for the maximum duration of dry spells.
- The modified growing degree days through the year in observations have a mean value of ~3842 GDDF (1951 to 2014). By mid-century (2031-2060), they will increase by ~825-1025 GDDF under the SSP126–SSP585 pathways. Uncertainties are approximately 5%.
- The stress degree days through the year in observations have a mean value of ~148 SDDF (1951-2014). By mid-century (2031-2060), they will increase by ~276-398 SDDF under the SSP126–SSP585 pathways. Uncertainties are approximately 24-27%.
- The number of hot days in observations is ~42 (1951 to 2014). By mid-century (2031-2060), they will increase by ~37-48 days under the SSP126–SSP585 pathways. Uncertainties are approximately 13%.
- The number of heat waves in observations is ~9, starting the first wave on May 29 and starting the last one on September 3 (1951-2014). These waves have a mean duration and temperature of ~4 days and ~89.0°F and maximum duration and temperature of ~10 days and ~91.6°F. The number of heat waves will increase by ~2-1, and the mean duration and temperature will increase by ~3-5 days and ~0.7°F-0.9°F under the SSP126–SSP585 pathways by mid-century (2031-2060). It is important to note that projections for the heat waves climatology at the end of the century (2071-2100) under the SSP585 pathway show a decrease in the number of heat waves (~1) but an increase in their duration and temperatures. Uncertainties are approximately 20-22% for the number of heat waves, approximately 25% for the maximum duration of the waves, and approximately 2% for the maximum temperature of the heat waves.
- The annual number of days with extreme precipitation in observations is ~18 (1951-2014), with a mean precipitation of ~1.02 inches and a maximum of ~2.16 inches. The number of these days will increase by ~3 days by mid-century (2031-2060) in all the pathways, and the maximum precipitation will increase by 10-14% of their twentieth century climatological value under the SSP126–SSP585 pathways. Uncertainties are ~21% for the number of days with extreme precipitation and approximately 21-24% for the maximum precipitation.

CHALLENGES

This research had such an extensive scope that it was challenging to obtain all the relevant data one could wish for and the time to do it. Consistent high-resolution data from observations, model simulations, and projections were not widely available at the start of the project. The observed data from NOAA had the temporal and spatial resolution needed for this project but did not provide additional important parameters such as humidity, solar radiation, or winds. In addition, because this product provides consistent averaged data on 5x4 km² cells from a heterogeneous station network, extreme values tend to be underestimated when compared to the closest observing station. On the other hand, while the downscaled CMIP6 model data provided all the needed parameters at the daily resolution, the spatial resolution was not sufficient to properly incorporate topographic and Bay effects. One year later, no new climate products are available that can improve what we already have.

Due to limited project time and funds, we were unable to download more models, analyze deeper the middle-of-the-road SSP245 emissions pathway, and address uncertainties.

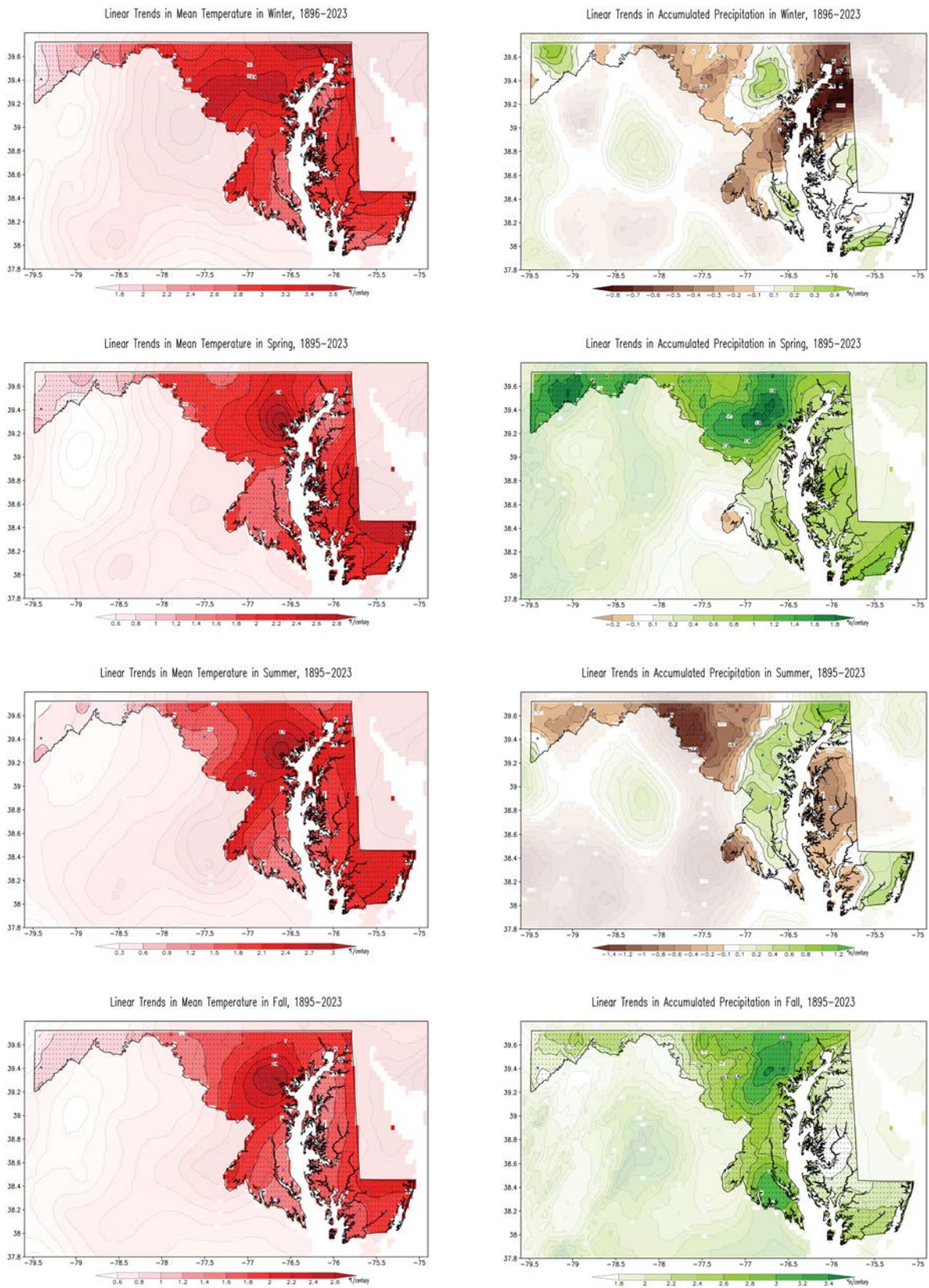


Figure 1. Linear trends in seasonal surface air temperature (left) and accumulated total precipitation (right) for the period 1895-2023. Seasons are defined by the common three-month meteorological definitions as follows: Winter (first row from top) includes December, January, and February; Spring (second row) includes March, April, and May; Summer (third row) includes June, July, and August; Fall (bottom row) includes September, October, and

November. Temperatures are in °F per century, and precipitation is measured in inches per century as indicated by the color bars. Red shading in the temperature map marks warming trends. Brown and green shading in the precipitation map shows drying and wetting trends respectively. Stippling in the maps shows regions where trends are statistically significant at the 95% level. Filled blue circles mark the county seats. Data from NOAA's NCLimGrid product at monthly resolution (Durre et al. 2022).

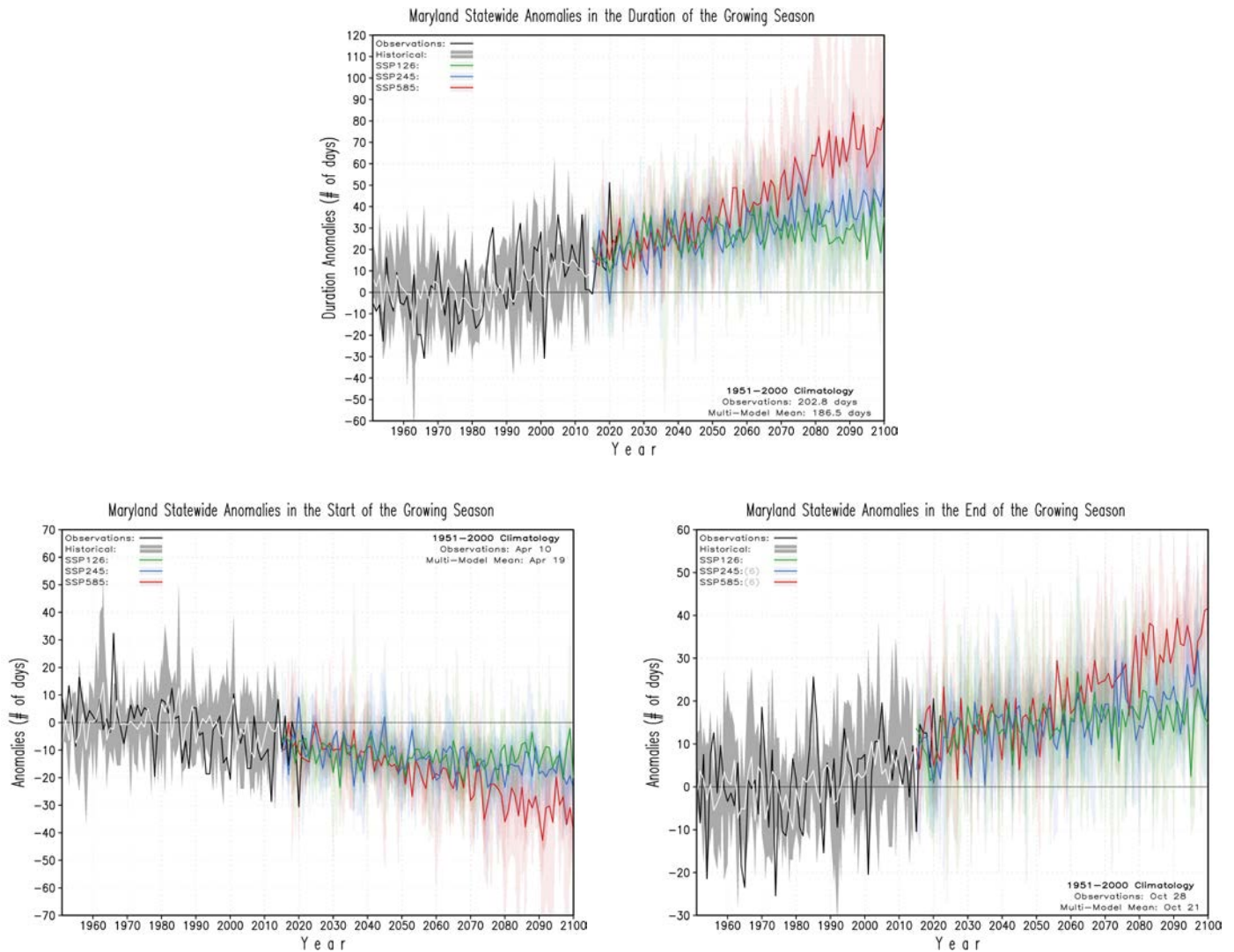


Figure 2. Anomalies in the growing season in Maryland statewide from observations and CMIP6 historical simulations and projections for the period 1950-2100. Anomalies are with respect to the common 20th century period 1951-2000. Panels show the duration of the growing season (upper), the start of the growing season (bottom left), and the end of the growing season (bottom right). Observations for the period 1951-2022 are shown with a black line; the multi-model mean of historical simulations for the period 1950-2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of the SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate that the growing season lasts ~203 days, starting on April 10 and ending on October 28, while the multi-model mean characterizes it as ~187 days in duration starting on April 19 and ending on October 21.

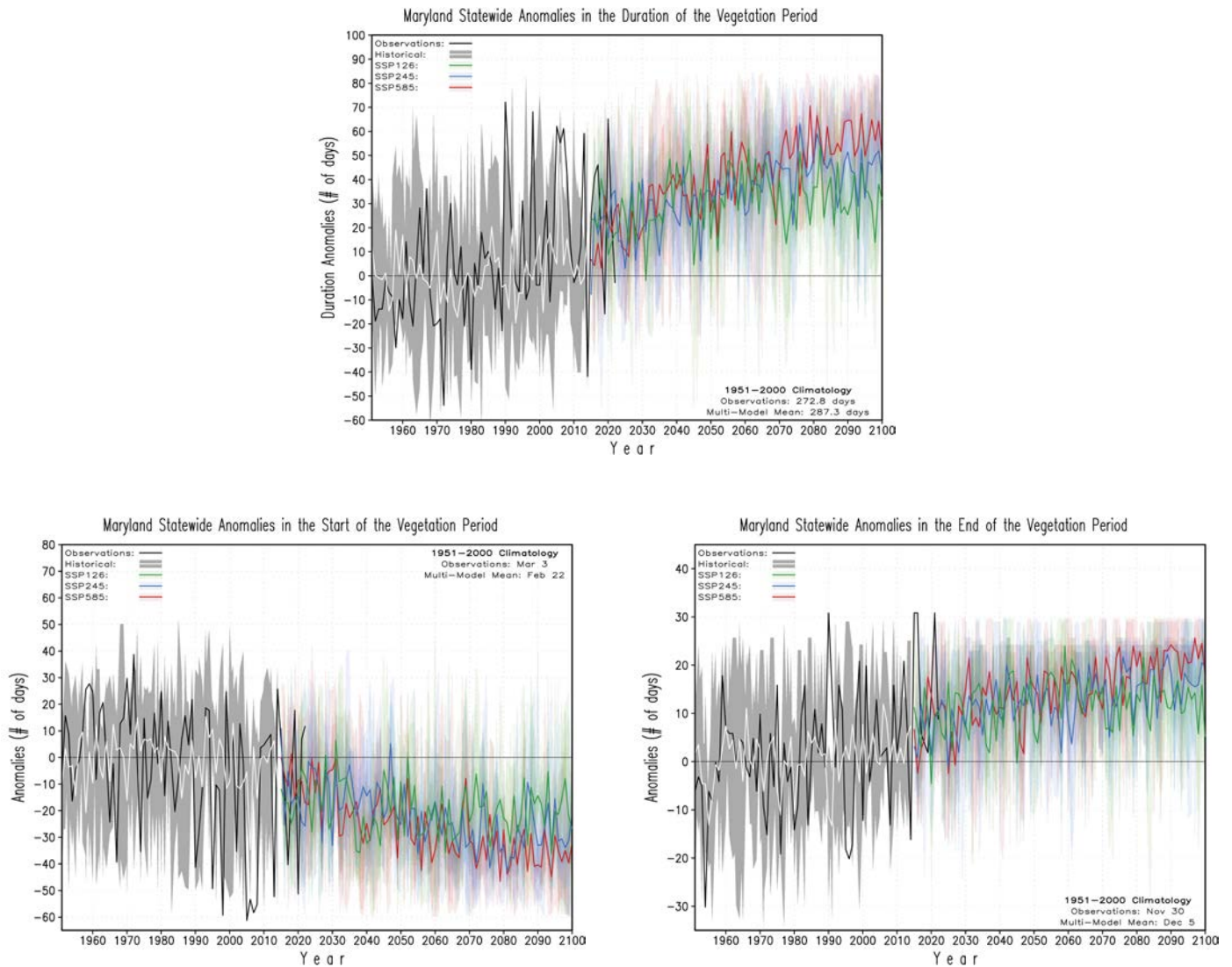


Figure 3. Anomalies in the vegetation period in Maryland statewide from observations and CMIP6 historical simulations and projections for the period 1950-2100. Anomalies are with respect to the common 20th century period 1951-2000. Panels show the duration of the vegetation period (upper), the start of the vegetation period (bottom left), and the end of the vegetation period (bottom right). Observations for the period 1951-2022 are shown with a black line; the multi-model mean of historical simulations for the period 1950-2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of the SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate that the vegetation period lasts ~273 days, starting on March 3 and ending on November 30, while the multi-model mean characterizes it as ~287 days in duration starting on February 22 and ending on December 5.

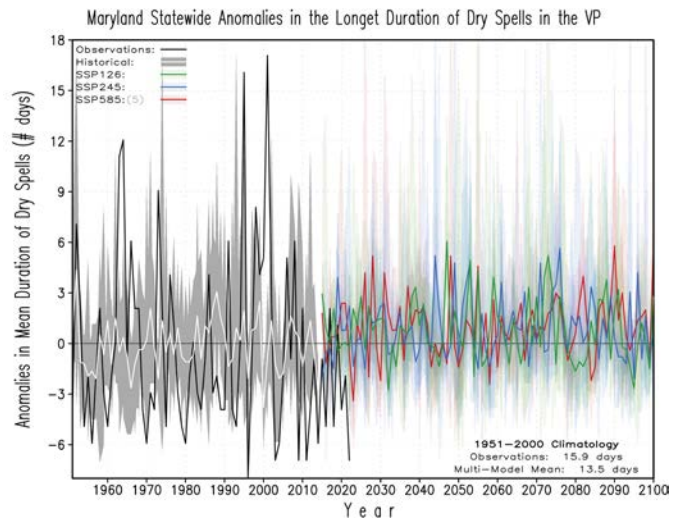
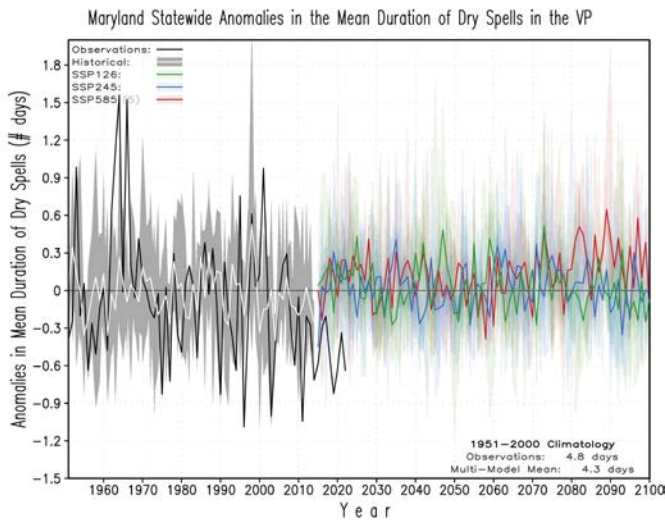
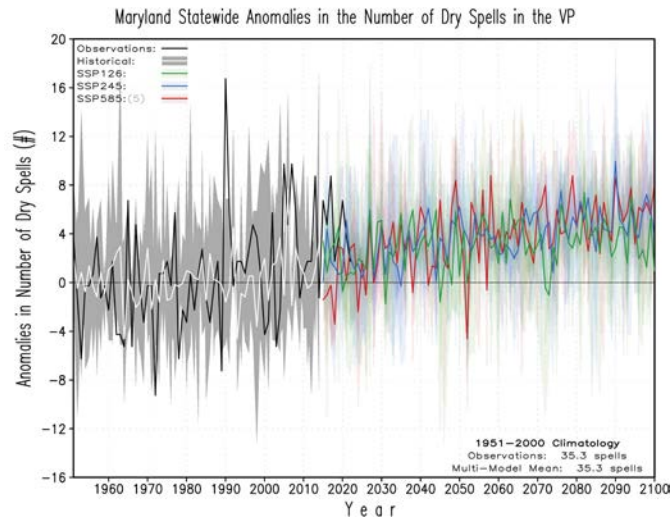


Figure 4. Anomalies in dry spells (consecutive days with precipitation less than 0.04 in) within the vegetation period in Maryland statewide from observations and CMIP6 historical simulations and projections for the period 1950-2100. Anomalies are with respect to the common 20th century period 1951-2000. Panels show the number of dry spells in the vegetation period (upper), the mean duration of the dry spells in the vegetation period (bottom left), and the longest dry spell in the vegetation period (bottom right). Observations for the period 1951-2022 are shown with a black line; the multi-model mean of historical simulations for the period 1950-2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of the SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate there are ~35 dry spells per year with a mean duration of ~5 days and a maximum duration of ~16 days, while the multi-model mean characterize them as ~35 dry spells per year with a mean duration of ~4 days and a maximum duration of ~14 days.

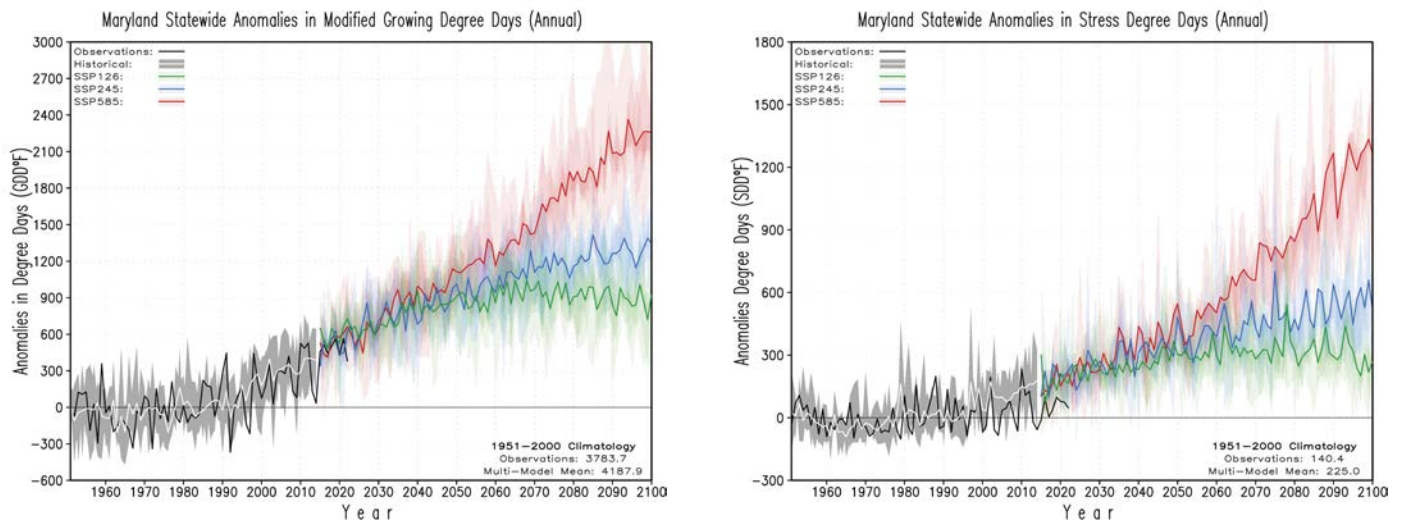


Figure 5. Anomalies in the annual modified degree days (upper panel) and stress degree days (lower panel) in Maryland statewide from observations and CMIP6 historical simulations and projections for the period 1950-2100. Anomalies are with respect to the common 20th century period 1951-2000. Observations for the period 1951-2022 are shown with a black line; the multi-model mean of historical simulations for the period 1950-2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of the SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate an accumulation of ~3784 Modified GDD and ~140 Stress DD, while the multi-model mean characterizes an accumulation of ~4188 Modified DD and ~225 Stress DD.

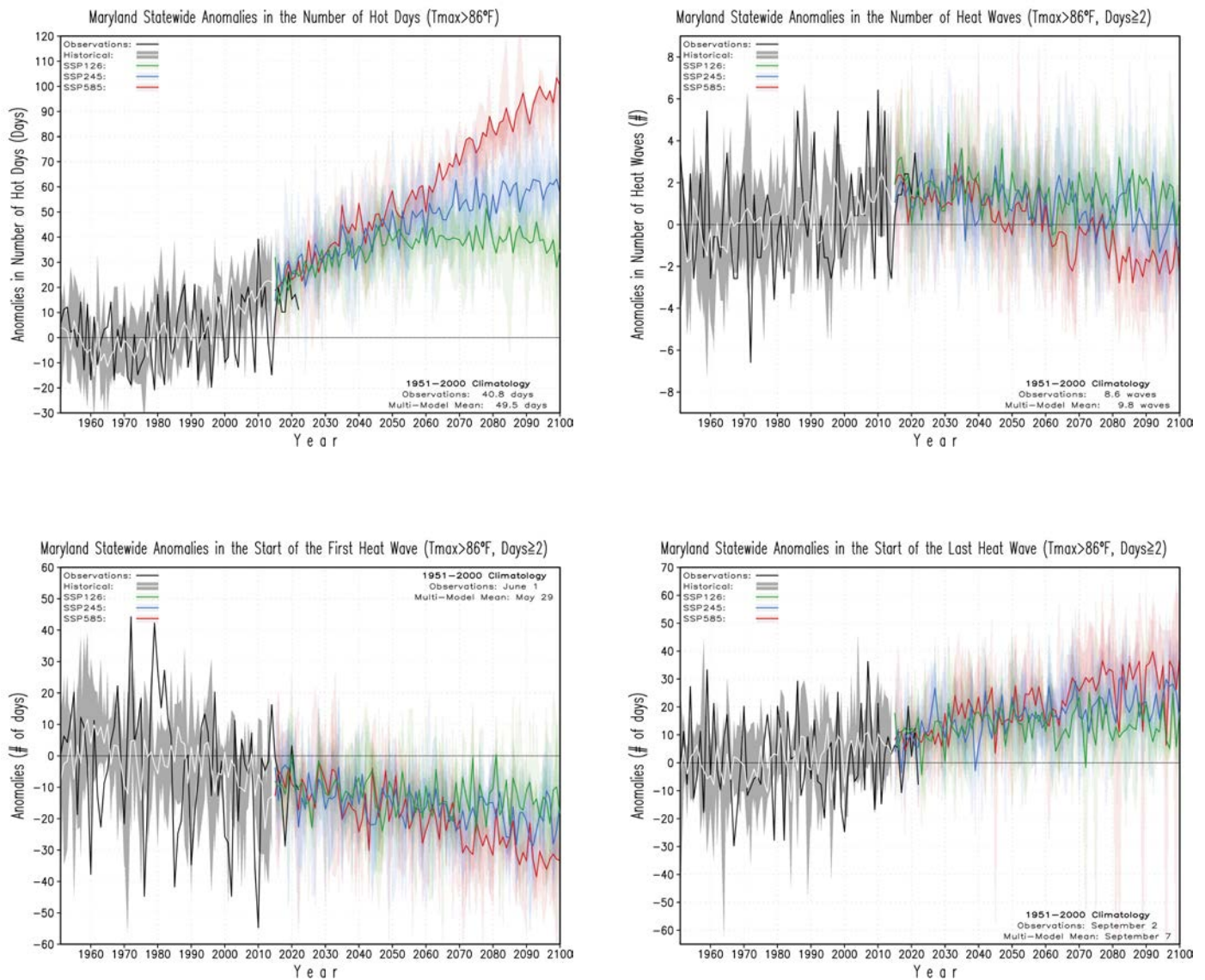


Figure 6. Anomalies in the annual number of hot days (maximum temperature larger than 86°F) and heat waves (consecutive hot days) in Maryland statewide from observations and CMIP6 historical simulations and projections for the period 1950-2100. Anomalies are with respect to the common 20th century period 1951-2000. Panels show the number of hot days (upper left), the number of heat waves (upper right), start of the first wave (bottom left), and the start of the last heat wave (bottom right). Observations for the period 1951-2022 are shown with a black line; the multi-model mean of historical simulations for the period 1950-2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of the SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate that there are ~41 hot days and ~9 heat waves per year, with the first heat wave starting on June 1 and the last one starting on September 2, while the multi-model mean characterizes ~50 hot days and ~10 heat waves, with the first heat wave starting on May 29, and the last one starting on September 7.

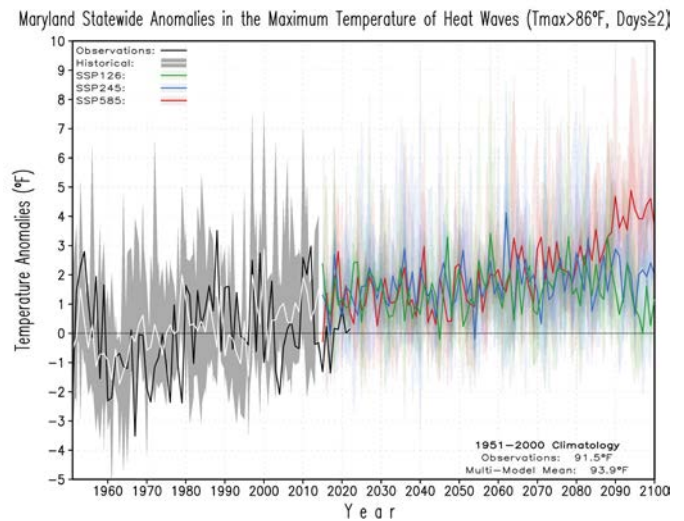
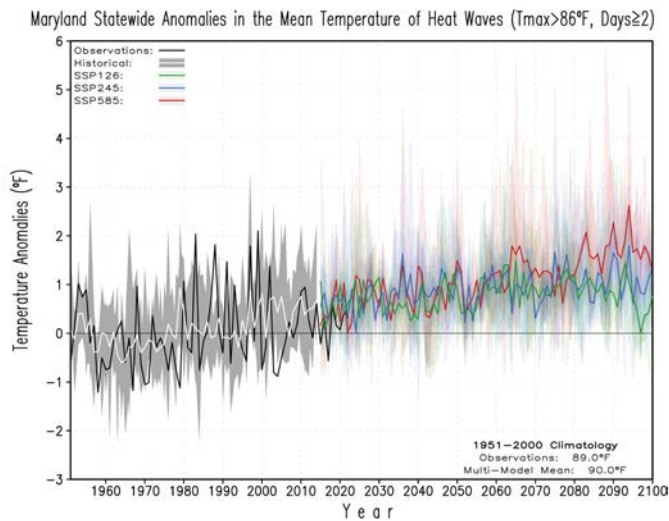
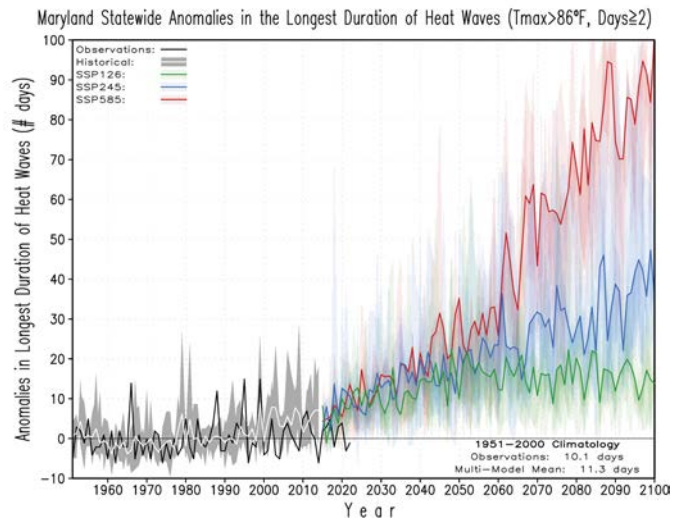
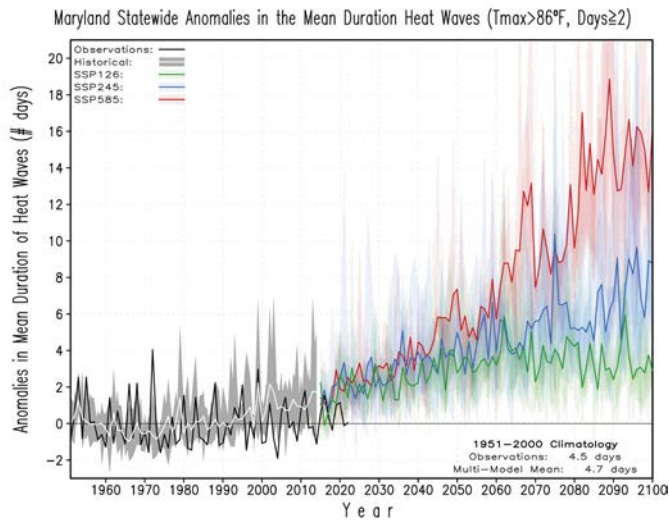


Figure 7. Anomalies in the duration and temperature of heat waves in Maryland statewide from observations and CMIP6 historical simulations and projections for the period 1950-2100. Anomalies are with respect to the common 20th century period 1951-2000. Panels show the mean duration of heat waves (upper left), the longest duration of heat waves (upper right), the mean temperature of the heat waves (bottom left), and the maximum temperature of the heat waves (bottom right). Observations for the period 1951-2022 are shown with a black line; the multi-model mean of historical simulations for the period 1950-2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of the SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate that heat waves have a mean duration of ~5 days and a maximum duration of ~10 days, with a mean temperature of 89.0°F, and a maximum temperature of 91.5°F, while the multi-model mean characterizes heat waves with a mean duration of ~5 days, a maximum duration of ~11 days, with a mean temperature of 90.0°F and a maximum temperature of 93.9°F.

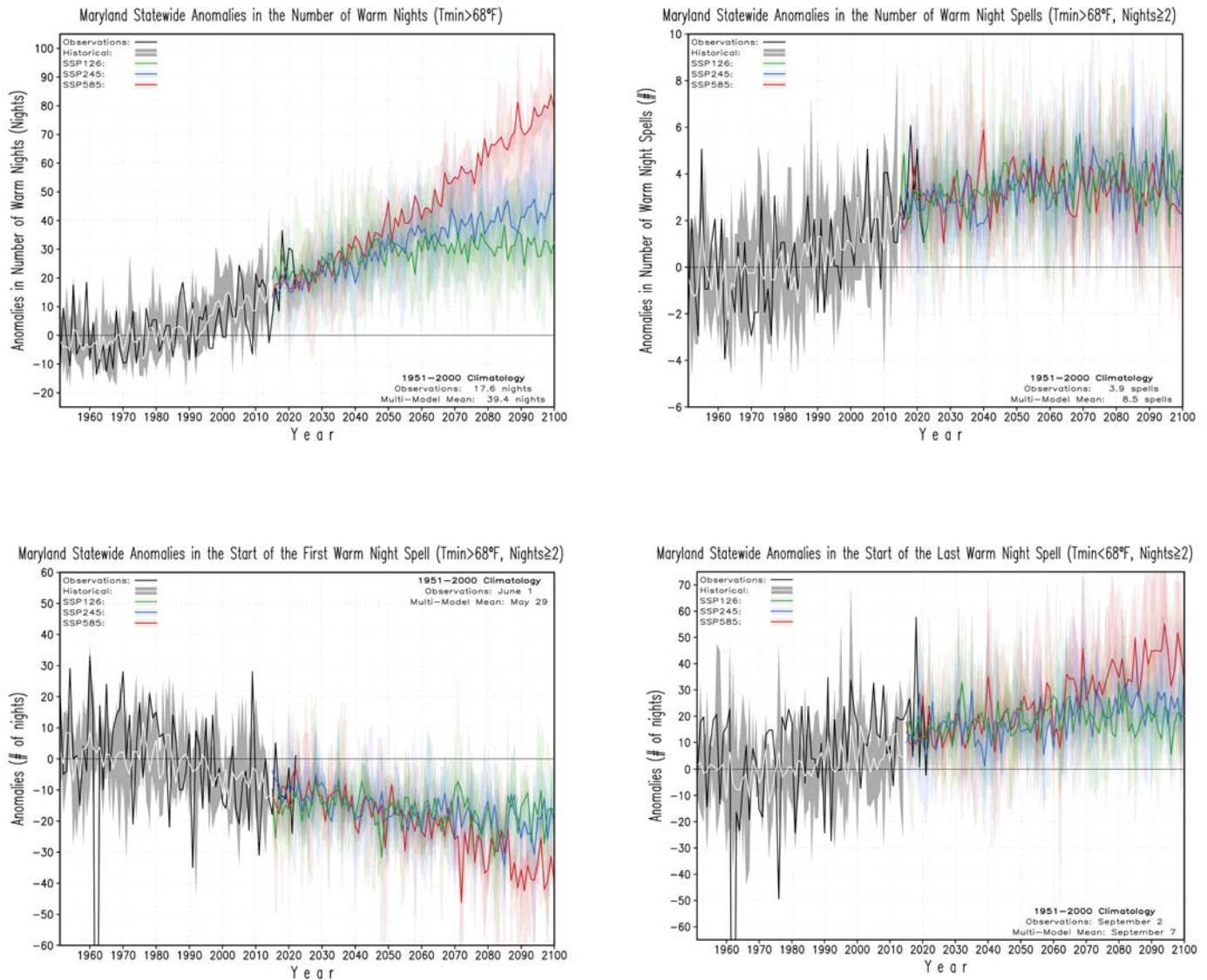


Figure 8 Anomalies in the annual number of warm nights (minimum temperature larger than 68°F) and warm night spells (consecutive warm nights) in Maryland statewide from observations and CMIP6 historical simulations and projections for the period 1950-2100. Anomalies are with respect to the common 20th century period 1951-2000. Panels show the number of warm nights (upper left), the number of warm night spells (upper right), start of the first warm night spell (bottom left), and the start of the last warm night spell (bottom right). Observations for the period 1951-2022 are shown with a black line; the multi-model mean of historical simulations for the period 1950-2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of the SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate that there are ~18 warm nights and ~4 warm night spells per year, with the first warm night spell starting on June 1 and the last one starting on September 2, while the multi-model mean characterizes ~39 warm nights and ~9 warm night spells, with the first heat wave starting on May 29, and the last one starting on September 7.

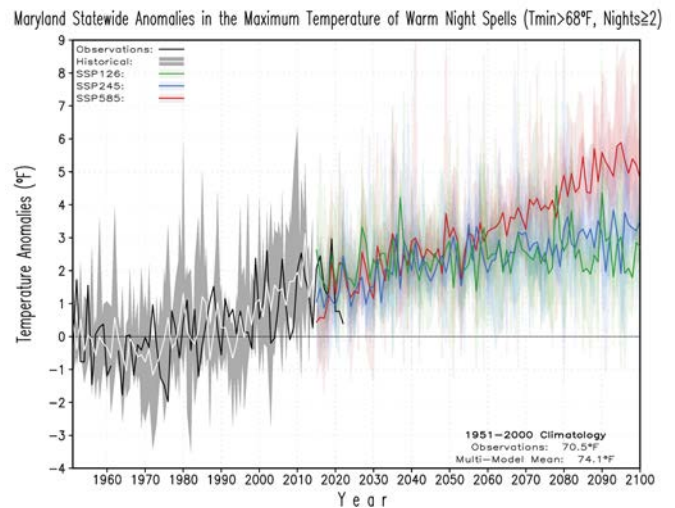
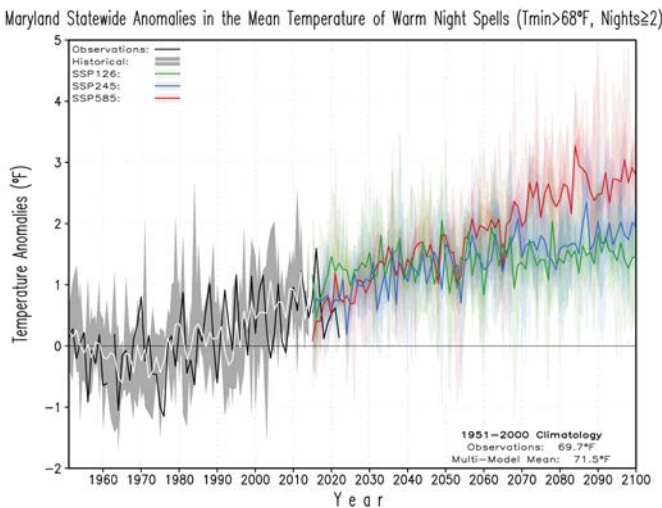
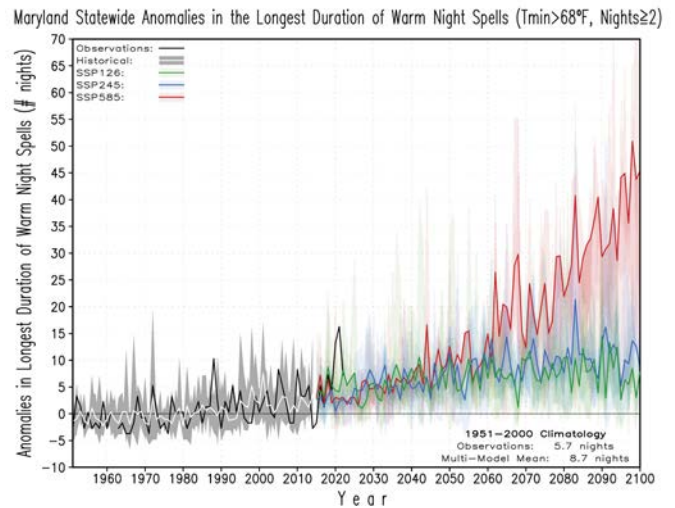
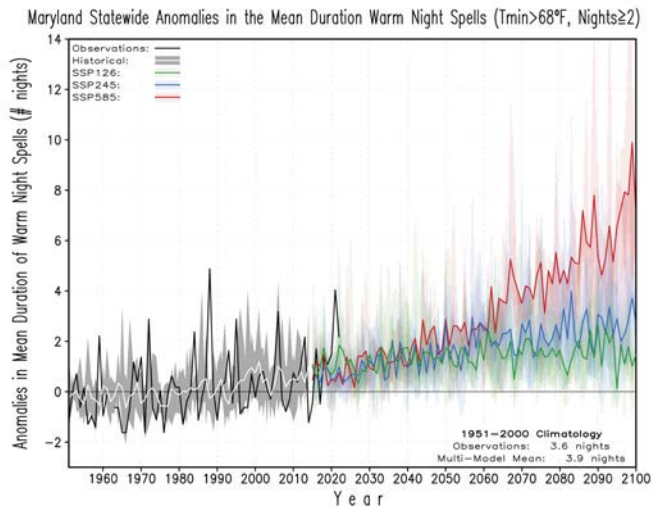


Figure 9. Anomalies in the duration and temperature of warm night spells in Maryland statewide from observation and CMIP6 historical simulations and projections for the period 1950 to 2100. Anomalies are with respect to the common twentieth century period 1951 to 2000. Panels show the mean duration of warm night spells (upper left), the longest duration of warm night spells (upper right), the mean temperature of warm night spells (bottom left), and the maximum temperature of warm night spells (bottom right). Observations for the period 1951 to 2022 are indicated with a black line; the multi-model mean of historical simulations for the period 1950 to 2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate that the warm night spells have a mean duration of ~4 days and a maximum duration of ~6 days, with a mean temperature of 69.7°F, and a maximum temperature of 70.5 °F, while the multi-model mean characterizes the warm night spells with a mean duration of ~4 days, a maximum duration of ~9 days, with a mean temperature of 71.5°F and a maximum temperature of 74.1°F.

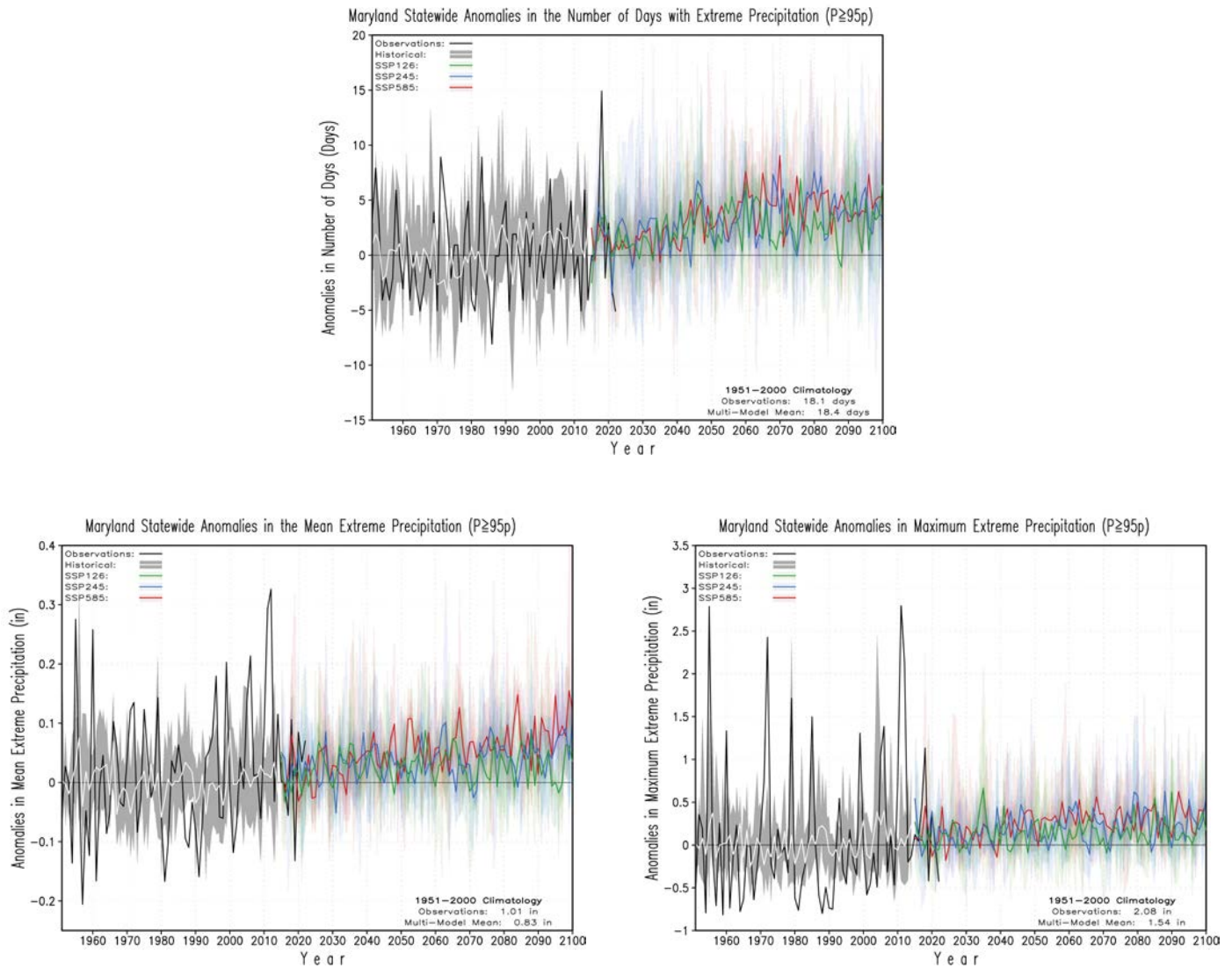


Figure 10. Anomalies in extreme precipitation (larger than the 95th percentile) in Maryland statewide from observations and CMIP6 historical simulations and projections for the period 1950-2100. Anomalies are with respect to the common 20th century period 1951-2000; the 95th percentile is calculated from daily precipitation in the same common period. Panels show the number of days with extreme precipitation (upper), the mean extreme precipitation (bottom left), and the maximum extreme precipitation (bottom right). Observations for the period 1951-2022 are shown with a black line; the multi-model mean of historical simulations for the period 1950-2014 is displayed with a white line; the simulations from the individual seven models are shown with gray shading. The multi-model means of the SSP126, SSP245, and SSP585 pathways are displayed with green, blue, and red lines for the period 2015-2100; the projections from the individual seven models for the SSP126, SSP245, and SSP585 pathways are shown with light green, light blue, and light red shading. The climatological values are shown in the inset of each panel, and observations indicate there are ~18 days with extreme precipitation per year with a mean amount of ~1.01 in and a maximum amount of ~2.08 in, while the multi-model mean characterizes them as ~18 days with extreme precipitation per year with a mean amount of ~0.83 in and a maximum amount of ~1.54 in.

Tables 1-9: Climatological Data: Observations and Multi-Model Means from Historical Simulations and Mean Model Spread in climate-related agriculture indices for the period 1951 to 2014.

Table 1. Growing season in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Duration of Growing Season (Days)	205.4	188.8	17.5
Start of Growing Season (Days from January 1)	98.1	108.1	11.7
End of Growing Season (Days from January 1)	302.5	295.9	12.2
Number of Days with Minimum Temperature above 32°F (Days)	266.1	273.9	11.8

Table 2. Vegetation period in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Duration of Vegetation Period (Days)	277.6	289.1	27.5
Start of Vegetation Period (Days from January 1)	58.5	51.9	24.9
End of Vegetation Period (Days from January 1)	335.1	340.0	13.5

Table 3. Dry spells in the vegetation period in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Number of Dry Spells (Days)	35.8	35.6	5.2
Mean Duration of Dry Spells (Days)	4.7	4.2	0.4
Longest Duration of Dry Spells (Days)	15.8	13.4	3.6

Table 4. Modified growing and stress degree days in Maryland statewide through the year (Annual) from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Modified Degree Days (GDDF)	3842.6	4260.1	190.3
Stress Degree Days (\pm SDDF)	148.3	251.6	91.0

Table 5. Annual number of hot days (maximum temperature larger than 86°F) and heat waves (consecutive hot days) in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Number of Hot Days (Days)	42.2	53.0	11.2
Number of Heat Waves (#)	8.8	10.0	2.0
Start of First Heat Wave (Days from January 1)	149.2	147.0	14.1
Start of Last Heat Wave (Days from January 1)	245.6	251.4	12.6

Table 6. Duration and temperature of heat waves in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Mean Duration of Heat Waves (Days)	4.4	4.9	1.2
Longest Duration of Heat Waves (Days)	10.1	12.4	4.7
Mean Temperature of Heat Waves (°F)	89.0	90.1	0.8
Maximum Temperature of Heat Waves (°F)	91.6	94.0	1.9

Table 7. Annual number of warm nights (minimum temperature larger than 68°F) and warm night spells (consecutive warm nights) in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Number of Warm Nights (Nights)	19.7	42.0	8.1
Number of Warm Night Spells (#)	4.4	8.9	2.0
Start of First Warm Night Spell (Nights from January 1)	180.0	162.8	10.8
Start of Last Warm Night Spell (Nights from January 1)	228.1	248.5	14.3

Table 8. Duration and temperature of warm nights and warm night spells (consecutive warm nights) in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Mean Duration of Warm Night Spells (Nights)	3.7	4.0	0.9
Longest Duration of Warm Night Spells (Nights)	6.3	9.1	3.5
Mean Temperature of Warm Night Spells (°F)	69.8	71.7	1.0
Maximum Temperature of Warm Night Spells (°F)	70.7	74.4	2.0

Table 9. Annual number of days with extreme precipitation (larger than the 95th percentile) in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014.

Variable	Observations	Historial Mean	Historical \pm SD
Number of Days with Extreme Precipitation (Days)	18.16	18.73	4.08
Mean Extreme Precipitation (in)	1.02	0.83	0.08
Maximum Extreme Precipitation (in)	2.16	1.56	0.38

Tables 10-18 Climatological Data: Multi-Model Means from Projections and Mean Model Spread in climate-related agriculture indices for the period 2031 to 2060.

Table 10. Growing season in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Duration of Growing Season (Days)	212.6	19.9	211.8	17.5	218.2	18.8
Start of Growing Season (Days from January 1)	97.1	12.6	97.5	11.5	94.8	11.6
End of Growing Season (Days from January 1)	308.7	14.1	306.9	11.6	309.5	12.5
Number of Days with Minimum Temperature above 32°F (Days)	297.2	13.6	296.6	11.8	302.0	13.1

Table 11. Vegetation period in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Duration of Vegetation Period (Days)	318.4	22.5	316.7	22.8	324.7	24.6
Start of Vegetation Period (Data from January 1)	33.9	21.0	35.6	21.1	29.0	20.9
End of Vegetation Period (Days from January 1)	351.3	11.6	351.3	12.1	352.7	11.5

Table 12. Dry spells in the vegetation period in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Number of Dry Spells (#)	38.2	4.5	38.7	4.6	39.7	4.4
Mean Duration of Dry Spells (Days)	4.3	0.5	4.3	0.4	4.3	0.4
Longest Duration of Dry Spells (Days)	14.5	4.2	14.3	4.4	14.5	3.5

Table 13. Modified growing and stress degree days in Maryland statewide through the year (Annual) from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Modified Degree Days - Annual (GDDF)	5012.6	252.1	5055.3	210.8	5209.0	256.8
Stress Degree Days - Annual (\pm SDDF)	501.0	133.8	561.1	133.6	622.8	147.0

Table 14. Annual number of hot days (maximum temperature greater than 86°F) and heat waves (consecutive hot days) in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Number of Hot Days (Days)	86.0	11.4	90.4	11.7	97.6	12.2
Number of Heat Waves (#)	11.5	2.3	11.0	2.3	10.8	2.4
Start of First Heat Wave (Days from January 1)	136.6	13.2	134.0	13.5	132.8	14.3
Start of Last Heat Wave (Days from January 1)	264.5	12.2	264.6	10.7	268.8	12.9

Table 15. Duration and temperature of heat waves in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Mean Duration of Heat Waves (Days)	7.5	2.0	8.4	2.6	9.5	3.2
Longest Duration of Heat Waves (Days)	25.6	11.6	29.0	13.4	34.5	16.0
Mean Temperature of Heat Waves ($^{\circ}$ F)	90.7	0.7	90.9	0.8	90.9	0.7
Maximum Temperature of Heat Waves ($^{\circ}$ F)	95.2	1.6	95.5	1.8	95.3	1.5

Table 16. Annual number of warm nights (minimum temperature greater than 68 $^{\circ}$ F) and warm night spells (consecutive warm nights) in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Number of Warm Nights (Nights)	67.5	11.8	67.7	10.1	73.9	10.4
Number of Warm Night Spells (#)	12.0	2.2	11.7	1.8	12.1	2.2
Start of First Warm Night Spell (Nights from January 1)	148.5	11.6	148.3	10.3	147.6	11.3
Start of Last Warm Night Spell (Nights from January 1)	265.9	15.0	262.2	13.1	266.7	16.1

Table 17. Duration and temperature of warm nights and warm night spells (consecutive warm nights) in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Mean Duration of Warm Night Spells (Nights)	5.3	1.4	5.4	1.3	5.8	1.5
Longest Duration of Warm Night Spells (Nights)	15.3	7.2	15.3	5.8	17.3	6.6
Mean Temperature of Warm Night Spells ($^{\circ}$ F)	72.9	0.8	72.8	0.9	73.0	0.8
Maximum Temperature of Warm Night Spells ($^{\circ}$ F)	76.5	1.7	76.4	1.9	76.8	1.8

Table 18. Annual number of days with extreme precipitation (greater than the 95th percentile) in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Number of Days with Extreme Precipitation (Days)	21.06	4.47	21.14	4.54	21.49	4.43
Mean Extreme Precipitation (in)	0.86	0.09	0.86	0.09	0.90	0.07
Maximum Extreme Precipitation (in)	1.69	0.40	1.71	0.37	1.85	0.38

REFERENCES

Boesch, D. F. 2008. *Global Warming in the Free State: Comprehensive Assessment of Climate Change Impacts in Maryland*. Report of the Scientific and Technical Working Group to the Maryland Commission on Climate Change. University of Maryland Center for Environmental Science, Cambridge. https://www.umces.edu/sites/default/files/pdfs/global_warming_free_state_report.pdf.

Boicourt, K., and Z. P. Johnson. 2011. *Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change Phase II: Building Societal, Economic, and Ecological Resilience*. Report of the Maryland Commission on Climate Change, Adaptation and Response and Scientific and Technical Working Groups. University of Maryland Center for Environmental Science, Cambridge, MD, and Maryland Department of Natural Resources, Annapolis, MD.

Durre, I., M. F. Squires, R. S. Vose, A. Arguez, W. S. Gross, J. R. Rennie, and C. J. Schreck. 2022. "NOAA's nClimGrid-Daily Version 1 - Daily Gridded Temperature and Precipitation for the Contiguous United States Since 1951." NOAA National Centers for Environmental Information. Accessed May 6, 2022. <https://doi.org/10.25921/c4gt-r169>.

EPA. 2023. *Climate Change Indicators in the United States*. Accessed May 2023. <https://www.epa.gov/climate-indicators>.

Heavens, N. G., D. S. Ward, and M. M. Natalie. 2013. "Studying and Projecting Climate Change with Earth System Models." *Nature Education Knowledge* 4 (5): 4.

IPCC. 2023. *AR6 Synthesis Report: Climate Change 2023*. <https://www.ipcc.ch/report/sixth-assessment-report-cycle>.

MDE. 2016. *Re-Examining Projected Climate Changes for Maryland*. MCCC Scientific and Technical Working Group. <https://mde.maryland.gov/programs/Air/ClimateChange/MCCC/STWG/STWGRe-examinCC01252016.pdf>.

Runkle, J., K. E. Kunkel, D. R. Easterling, B. C. Stewart, S. M. Champion, R. Frankson, W. Sweet, and J. Spaccio. 2022. *Maryland and the District of Columbia State Climate Summary 2022*. NOAA Technical Report NE \pm SDIS 150-MD. NOAA/NE \pm SDIS, Silver Spring, MD.

Thrasher, B., W. Wang, A. Michaelis, and co-authors. 2021. "NEX-GDDP-CMIP6." NASA Center for Climate Simulation. <https://doi.org/10.7917/OFSG3345>.

Thrasher, B., W. Wang, A. Michaelis, and co-authors. 2022. "NASA Global Daily Downscaled Projections, CMIP6." *Scientific Data* 9: 262. <https://doi.org/10.1038/s41597-022-01393-4>.

Tschurr, F., I. Feigenwinter, A. M. Fischer, and S. Kotlarski. 2020. "Climate Scenarios and Agricultural Indices: A Case Study for Switzerland." *Atmosphere* 11 (5): 535. <https://doi.org/10.3390/atmos11050535>.

USDA. 2023. *2022-2023 Agricultural Statistics Annual Bulletin, Maryland*. U.S. Department of Agriculture. https://www.nass.usda.gov/Statistics_by_State/Maryland/Publications/Annual_Statistical_Bulletin/2022/2022-2023_MD%20Bulletin.pdf.

USGS. 2021. *U.S.A. County Boundaries*. Accessed September 2021. <https://www.sciencebase.gov/catalog/item/4f4e4a2ee4b07f02db615738>.

Vavrus, S. J., M. Notaro, and D. J. Lorenz. 2015. "Interpreting Climate Model Projections of Extreme Weather Events." *Weather and Climate Extremes* 10, Part B. <https://doi.org/10.1016/j.wace.2015.10.005>.

Walsh, M. K., P. Backlund, L. Buja, A. DeGaetano, R. Melnick, L. Prokopy, E. Takle, D. Todey, and L. Ziska. 2020. *Climate Indicators for Agriculture*. USDA Technical Bulletin 1953. Washington, DC. <https://doi.org/10.25675/10217/210930>.

Appendix A: Annual and Seasonal Temperature and Precipitation Assessments

This appendix contains the following:

- Statewide area-averaged temperatures and accumulated precipitation departures from climatology (i.e., anomalies) from observations, historical simulations for 1951-2014, and SSP126, SSP245, and SSP585 projections for the period 2015 to 2100 (Figures A1-A5). Anomalies are with respect to their corresponding 1951 to 2000 climatology; the anomalies from model simulations and three projections are with respect to the 1951 to 2000 climatology from the historical simulation. Anomalies are displayed for annual and seasonal means.
- Tables for temporal means and standard deviations from statewide observations and multi-model mean (i.e., the average of the seven models) historical simulations at annual and seasonal resolutions for the period 1951 to 2014 (Tables A1-A5).

- Tables for temporal annual and seasonal means from statewide observations and multi-model mean historical simulations, and standard deviation of the seven models with respect to the multi-model mean (i.e., intra-model variability or model spread) for the period 1951 to 2014 (Tables A6-A10).
- Tables for temporal annual and seasonal means from statewide multi-model mean climate projections and standard deviation of the seven models with respect to the multi-model mean (i.e., intra-model variability or model spread) for the period 2031 to 2060 (Tables A11-A15).

Notably, models have a warm bias; the mean temperatures they simulate for the 1951 to 2014 period are warmer than observed (Tables A1-A5). The range of possibilities for the temperature anomalies they simulate (gray shading in figures) is consistent with the observed anomalies that they enclose (Figures A1-A5). The observed warming trend in annual mean surface temperatures in 1951 to 2014 (0.41°F per decade) is well captured by the trend in the multi-model mean temperature (0.40°F per decade); however, the observed winter and spring trends (0.40 and 0.35°F per decade) are slightly underestimated (0.30 and 0.32°F per decade) by the multi-model mean, while the summer and fall trends (0.33 and 0.25°F per decade) are overestimated (0.45 and 0.43°F per decade). On the other hand, there is no bias in the accumulated precipitation at the annual resolution, but there is a small wet bias in winter and summer and a small dry bias in spring and fall. The range of possibilities for the precipitation anomalies they simulate (gray shading in figures) has a looser fit to the observed anomalies than the one seen for the temperatures; a better way to capture the model spread, or uncertainty, would have been to display the 5-95th-percentiles spread across the multi-model means. The observed trend in annual accumulated precipitation in 1951-2014 (0.62 inches per decade) is underestimated by the trend in the multi-model mean (0.24 inches per decade), which reflects the underestimation of the observed trends in spring, summer, and fall.

The temporal variability of the temperatures and precipitation in the multi-model mean is smaller than the variability from observations (Tables A1-A5); however, this may be due to the smoothed nature (i.e., the average of the seven models) of the multi-model mean.

Considerable warming is projected during this century (Figures A1-A5, Tables A11-A15). Under the low-emissions SSP126 pathway, the mid-century projected annual climatology (2031 to 2060) in mean temperatures would be ~4°F warmer than the historical 1951-2000 average (see inset value in graphs). Under the high-emissions SSP585 pathway, the mid-century (2031 to 2060) projected annual climatology in mean temperatures would be ~5°F warmer than the historical 1951 to 2000 average; under this pathway, the projected climatological annual temperature at the end of the century (2071 to 2100) would be ~10°F warmer than the 1951 to 2000 climatology. The warming in annual temperatures is also evident in the seasonal temperatures. In the middle-of-the-road SSP245 pathway, projected climatological conditions in the mid-century (2031 to 2060) are not much different than those under the SSP126 pathway.

A small increase in the annual precipitation is projected during this century (Figures A1-A5, Tables A11-A15). Under the low-emissions SSP126 pathway, the mid-century (2031 to 2060) projected annual climatology in precipitation would be ~3.6 inches wetter than the historical 1951 to 2000 average (see inset value in graphs). Under the high-emissions SSP585 pathway, the mid-century (2031 to 2060) projected annual climatology in precipitation would be ~3.9 inches wetter than the historical 1951 to 2000 average; under this pathway, the projected climatological annual precipitation at the end of the century (2071 to 2100) would be ~5 inches wetter than the 1951 to 2000 climatology. The projected larger annual precipitation is also evident in the projected seasonal precipitation, especially in winter and spring.

The spread in the models, as identified by the ratio of the multi-model standard deviation to the mean (Tables A6-A15), is larger in precipitation than in temperatures, indicating a larger uncertainty in their projections. Uncertainties in the temperature and precipitation projections for the mid-century (2031 to 2060) climatology are in the ~2-9% and ~11-27% range, respectively. The lowest uncertainties in temperature are ~2-3% with the annual and summer temperature climatologies, followed by uncertainty of ~3-5% with the spring and fall climatologies, and topped with uncertainties of ~6-9% for the winter climatologies. The lowest uncertainty in precipitation is ~10-11% with the annual climatology, followed by ~16-18% in summer, then ~17-21% in spring, ~21-22% in winter, and the largest uncertainty ~25-27% in fall.

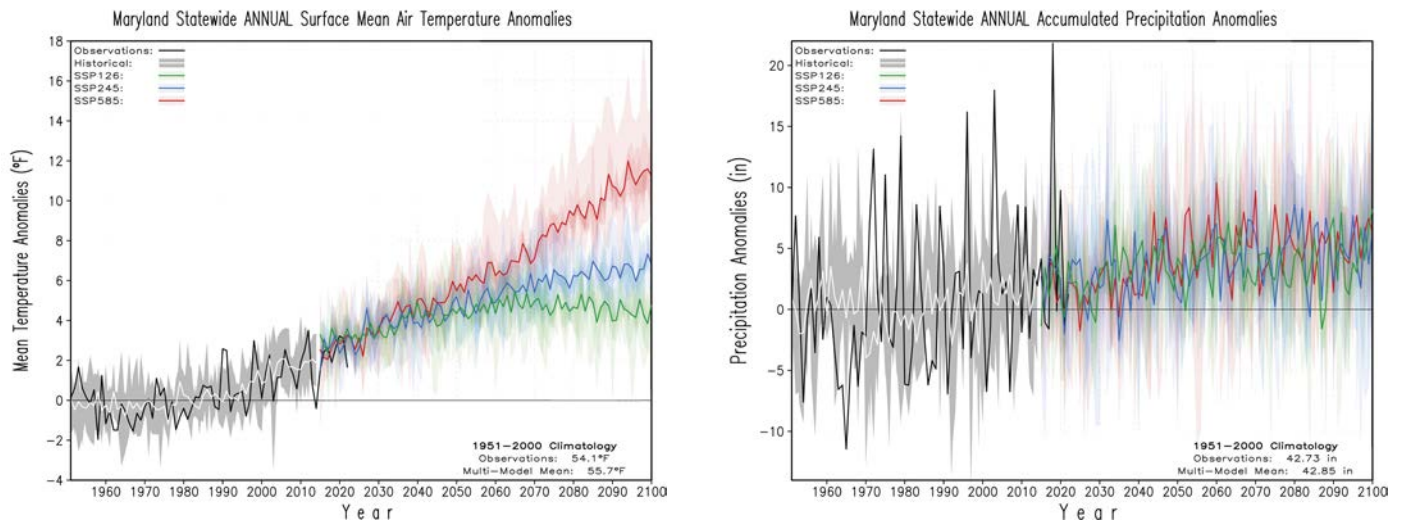


Figure A1. Observed and simulated Maryland’s statewide anomalies in annual surface mean air temperature and accumulated precipitation for the 1951-2100 period. Observations from the nClimGrid-Daily dataset are in black for 1951-2022. Shading indicates the range of the annual anomalies from the seven downscaled CMIP6 Earth System models. The historical simulations cover 1951-2014, and the projections cover 2015-2100. As indicated by the labels, gray/white shows historical simulations, red shows the high emission scenario SSP585, blue shows the middle of the road SSP245 scenario, and green shows the green pathway scenario. Anomalies are with respect to the climatology for the 1951-2000 period. Anomalies in the projections are with respect to the climatology from the corresponding historical simulations. The thick white line is the multi-model mean of the historical simulations, the thick green line is the multi-model mean of the SSP126 projection, the thick blue line is the multi-model mean of the SSP245 projection, and the thick red line is the multi-model mean of the SSP585 projection. Climatological values are 54.1°F and 42.73 inches for observations and 55.7°F and 42.85 inches for the multi-model mean of the historical simulations.

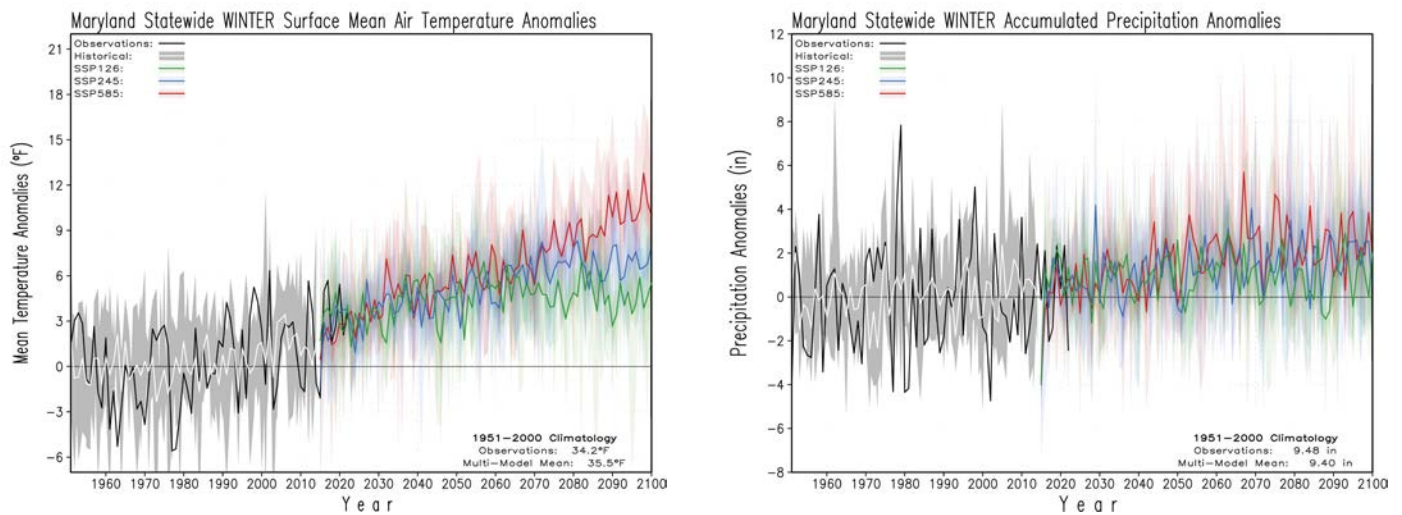


Figure A2. Observed and simulated Maryland’s statewide anomalies in winter surface mean air temperature and accumulated precipitation for the 1951-2100 period. Observations from the nClimGrid-Daily data set are in black for 1951-2022. Shading indicates the range of the annual anomalies from the seven downscaled CMIP6 Earth System models. The historical simulations cover 1951-2014, and the projections cover 2015-2100. As indicated by the labels, gray/white shows historical simulations; red shows the high emission scenario SSP585, blue shows the middle of the road SSP245 scenario, and green shows the green pathway scenario. Anomalies are with respect to the climatology for the 1951-2000 period. Anomalies in the projections are with respect to the climatology from the corresponding historical simulations. The thick white line is the multi-model mean of the historical simulations, the thick green line is the multi-model mean of the SSP126 projection, the thick blue line is the multi-model mean of the SSP245 projection, and the thick red line is the multi-model mean of the SSP585 projection. Climatological values are 34.2°F and 9.48 inches for observations and 35.5°F and 9.40 inches for the multi-model mean of the historical simulations.

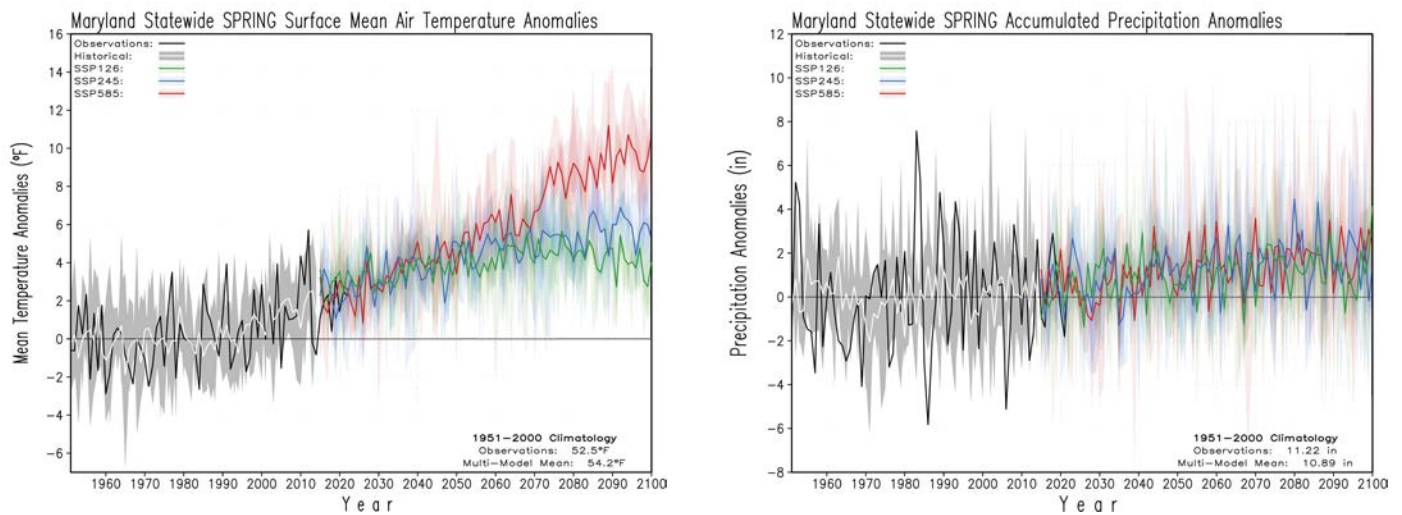


Figure A3: Observed and simulated Maryland’s statewide anomalies in spring surface mean air temperature and accumulated precipitation for the 1951-2100 period. Observations from the NClimDiv-daily dataset are in black for 1951-2022. Shading indicates the range of the annual anomalies from the seven downscaled CMIP6 Earth system models. The historical simulations cover 1951-2014, and the projections cover 2015-2100. As indicated by the labels, gray/white shows historical simulations; red shows the high emission scenario SSP585, blue shows the middle of the road SSP245 scenario, and green shows the green pathway scenario. Anomalies are with respect to the climatology for the 1951-2000 period. Anomalies in the projections are with respect to the climatology from the corresponding historical simulations. The thick white line is the multi-model mean of the historical simulations, the thick green line is the multi-model mean of the SSP126 projection, the thick blue line is the multi-model mean of the SSP245 projection, and the thick red line is the multi-model mean of the SSP585 projection. Climatological values are 52.5°F and 11.22 inches for observations and 54.2°F and 10.89 inches for the multi-model mean of the historical simulations.

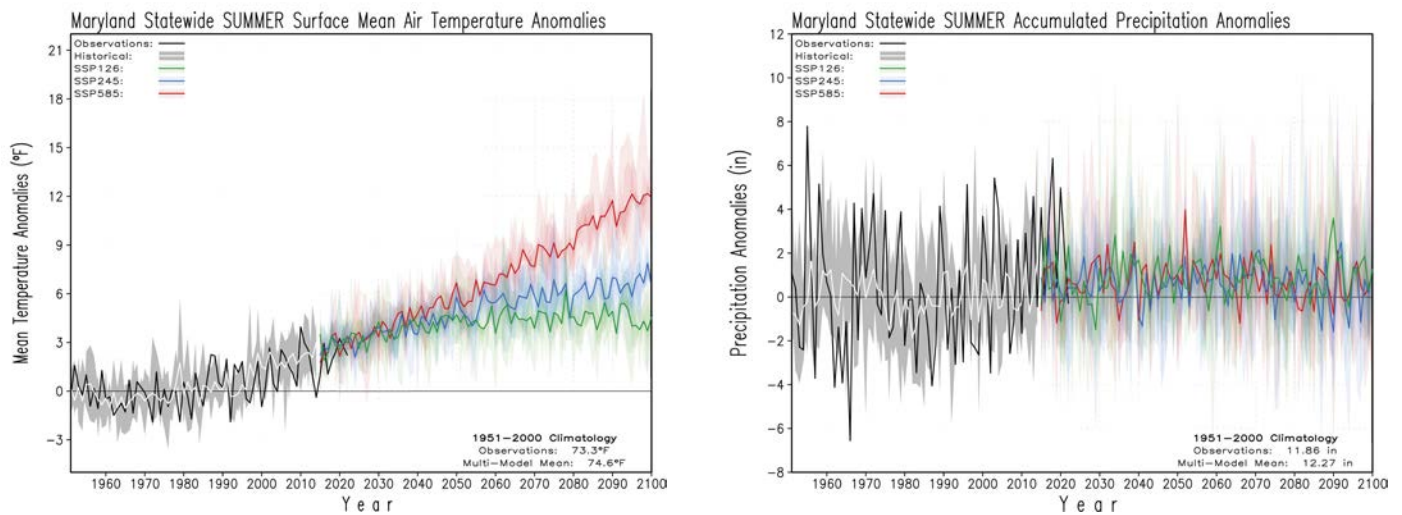


Figure A4. Observed and simulated Maryland’s statewide anomalies in summer surface mean air temperature and accumulated precipitation for the 1951-2100 period. Observations from the nClimGrid-Daily dataset are in black for 1951-2022. Shading indicates the range of the annual anomalies from the seven downscaled CMIP6 Earth system models. The historical simulations cover 1951-2014, and the projections cover 2015-2100. As indicated by the labels, gray/white shows historical simulations; red shows the high emission scenario SSP585, blue shows the middle of the road SSP245 scenario, and green shows the green pathway scenario. Anomalies are with respect to the climatology for the 1951-2000 period. Anomalies in the projections are with respect to the climatology from the corresponding historical simulations. The thick white line is the multi-model mean of the historical simulations, the thick green line is the multi-model mean of the SSP126 projection, the thick blue line is the multi-model mean of the SSP245 projection, and the thick red line is the multi-model mean of the SSP585 projection. Climatological values are 73.3°F and 11.86 inches for observations and 74.6°F and 12.27 inches for the multi-model mean of the historical simulations.

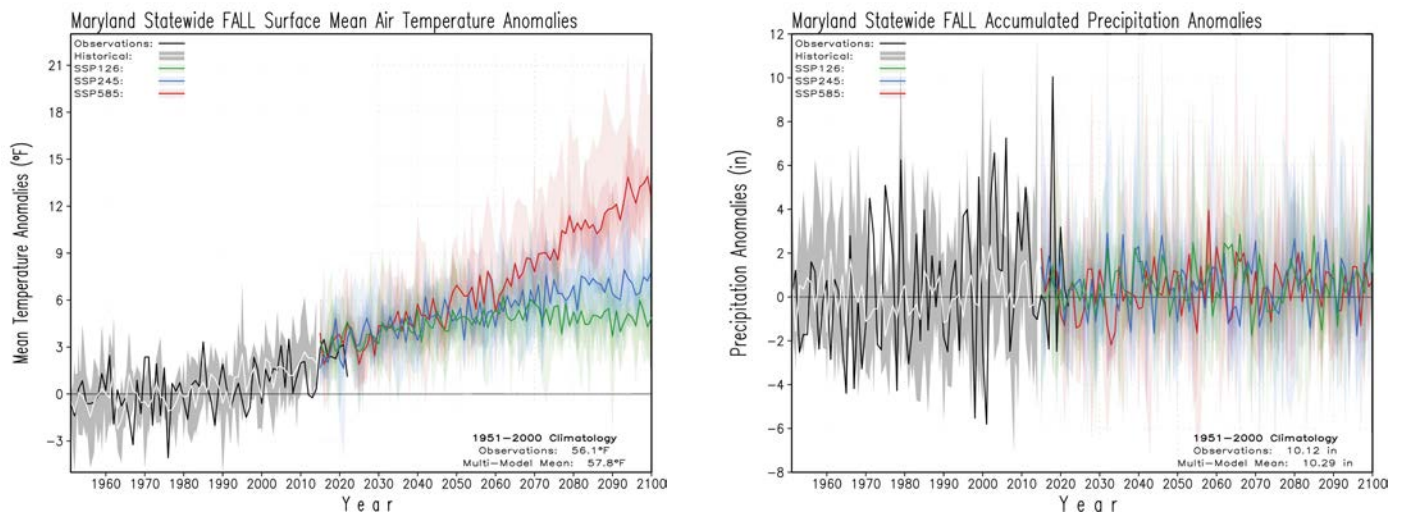


Figure A5. Observed and simulated Maryland’s statewide anomalies in fall surface mean air temperature and accumulated precipitation for the 1951-2100 period. Observations from the nClimGrid-Daily dataset are in black for 1951-2022. Shading indicates the range of the annual anomalies from the seven downscaled CMIP6 Earth System models. The historical simulations cover 1951-2014, and the projections cover 2015-2100. As indicated by the labels, gray/white shows historical simulations, red shows the high emission scenario SSP585, blue shows the middle of the road SSP245 scenario, and green shows the green pathway scenario. Anomalies are with respect to the climatology for the 1951-2000 period. Anomalies in the projections are with respect to the climatology from the corresponding historical simulations. The thick white line is the multi-model mean of the historical simulations, the thick green line is the multi-model mean of the SSP126 projection, the thick blue line is the multi-model mean of the SSP245 projection, and the thick red line is the multi-model mean of the SSP585 projection. Climatological values are 56.1°F and 10.12 inches for observations and 57.8°F and 10.29 inches for the multi-model mean of the historical simulations.

Table A1. Mean and temporal standard deviation from annual mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the temporal variability in the 1951 to 2014 period.

Variable	Observations	Historical	Observations ±SD	Historical ±SD
Mean Temperature (°F)	54.4	56.0	1.2	0.9
Maximum Temperature (°F)	64.6	66.6	1.3	0.9
Minimum Temperature (°F)	44.2	45.4	1.2	0.9
Total Precipitation (in)	43.21	43.21	6.04	1.97

Table A2. Mean and temporal standard deviation from winter mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the temporal variability in the 1951 to 2014 period.

Variable	Observations	Historical	Observations ±SD	Historical ±SD
Mean Temperature (°F)	34.5	35.9	2.8	1.3
Maximum Temperature (°F)	43.3	45.1	3.0	1.2
Minimum Temperature (°F)	25.5	26.6	2.7	1.4
Total Precipitation (in)	9.37	9.51	2.54	1.0

Table A3. Mean and temporal standard deviation from spring mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the temporal variability in the 1951 to 2014 period.

Variable	Observations	Historical	Observations ±SD	Historical ±SD
Mean Temperature (°F)	52.9	54.6	1.8	1.0
Maximum Temperature (°F)	63.8	65.9	2.1	1.0
Minimum Temperature (°F)	42.0	43.2	1.8	1.0
Total Precipitation (in)	11.23	10.95	2.66	0.83

Table A4. Mean and temporal standard deviation from summer mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the temporal variability in the 1951 to 2014 period.

Variable	Observations	Historical	Observations ±SD	Historical ±SD
Mean Temperature (°F)	73.6	75.1	1.3	1.1
Maximum Temperature (°F)	84.2	86.0	1.6	1.2
Minimum Temperature (°F)	63.1	64.2	1.4	1.1
Total Precipitation (in)	12.07	12.33	2.95	0.92

Table A5. Mean and temporal standard deviation from fall mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the temporal variability in the 1951 to 2014 period.

Variable	Observations	Historical	Observations ±SD	Historical ±SD
Mean Temperature (°F)	56.3	58.2	1.5	1.1
Maximum Temperature (°F)	66.8	69.1	1.6	1.2
Minimum Temperature (°F)	45.9	47.3	1.7	1.1
Total Precipitation (in)	10.48	10.42	3.06	0.99

Table A6. Annual mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (±SD) with respect to the multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the variability among the models.

Variable	Observations	Historical Mean	Historical ±SD
Mean Temperature (°F)	54.4	56	1.1
Maximum Temperature (°F)	64.6	66.6	1.2
Minimum Temperature (°F)	44.2	45.4	1.1
Total Precipitation (in)	43.21	43.21	4.20

Table A7. Winter mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the variability among the models.

Variable	Observations	Historical Mean	Historical \pm SD
Mean Temperature ($^{\circ}$ F)	34.5	35.9	3.1
Maximum Temperature ($^{\circ}$ F)	43.4	45.1	3.1
Minimum Temperature ($^{\circ}$ F)	25.5	26.6	3.2
Total Precipitation (in)	9.37	9.51	2.07

Table A8. Spring mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the variability among the models.

Variable	Observations	Historical Mean	Historical \pm SD
Mean Temperature ($^{\circ}$ F)	52.9	54.6	1.9
Maximum Temperature ($^{\circ}$ F)	63.8	65.9	1.9
Minimum Temperature ($^{\circ}$ F)	42.0	43.2	1.9
Total Precipitation (in)	11.23	10.95	2.04

Table A9. Summer mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the variability among the models.

Variable	Observations	Historical Mean	Historical \pm SD
Mean Temperature ($^{\circ}$ F)	73.6	75.1	1.2
Maximum Temperature ($^{\circ}$ F)	84.2	86.0	1.5
Minimum Temperature ($^{\circ}$ F)	63.1	64.2	1.4
Total Precipitation (in)	12.07	12.33	2.09

Table A10. Fall mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 1951 to 2014. Note that the standard deviation refers to the variability among the models.

Variable	Observations	Historical Mean	Historical \pm SD
Mean Temperature ($^{\circ}$ F)	56.3	58.2	1.6
Maximum Temperature ($^{\circ}$ F)	66.8	69.1	1.7
Minimum Temperature ($^{\circ}$ F)	45.9	47.3	1.7
Total Precipitation (in)	10.48	10.42	2.52

Table A11. Annual mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060. Note that the standard deviation refers to the variability among the models.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Mean Temperature ($^{\circ}$ F)	59.9	1.3	60.1	1.1	60.9	1.3
Maximum Temperature ($^{\circ}$ F)	70.3	1.3	70.8	1.2	71.5	1.5
Minimum Temperature ($^{\circ}$ F)	49.4	1.6	49.3	1.2	50.3	1.3
Total Precipitation (in)	46.47	4.72	46.2	5.15	46.73	5.15

Table A12. Winter mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060. Note that the standard deviation refers to the variability among the models.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Mean Temperature ($^{\circ}$ F)	40.0	2.8	40.0	2.6	41.1	2.9
Maximum Temperature ($^{\circ}$ F)	49.0	3.0	49.3	2.7	50.2	3.1
Minimum Temperature ($^{\circ}$ F)	31.1	2.9	30.8	2.7	32.0	2.9
Total Precipitation (in)	10.33	2.2	10.40	2.17	10.88	2.41

Table A13. Spring mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060. Note that the standard deviation refers to the variability among the models.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Mean Temperature ($^{\circ}$ F)	57.9	1.8	58.2	1.8	58.8	1.9
Maximum Temperature ($^{\circ}$ F)	69.2	1.9	69.8	1.9	70.2	2.2
Minimum Temperature ($^{\circ}$ F)	46.7	2.0	46.7	1.8	47.3	1.9
Total Precipitation (in)	11.82	2.18	11.91	2.44	12.06	2.09

Table A14. Summer mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060. Note that the standard deviation refers to the variability among the models.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Mean Temperature ($^{\circ}$ F)	78.7	1.4	79.1	1.2	79.9	1.3
Maximum Temperature ($^{\circ}$ F)	89.5	1.6	90.3	1.5	90.9	1.5
Minimum Temperature ($^{\circ}$ F)	67.9	1.6	67.9	1.3	69.0	1.4
Total Precipitation (in)	13.30	2.36	12.91	2.15	13.16	2.13

Table A15. Fall mean surface air temperature and accumulated total precipitation in Maryland statewide from observations and multi-model mean and mean standard deviation (\pm SD) with respect to the multi-model mean for the period 2031 to 2060. Note that the standard deviation refers to the variability among the models.

Variable	SSP126 Mean	SSP126 \pm SD	SSP245 Mean	SSP245 \pm SD	SSP585 Mean	SSP585 \pm SD
Mean Temperature ($^{\circ}$ F)	62.4	1.9	62.5	1.7	63.3	2.1
Maximum Temperature ($^{\circ}$ F)	73.1	1.8	73.6	1.8	74.3	2.2
Minimum Temperature ($^{\circ}$ F)	51.6	2.3	51.5	1.8	52.3	2.3
Total Precipitation (in)	10.99	2.7	10.98	2.72	10.59	2.81

Objective II: Sector-Specific Impacts

POTENTIAL CARBON SEQUESTRATION

Eric Davidson

In this section, we assessed climate impacts on soil carbon sequestration with two objectives: (1) to evaluate the evidence that current best management practices (BMPs) do, indeed, sequester carbon (C) in Maryland's soils and (2) to evaluate whether the current rate of agricultural soil C sequestration can be sustained and increased by the expansion of BMPs at the same time that the impacts of climate change will also be increasing.

SUMMARY

The goals of Maryland's Climate Pollution Reduction Plan for agricultural soil C sequestration are not unreasonable in light of the measurement and modeling studies reported here for Maryland. However, they are tenuous because simulated responses of crop yields to climate change in Maryland appear to affect soil C stocks at rates similar to the gains expected from increased adoption of best management practices. It is possible that, through adaptation to climate change with appropriate crop varieties, multiple cropping, and irrigation, climate change and CO₂ fertilization could have a beneficial effect on agricultural productivity in Maryland. On the other hand, climate change, including heat waves, droughts, and storms, could also have a negative impact on crop yield, which would likely decrease rates of soil C sequestration. A significant negative response of crop yield to climate change could have a large enough impact on C sequestration rates to negate the gains that might have been conferred by expanded adoption of BMPs, such as no-till and cover crops. Furthermore, these calculations do not consider soil C loss due to potentially significant loss of agricultural land in Maryland to commercial development and sea level rise (Hutton et al. 2023). These modeling results are uncertain, but the apparent sensitivity of soil C stocks to rates of crop residue inputs renders soil C sequestration vulnerable to climate change. Overall, the responses of crop yields to climate change in Maryland will likely affect the ability to achieve the stated soil C sequestration goal of Maryland's Climate Pollution Reduction Plan.

METHODS

I assembled relevant peer-reviewed and gray literature to assess the factors affecting soil C sequestration and the vulnerability of soil carbon stocks to climate change in Maryland. I consulted with Michel Cavigelli, USDA-Beltsville, who published one of the few papers that specifically modeled soil C responses to climate change in Maryland (Cavigelli et al. 2018). I also obtained model projections from the online tool of the Conservation Technology Information Center (<https://www.ctic.org/OpTIS>).

RESULTS

Context-Maryland's Goals for Net-Zero Greenhouse Gas Emissions

Maryland's Climate Pollution Reduction Plan (MDE 2023) includes a modest role for agricultural soils to sequester an increasing amount of carbon: "Current levels of adoption in agricultural best management practices, including commitments under the state's Phase III Watershed Implementation Plan, are already expected to remove 0.7 million metric tons of CO₂-equivalents (MMTCO₂eq) annually by 2045. Scaling the adoption of practices to 80% of cropland statewide by 2035 could increase the annual removal to 0.9 MMTCO₂eq." In other words, current and committed agricultural practices are assumed to be sequestering 0.7 MMTCO₂eq per year, and that amount is expected to grow by 0.2 MMTCO₂eq per year with an ambitious expansion of best management practices (BMPs).

Measured Changes in Soil C with Tillage Management

Unfortunately, measuring rates of soil C sequestration is made difficult by large spatial variation in soil C stocks, thus requiring sampling and analyzing large numbers of soil samples to detect statistically significant change between two time points within a study field or between different treatment and control experimental fields. It also requires measurement of both C concentration (g C g⁻¹ soil) and the bulk density (g soil cm⁻³), which is labor-intensive. Finally, it also requires consideration that soil C stocks may change differently at different depths, and so concentrations and bulk density should be measured at more than one depth, including below the usual 15 cm plow layer (Davidson and Ackerman 1993).

One such study was conducted at the Agricultural Research Center in Beltsville, MD, by Cavigelli et al. (2018). Soils were sampled, and C concentrations and bulk densities were measured to a depth of 50 cm in 1996, 2006, and 2011 from fields treated with conventional tillage (CT), with chisel plow and disking, and with continuous no-till (NT), with four replicated plots per treatment and four soil cores per replicate plot. Both systems followed the same three-year crop rotation: corn/rye-soybean/winter wheat-soybean. For the 15-year study period, the CT soils lost an average of 0.55 Mg C ha⁻¹ yr⁻¹, whereas the NT soils gained 0.37 Mg C ha⁻¹ yr⁻¹ (Table 1; note the units of C rather than CO₂eq - there are 12 MtC per 44 MtCO₂).

Modeled Changes in Soil C with Tillage Management, Cover Crops, and Climate Change

Cavigelli et al. (2018) used the data from this experiment and other data from the long-term Farming Systems Project at Beltsville, MD, to parameterize a process-based soil C model, CQESTR, which had previously been calibrated across North America to simulate the effects of management practices and climate change (Liang et al. 2009). The CQESTR model simulates decomposition of soil organic matter and crop residues as functions of soil texture, drainage class, temperature, water content, crop residue N content, and whether the crop residue is incorporated into the soil through tillage. Simulations of the 1996-2011 experiment reproduced the observations that soil C was higher in the NT treatment, and that soil C had declined in the CT, although simulated changes during the 15-year experiment were less than observed in both treatments.

The authors then simulated changes in soil C from 2012 to 2052 under scenarios with and without climate change. Without climate change, the model predicted average increases of soil C stocks of 0.021 and 0.014 Mt soil C ha⁻¹ yr⁻¹ under NT and CT management, respectively (Table 1). Under a climate change scenario of mean annual air temperature increasing by 2°C and mean annual precipitation increasing by 1.3 mm yr⁻¹, model simulations reduced the soil C gain under NT to near

zero and converted the gain to a loss of 0.02 Mt soil C ha⁻¹ yr⁻¹ under CT. Hence, the effect of simulated climate change alone on soil C decomposition caused an average change of -0.02 to -0.03 Mt soil C ha⁻¹ yr⁻¹ relative to the rates of soil C without climate change (Table 1).

Table 1. Summary of measured and simulated changes in soil C sequestration rates for Maryland agricultural soils.

Source	Conventional tillage	No-till	Changed Management	Reference
	Mt soil C ha ⁻¹ ya ⁻¹			
Measured at Beltsville farm, 1996-2011	-0.55	+0.37		Cavigelli et al. (2018)
Simulated at Beltsville farm, 2012-2052: <ul style="list-style-type: none"> • Without climate change • With climate change • With climate change and 30% crop yield loss • With climate change and 30% crop yield gain 	+0.01 -0.02 -0.12 +0.08	+0.02 0.00 -0.10 +0.10		Cavigelli et al. (2018)
Simulated change for Maryland soil C stocks: <ul style="list-style-type: none"> • Conventional tillage to no-till • Conventional tillage to reduced tillage • No cover crop to legume cover with 50% fertilizer reduction • No cover crop to non-legume cover with 25% fertilizer reduction 			+0.32 +0.25 -0.53 +0.20	Via (2021)
Simulated average for Maryland row cropland, 2015-2021	0.21			CTIC (2024)

In addition to the direct effect of climate change on crop residue decomposition and soil organic matter-C stocks, Cavigelli et al. (2018) also simulated the effects of changes in crop yield by -30%, -10%, +10%, and +30%. Climate change could potentially have either positive or negative effects on crop yield, depending upon its severity, the occurrence of extreme events, and management adaptation. This range of change from -30% to +30% in crop yield was meant to simulate a plausible range of positive or negative crop yield responses to climate change. Model simulations calculated a change of 0.8% of inputs to the soil from aboveground and belowground crop residues for every 1.0% change in crop yield. Consequently, the model simulated a change of 0.0033 Mt soil C ha⁻¹ yr⁻¹ for every 1.0% change in crop yield. Over the course of the 40-year simulated period, the combination of the direct effects of climate change on decomposition and the effects of climate change on crop yield and residue inputs to the soil resulted in a simulated change of +4.0 to -4.0 Mt soil C ha⁻¹ for +30% to -30% crop yield change under NT and +3.3 to -4.7 Mt soil C ha⁻¹ for +30% or -30% crop yield change under CT (Figure 1, Table 1).

These modeling results suggest that the most important factors determining the effect of climate change on soil C stocks are not simply the climate-dependent rate of decomposition of soil organic matter, but also the effects of climate change on crop yield and, hence, the rates of inputs of crop

residues to the soil. If this model result is correct, it implies that changes in soil C will be proportional to changes in crop yields in response to climate change, resulting in either gains or losses in soil C stocks that accompany gains or losses in crop yields.

The effects of NT on soil C stocks reported by Cavigelli et al. (2018) are qualitatively corroborated in a study by Via (2021), which used the COMET-Planner tool of the USDA Natural Resources Conservation Service. Via (2021) estimated that the conversion from CT to NT could sequester 0.32 Mt soil C ha⁻¹ yr⁻¹ in Maryland (Table 1), with a modest additional benefit of reduced emissions of nitrous oxide. This is similar to the change in soil C stocks observed at the Beltsville experimental farm by Cavigelli et al. (2018) under NT from 1996 to 2011, but much larger than their simulated soil C sequestration rate under NT through 2052 (Table 1). The difference may be that Via (2021) estimates the change in sequestration rates due to a switch from CT to NT, but that effect of sustained NT management is likely to decline over the long term as the sequestration capacity of the soil approaches a saturation point and a new equilibrium in soil C stocks is established (Moinet et al. 2023).

Via (2021) also estimated the potential for increased soil C sequestration by adoption of cover crops in Maryland using the COMET-Planner tool. She reported a potential for added sequestration of 0.20 Mt soil C ha⁻¹ yr⁻¹ for non-legume cover crops with a 25% fertilizer reduction (Table 1).

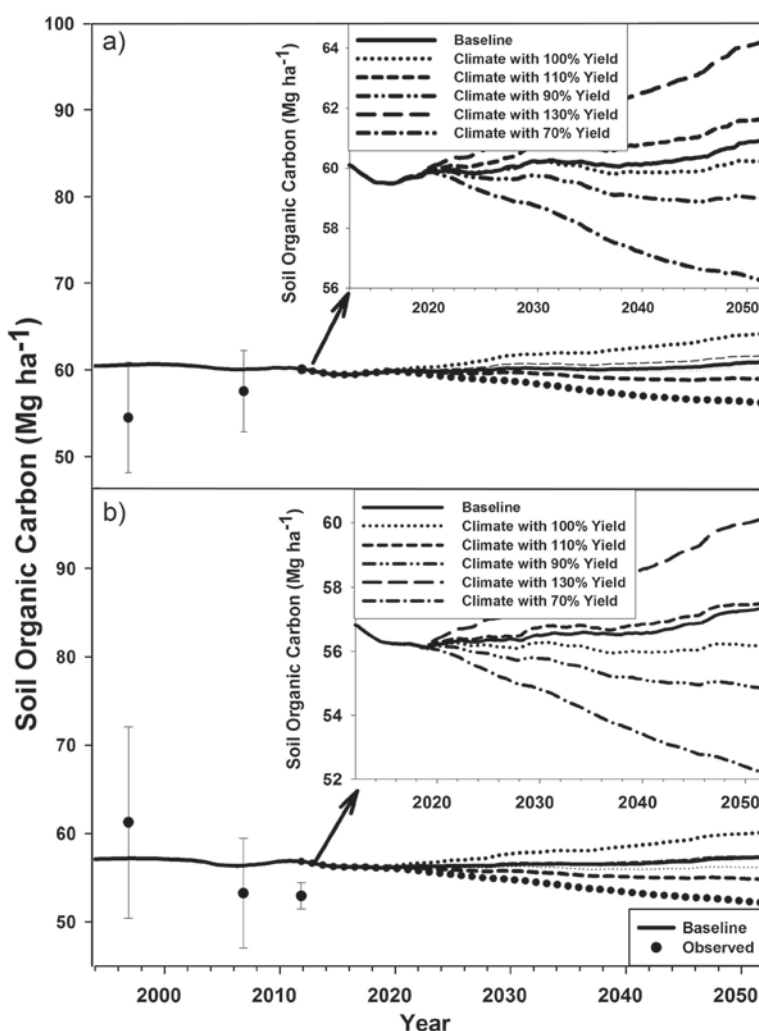


Figure 1. Observed (points with SD bars) and CQESTR model-simulated (lines) soil organic carbon at the at 0-50 cm soil depth (1996-2052) for (a) a no-till, and (b) a conventionally tilled corn/rye-soybean/winter wheat-soybean rotation at the USDA-ARS Farming System Project in Beltsville, MD. Six climate and crop yield scenarios were simulated. The baseline scenario assumed that crop yields and biomass inputs remained at the 1996 to 2014 average, and climate (mean monthly air temperature and precipitation) remained at the 2005 to 2014 average. The climate-only scenario assumed that biomass inputs remained at the 1996-2014 average whereas mid-century climate predictions (mean monthly air temperature and precipitation) were used to modify the 2005 to 2014 average climate values over the predictive period. Four climate and yield scenarios were factored in climate change but also included change to the average biomass input values proportional to crop yield change of 10 and 30% less and more than the 1996 to 2014 average. Thus, these four scenarios are termed climate with X% yield, where X is 70, 90, 110, and 130 of baseline yields.

Another relevant modeling estimate comes from the Conservation Technology Information Center (CTIC 2024), which uses remote sensing data on crop diversity, conservation tillage, and cover crops, along with databases on soil properties and climate, to run the DeNitrification-DeComposition (DNDC) model to estimate crop growth and yield, soil carbon and nitrogen dynamics, and greenhouse gas emissions (Gilhespy et al. 2014). During the 7-year period (2015-2021) of remote sensing data availability, adoption of NT in Maryland row crop area ranged from 25% to 43%, reduced tillage ranged from 28% to 42%, and conventional tillage ranged from 4% to 12% across the five Hydrologic Unit Codes (HUC8) regions of the state (Figure 2). According to this database, the percentage of row crop area with cover crops ranged from 3% to 28% and averaged 19% for the 7-year record (Figure 3). The statewide average cover crop area peaked at 30% in 2018 and declined to 19% in 2021.

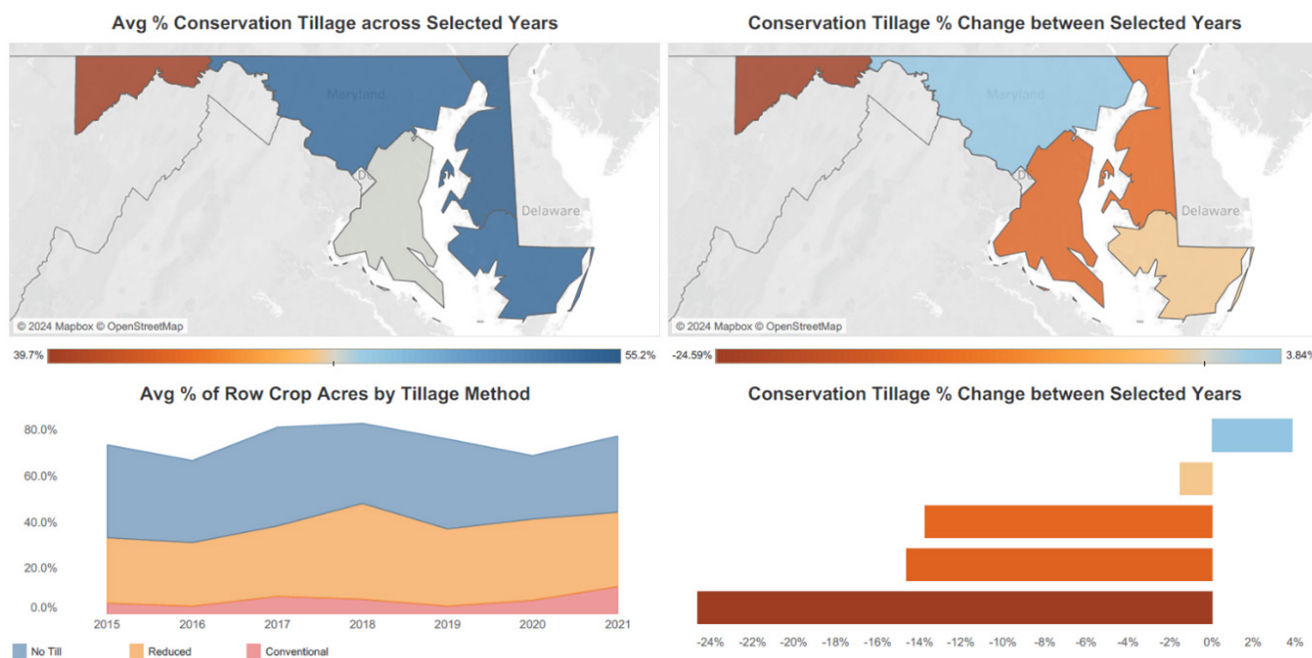


Figure 2. Tillage by HUC8 region, 2015-2021, from the Operational Tillage Information System, Conservation Technology Information Center. https://www.ctic.org/OpTIS_Tillage

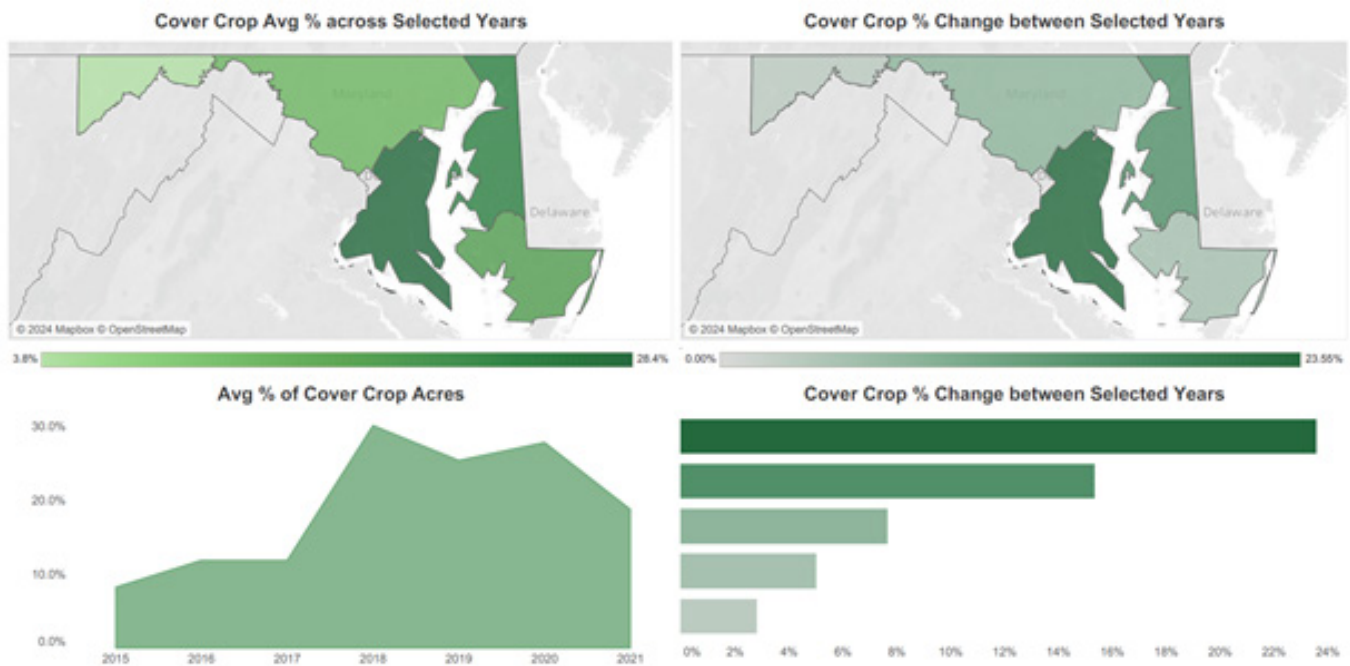


Figure 3. Cover crop area by HUC8 region, 2015-2021, from the Operational Tillage Information System, Conservation Technology Information Center. <https://www.ctic.org/OpTIS>

Using these remote sensing data on tillage and cover crop BMP adoption obtained by CTIC, the DNDC model simulated that average annual soil C stocks in Maryland’s row crop agriculture increased over the 7-year period by 0.21 Mt soil C ha⁻¹ yr⁻¹ (Table 1). Within-state variation among five HUC8 regions included soil C gains of 0.10, 0.24, 0.19, 0.30, and 0.24 Mt soil C ha⁻¹ yr⁻¹ in the lower Eastern Shore, upper Eastern Shore, southern, north-central, and western HUC8 regions, respectively. These gains in soil C occurred despite a remote-sensing-estimated reduction in the area of no-till and reduced tillage in all parts of the state between 2015 and 2021 (Figure 2), except for the north-central region, which experienced a small gain in NT area and is the region with the largest simulated increase in soil C. There was a statewide uptick in CT in 2021, which corresponded with a simulated decrease in the rate of soil C sequestration. Hence, it appears that average simulated soil C sequestration rates were affected by spatial and temporal estimates of the area of NT and CT, but that decreases in NT and increases in CT only caused a decreased rate of C sequestration rather than a complete halt or reversal. A decline in detected cover crop area between 2018 and 2021 (Figure 3) could have also contributed to a lower simulated rate of soil C sequestration simulated for 2021.

The CTIC simulated estimates of soil C sequestration, averaging 0.21 Mt soil C ha⁻¹ yr⁻¹ in Maryland’s row crop agriculture from 2015 to 2021, are affected by detected variation in areas of tillage and cover crop BMPs and the climatic conditions experienced during those seven years, but the reported results do not include specific attribution of C sequestration rates to each contributing factor, and only the combined impacts of these factors on model outputs are shown. It is not surprising that the simulated average soil C sequestration rate by the CTIC study is lower than the estimated potentials from adopting NT and cover crops from the Via (2021) study (Table 1), because the CTIC simulations include areas of row crop farms throughout Maryland that have not yet adopted these BMPs. Similarly, the larger observed gain in soil C reported by Cavigelli et al. (2018) was for a specific farm experiment at Beltsville, MD, where NT was in place for 15 years.

Prospects for Achieving Maryland's Goal for Increased Soil Carbon Sequestration in Agricultural Soils

Maryland's Climate Pollution Reduction Plan first calls for maintaining a purported agricultural soil C sink of 0.7 MMtCO₂eq yr⁻¹. Averaged across all two million acres of cropland and converting to units reported above, this is equivalent to an average soil C sequestration rate of 0.24 Mt soil C ha⁻¹ yr⁻¹, which is only modestly higher than the average of 0.21 Mt soil C ha⁻¹ yr⁻¹ reported by the CTIC modeling study for 2015-2021, and is smaller than the observed gain of 0.37 Mt soil C ha⁻¹ yr⁻¹ under NT at an experimental farm at Beltsville, MD (Cavigelli et al. 2018). While there are model uncertainties, and measurements from one farm may not be broadly applicable, the 0.7 MMtCO₂eq yr⁻¹ current agricultural soil sink for Maryland appears plausible.

The Maryland Climate Pollution Reduction Plan also calls for an increase of the agricultural soil C sink beyond current rates by an additional 0.2 MMtCO₂eq yr⁻¹ by 2045 through scaling up adoption of BMPs to 80% of Maryland's croplands. Counting both no-till and reduced tillage, adoption in Maryland is already 60-70% of row crop area, according to the CTIC remote sensing data (Figure 2). However, adoption of cover cropping, while high relative to the rest of the U.S., varies between only about 20% and 30% of row crop area in Maryland (Figure 3). According to the estimates of Via (2021), adoption of cover crops over another 50% of Maryland row crop area (one million acres; 400,000 hectares) could sequester 0.3 to 0.6 MMtCO₂eq yr⁻¹, suggesting that the 0.2 MMtCO₂eq yr⁻¹ goal is feasible if cover cropping were aggressively adopted. However, as already noted above regarding changes in tillage management, the Via (2021) estimates refer to the increased soil C sink following a switch from no cover cropping to consistent cover cropping, and it is unclear how long after the switch the additional rate of soil C sequestration would continue as a new soil C stock equilibrium is reached (Moinet et al. 2023).

Another way of thinking of this challenge is that, when averaged over all two million acres (0.81 million hectares) of cropland in Maryland, the additional 0.2 MMtCO₂eq yr⁻¹ goal could be met by an average soil C sequestration rate increase of 0.067 Mt C ha⁻¹ yr⁻¹. According to the model of Cavigelli et al. (2018), this additional soil C sequestration beyond current rates could result from a 20% increase in crop yield (0.0033 MtC ha⁻¹ yr⁻¹ for each 1% increase in crop yield).

In summary, Maryland's Climate Pollution Reduction Plan calls for maintaining a purported agricultural soil C sink of 0.7 million metric tons of CO₂-equivalents per year (MMtCO₂eq yr⁻¹), plus an additional 0.2 MMtCO₂eq yr⁻¹ by 2045 through scaling up adoption of best management practices (BMPs) to 80% of Maryland's croplands. Analyses of three studies, including a measurement and modeling study at the Beltsville, MD, experimental farm; an application of the USDA's COMET-Planner tool; and a remote sensing and modeling study, indicate that current rates of C sequestration in Maryland's agricultural soils could plausibly maintain a sink of 0.7 MMtCO₂eq yr⁻¹, although uncertainties are large. Average statewide simulated soil C sequestration rates from 2015 to 2021 in the modeling study with remote sensing were 0.21 Mt soil C ha⁻¹ yr⁻¹, which is consistent with a current sink on the order of 0.7 MMtCO₂eq yr⁻¹. The modeling studies also suggest a potential for increased soil C sequestration with additional adoption of tillage and cover crop BMPs, although the persistence of an increased soil C sequestration rate over the long term is uncertain. Most importantly, one modeling study indicates that soil C sequestration may be especially sensitive to changes in crop yields affected by climate change. For every 1% increase or decrease in crop yield, the simulated soil C sequestration increased or decreased by 0.0033 Mt soil C ha⁻¹ yr⁻¹. If crop yields increase, which could be possible with appropriate adaptations to a changing climate and attendant extreme climate events, increased inputs of crop residues to the soil could help achieve the goal of an additional soil sequestration of 0.2 MMtCO₂eq yr⁻¹ by 2045. On the other hand, if crop

yields decline in response to climate change, the expected increases in soil C sequestration due to expanded adoption of tillage and cover crop BMPs could be negated. The responses of crop yields to climate change in Maryland will likely affect the ability to achieve the stated soil C sequestration goal of Maryland's Climate Pollution Reduction Plan.

CONCLUSIONS

The goals of Maryland's Climate Pollution Reduction Plan for agricultural soil C sequestration are not unreasonable in light of the measurement and modeling studies reported here. However, they are tenuous because simulated responses of crop yields to climate change in Maryland appear to affect soil C stocks at rates similar to the gains expected from increased adoption of best management practices. It is possible that, with adaptation through appropriate crop varieties, multiple cropping, and irrigation, climate change and CO₂ fertilization could have a beneficial effect on agricultural productivity in Maryland. On the other hand, climate change, including heat waves, droughts, and storms, could also have a negative impact on crop yield, which would likely decrease rates of soil C sequestration. A significant negative response of crop yield to climate change could have a large enough impact on C sequestration rates to negate the gains that might have been conferred by expanded adoption of BMPs, such as NT and cover crops. Furthermore, these calculations do not consider soil C loss due to potentially significant loss of agricultural land in Maryland to commercial development and to sea level rise (Hutton et al. 2023). These modeling results are uncertain, but the apparent sensitivity of soil C stocks to rates of crop residue inputs renders soil C sequestration vulnerable to climate change.

RECOMMENDATIONS

- Support adaptations of agricultural management to climate change to maintain high crop productivity and large inputs of crop residues to soil. These C inputs to the soil are key to maintaining soil carbon stocks and perhaps sequestering additional soil C.
- Incentivize continued adoption of cover crops and conservation tillage, which have been shown to protect soil C and promote further soil C sequestration.

REFERENCES

- Cavigelli, M. A., P. R. Nash, H. T. Gollany, C. Rasmann, R. W. Polumsky, A. N. Le, and A. E. Cronk-lin. 2018. "Simulated Soil Organic Carbon Changes in Maryland Are Affected by Tillage, Climate Change, and Crop Yield." *Journal of Environmental Quality* 47: 588-595. <https://doi.org/10.2134/jeq2017.07.0291>.
- Conservation Technology Information Center. Accessed February 29, 2024. <https://www.ctic.org/>.
- Davidson, E. A., and I. L. Ackerman. 1993. "Changes in Soil Carbon Inventories Following Cultivation of Previously Untilled Soils." *Biogeochemistry* 20: 161-193.
- Gilhespy, S. L., Anthony, S., Cardenas, L., Chadwick, D., del Prado, A., Li, C., Misselbrook, T., Rees, R. M., Salas, W., Sanz-Cobena, A., Smith, P., Tilston, E. L., Topp, C. F. E., Vetter, S., and Yeluripati, J. B. 2014. "First 20 Years of DNDC (DeNitrification DeComposition): Model Evolution." *Ecological Modelling* 292: 51-62.

Hutton, P. C., Mikhailova, E. A., Lin, L., Hao, Z., Zurqani, H. A., Post, C. J., Schlautman, M. A., and Shepherd, G. B. 2023. "Net-Zero Target and Emissions from Land Conversions: A Case Study of Maryland's Climate Solutions Now Act." *Geographies* 3: 40-59. <https://doi.org/10.3390/geographies3010003>.

IPCC. 2022. *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by P. R. Shukla et al. Cambridge University Press, Cambridge.

Liang, Y., H. T. Gollany, R. W. Rickman, S. L. Albrecht, R. F. Follett, W. W. Wilhelm, J. M. Novak, and C. L. Douglas Jr. 2009. "Simulating Soil Organic Matter with CQESTR (v.2.0): Model Description and Validation Against Long-Term Experiments Across North America." *Ecological Modelling* 220: 568-581. <https://doi.org/10.1016/j.ecolmodel.2008.11.012>.

Maryland Department of the Environment (MDE). 2023. *Maryland's Climate Pollution Reduction Plan*. <https://mde.maryland.gov/programs/air/ClimateChange/Maryland%20Climate%20Reduction%20Plan/Maryland%27s%20Climate%20Pollution%20Reduction%20Plan%20-%20Final%20-%20Dec%2028%202023.pdf>.

Moinet, G. Y. K., Hijbeek, R., van Vuuren, D. P., and Giller, K. E. 2023. "Carbon for Soils, Not Soils for Carbon." *Global Change Biology* 29: 2384-2398. <https://doi.org/10.1111/gcb.16570>.

Via, S. 2021. "Increasing Soil Health and Sequestering Carbon in Agricultural Soil: A Natural Climate Solution." Izaak Walton League of America and National Wildlife Federation. <https://www.iwla.org/soils-agriculture/soilhealthreport>.

DAIRY PRODUCTION SYSTEMS

Eduardo Rico

SUMMARY

Similar to worldwide trends, ambient temperatures in the State of Maryland have progressively increased over the past few decades. Relative to 1971, the current average temperature (past five years) is 1-3°F higher than the historical average (NOAA). Despite this seemingly small variation, higher temperatures pose a threat to dairy cow production, welfare, and health, particularly for high-producing dairy cows that generate high amounts of metabolic heat during the summer months. Heat stress substantially increases the energy required for physiological maintenance, reducing the energy available for meat or milk production. Furthermore, dairy cows typically display reduced appetite and metabolic dysfunction originating from endotoxemia. Overall, unmitigated heat stress represents an annual loss of nearly \$1,460 million (Nigel et al. ESDA ERS, 2014). Extrapolation of available data from neighboring states to Maryland, suggests that increasingly larger productivity losses can be expected as temperatures rise over the next few decades, particularly under modeling scenarios where no heat abatement practices are implemented. Wide adoption and proper implementation of currently available technologies for heat abatement are deemed critical to overcoming this threat.

REPORT ON THE EFFECTS OF INCREASED TEMPERATURES ON DAIRY COW PRODUCTIVITY

Seasonal impacts in the U.S. Northeast

The impacts of heat stress on productivity are best exemplified by the seasonal variation in milk components, namely fat and protein. The effects of season on milk fat and protein in the U.S. Northeast region have been described by Bailey et al. (2005; Figure 1). The hot, humid months (July and August) typically correspond with depressed milk fat and protein content. Gradual reductions in component concentrations are observed as temperatures progressively increase. In addition to changes in milk fat and protein contents, the total amounts (grams per day) of these components also fit an annual rhythm at both the regional and cow levels.

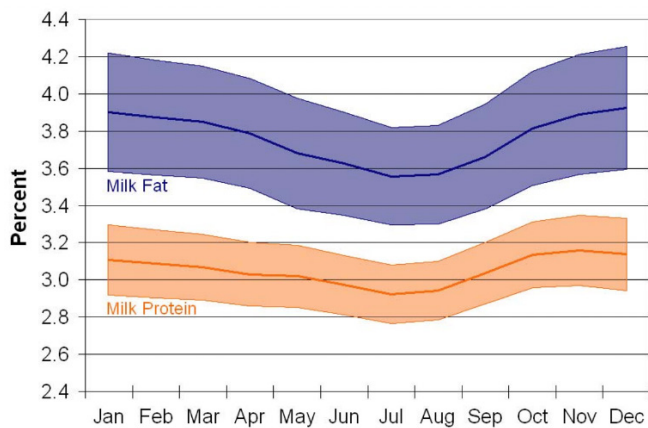


Figure 1. Level of fat and protein varies across herds and seasonally. Ranges represent one standard deviation above and below the average. The solid line in the center of each range indicates the average for that month. For the three years studied, milk fat % averaged 3.76 ± 0.32 (blue), and milk protein % averaged 3.05 ± 0.19 (orange). Taken from Bailey et al. (2005).

In addition to changes in milk fat and protein contents, the total amounts of these components also follow an annual rhythm at both the regional and cow levels. A cosine function with a 12-month rhythm was used by Salfer et al. (2019) to test for an annual rhythm in milk fat and protein concentration using USDA Federal Milk Market data. Figure 2 exemplifies the pattern of changes in milk protein content (%). Similar patterns are typically observed for milk fat content.

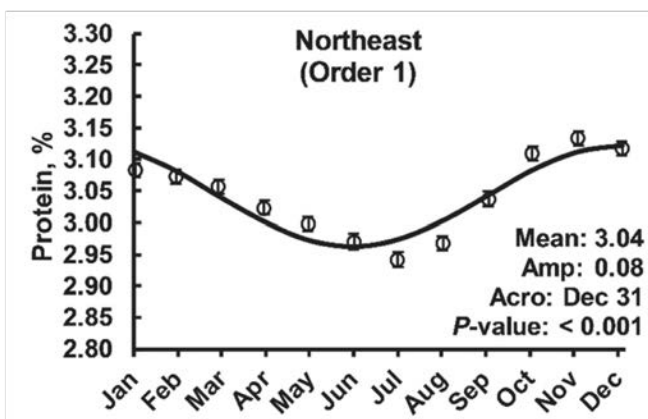


Figure 2. Annual rhythms of protein concentration in Federal Milk Market Orders in the Northeast. Data presented as LSM with error bars representing SEM of each month and the solid line representing a fitted cosine function with a 12-month period. Characteristics of fitted rhythm are displayed, including mean, amplitude (Amp; peak minus mean), acrophase (Acro; time at peak), and P-value for the zero-amplitude test corresponding to the fit of the 12-month cosine rhythm (Salfer et al. 2019).

Impacts in Maryland

In consideration of the limited amount of on-farm data in Maryland, representative neighboring states in the U.S. Northeast (i.e., Pennsylvania) were used to extrapolate the effects of increasing temperatures in Maryland. Dairy farms commonly implement several mitigation strategies to attempt a reduction in the environmental heat experienced by dairy cows during the hot months of the year. These strategies include heat abatement (e.g., fans, sprinklers, mist, and increased access to cool water) and nutritional modifications (e.g., increasing dietary fat content to reduce fermentation heat). Despite these efforts, the lactational performance of dairy cows continues to be reduced during the summer months (Figure 3; AMS report, USDA). This represents a concern for dairy production because of the trends for increased temperatures in the region.

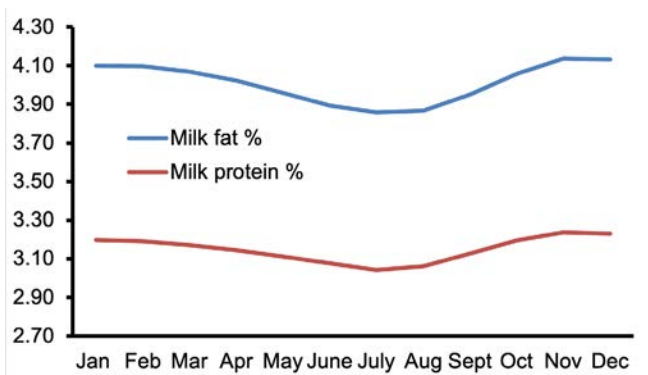


Figure 3. Producer Milk Components report. Data corresponds to dairy farms in the U.S. Northeast region (Agricultural Marketing Service [AMS], 2023, United States Department of Agriculture).

Although it is known that increasing temperatures in the Northeast compromise lactation performance, the quantification of the effects of heat stress on statewide dairy production is complicated by a number of confounding factors, particularly the continuous genetic progress in yearly milk production per cow. Figure 4 displays the trends in milk production per cow per year in two representative states of the Northeast, namely Pennsylvania and Maryland. These two states display similar trends in milk production per cow, mostly due to the similarities in geographical conditions and climate, as well as the similarities in genetics and farming practices used in these neighboring states.

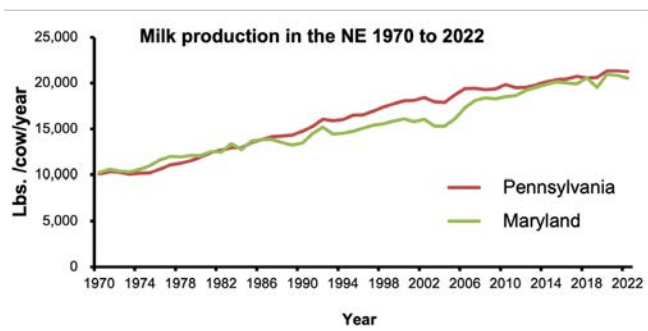


Figure 4. Historic trends in milk production in Maryland and Pennsylvania, as representative states of the northeastern U.S. (U.S. Department of Agriculture [USDA], Economic Research Service calculations using USDA, National Agricultural Statistics Service data).

Projection for Future Impacts in Maryland Dairy Herds

Based on the above-mentioned similarities between the states of Pennsylvania and Maryland, and considering the higher availability of farm-specific data for the former, the expected impacts of increased temperatures on milk production and economic losses were assumed to be similar across the two states. Climate change in southern Pennsylvania is projected to increase ambient temperatures and annual precipitation (Rotz et al. 2016). The severity of these effects will depend on the degree of projected warming, and for this reason, different warming scenarios are considered. Because of the impacts of heat stress on cow physiology (Baumgard and Rhoads, 2013), which are also manifested in loss of appetite, the projections of the effects of increased temperature on cow productivity are often reliant on the estimation of changes in nutrient intake (i.e., dry matter intake [DMI]; Hristov et al. 2018). For instance, Eastridge et al. (1998) indicate this relationship can be modeled for temperatures $>20^{\circ}\text{C}$ as $\text{DMI} \times \{1 - [(\text{C} - 20) \times 0.005922]\}$.

For a typical southern Pennsylvania farm, average annual losses in milk production from excess heat (mild to moderate increase scenarios) were projected to be approximately 2% by the year 2050, and as much as 7% by 2100 if no adaptation measures are adopted (Rotz et al. 2016). Overall, these changes can represent economic losses in the order of \$49 to \$140 per cow per year,* which would represent losses of ~\$2-6 million per year for the dairy industry in the State of Maryland (assuming no change in cow numbers from current).

**Estimates are based on 110,805 cows (2015 data) in Lancaster County, PA and \$20 per cwt (approximately \$0.44 per kg) milk price. From Hristov et al. 2018.*

Strategies for Heat Stress Mitigation in Dairy Farms

It is estimated that heat stress results in economic losses of over \$1 billion for the dairy industry when cows are not properly cooled, due to losses in productive performance, reduced fertility, and increased culling (St. Pierre et al. 2003). The economic analysis by Ferreira et al. (2016) indicates that, when not cooled, the average U.S. dairy cow can experience 96 heat stress days during the year, with losses of ~447 kg of milk in the subsequent lactation if not cooled during the dry period (i.e., the non-lactating period between lactations). A complete description of milk

losses across states in the U.S. can be seen in Figure 5. The incorporation of cooling systems appears to be largely beneficial for U.S. dairies, being profitable for 89% of farms when building a new barn is required, and very profitable when construction of a dry cow barn is not required (Ferreira et al. 2016).

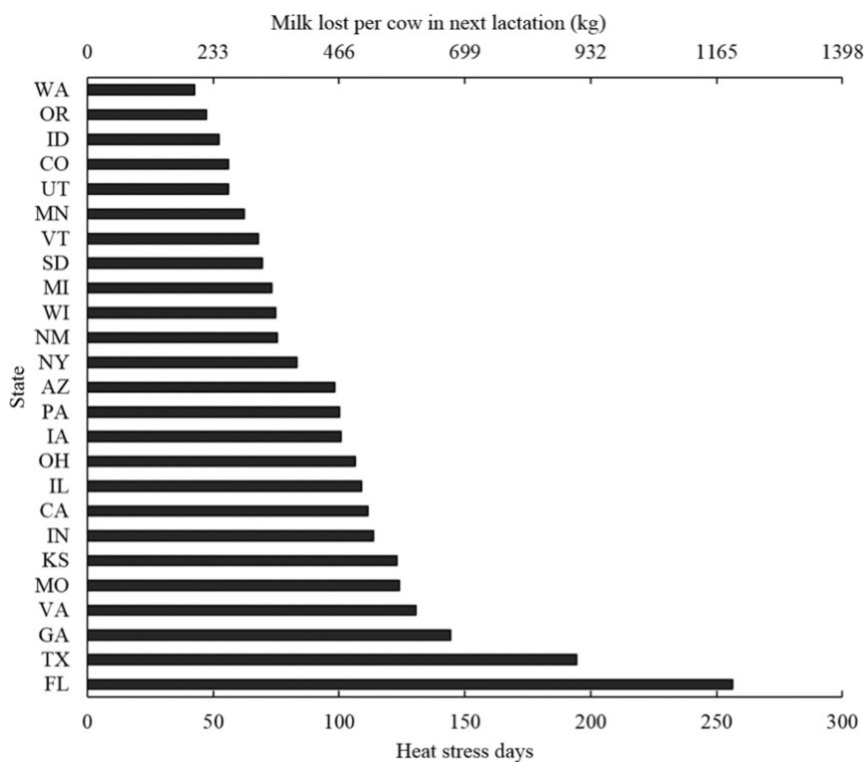


Figure 5. Milk lost per cow in the subsequent lactation (340 days) and days under heat stress for the top 25 states with the most dairy cows. We assumed an average loss of 4.66 kg per 340 days for each day of heat stress (Ferreira et al. 2016).

The basic heat abatement techniques available to dairy producers include **Shade, Air, and Water** - or **S-A-W** (McFarland, 2022). A summary of what these techniques entail follows:

- **Shade:** The objective is to protect cows from direct solar radiation, thus helping them maintain a lower body temperature and normal respiration rate. Shade can be provided in the form of trees, buildings, or shade structures.
- **Air Exchange:** Either via mechanical or natural systems, the goal is to perform air exchange every minute or less in order to remove moisture, heat, and other pollutants from the animal space.
- **Air Circulation:** Air movement can be supported by fans to allow increased convective heat transfer, enhance evaporation, and reduce hot spots.
- **Drinking Water:** Increased respiration and urination during hot weather may increase drinking water intake by 20% or more. Watering stations need to be located conveniently, allow multiple cows access, and keep up with water demand.
- **Evaporative Cooling (water):** Water is used to increase heat transfer from cows. Direct evaporative cooling (DEC) systems intermittently apply and evaporate water from the cow's skin, drawing heat directly from her body, while indirect evaporative cooling (IEC; e.g., fogging and misting) lowers the temperature of air surrounding the cow, increasing her heat transfer rate.

While implementation of cooling techniques is paramount for achieving heat abatement, sustained benefits can only be attained with regular maintenance of structures (buildings) and equipment (e.g., fans and water distribution systems; University of Minnesota Extension).

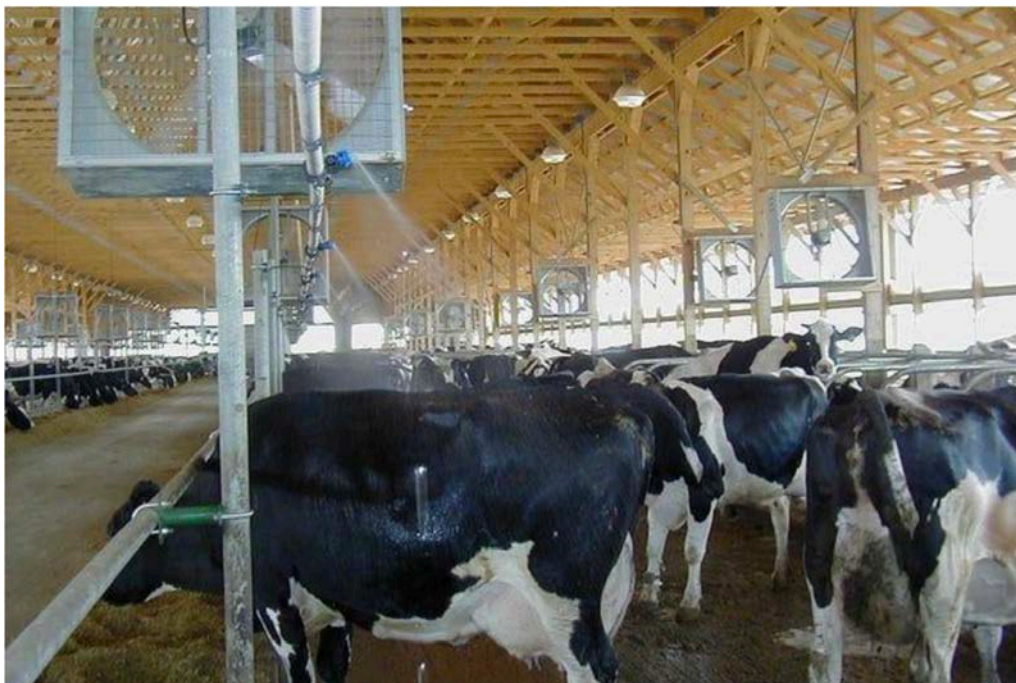


Image credit: Dan McFarland; Penn State extension.

In summary, although heat stress can significantly impact a cow's productivity and dairy farm profitability, currently available techniques for heat abatement can largely aid in overcoming these issues. Most dairy farms in the U.S., including those in Maryland, are predicted to experience increased productivity and profitability from the adoption of heat abatement technologies.

SUMMARY OF FINDINGS

Because of improvements in management practices and genetics, a weak correlation between dairy cow productivity and ambient temperature across the years is apparent. While this does not mean that climate change does not impact dairy cow performance and the productivity of the dairy sector, it highlights the major effect that genetic selection and improved management practices (e.g., improved nutrition) can have on animal productivity, even in the face of increased temperatures. Although a yearly pattern is difficult to assess, seasonal data indicates that dairy cow productivity is reduced during the summer months every year.

Higher temperatures pose a threat to dairy cow production, welfare, and health, particularly for high-producing dairy cows generating high amounts of metabolic heat during the summer months. Heat stress substantially increases the energy required for physiological maintenance, reducing the energy available for meat or milk production. Furthermore, dairy cows typically display reduced appetite and metabolic dysfunction originating from endotoxemia. Overall, unmitigated

heat stress represents an annual loss of nearly \$1,460 million (Nigel et al. ESDA ERS, 2014). Because mitigation strategies are not 100% sufficient to reduce excess thermal load, ultimately, milk production losses can still be expected to represent 2.5-6 lbs. per cow per day.

The impacts of heat stress on productivity are best exemplified by the seasonal variation in milk production per cow, as well as that of components, namely fat and protein. The hot, humid months (July and August in the Northeast) typically correspond with depressed milk fat and protein content. Gradual reductions in milk yield and milk component concentrations are observed as temperatures progressively increase.

Using data from neighboring states (i.e., Pennsylvania), we extrapolated that the average annual losses in milk production from excess heat (mild to moderate increase scenarios) can represent approximately 2% by the year 2050, and as much as 7% by 2100 if no adaptation measures are adopted (Rotz et al. 2016). Overall, these changes can represent economic losses in the order of \$49 to \$140 per cow per year,* which would represent losses of ~\$2-\$6 million per year for the dairy industry in Maryland (assuming no change in cow numbers from current). Importantly, heat abatement strategies are widely used by dairy farms in the Northeast U.S., including those in Maryland. This indicates that with the widespread adoption of heat abatement measures on dairy farms, significant productivity losses can largely be negated.

CHALLENGES AND CONCLUDING REMARKS

Obtaining precise data on the impacts of climate change on dairy cow productivity is difficult due to the large variability that can be expected regarding individual animal susceptibility and the effectiveness of heat abatement management strategies across dairy farms. Limited precision in quantifying these impacts stems from two main factors.

- 1)** The impact of increased temperatures on cow physiology, and ultimately on milk yield, depends partly on the productivity level of a cow. High-producing dairy cows produce more basal metabolic heat and therefore face increased thermoregulation challenges.
- 2)** Although heat abatement technologies are widely used in dairy farms of the northeastern United States, the effectiveness of these strategies in cooling the animals may vary extensively depending on individual farm practices and protocols. Consequently, the actual impact of increased ambient temperatures may be minimal in well-managed dairy farms but substantial in poorly managed operations.

The impacts of increased temperatures on dairy cow productivity can be largely attenuated by the implementation of currently available mitigation measures, such as cooling via the use of fans (i.e., air movement), shade, and water sprinkling and misting systems. However, as mentioned above, the exact quantification of the effectiveness of these mitigation measures may vary extensively due to differences in the effectiveness of implementation at the farm level, which in turn is dictated by the methods used and precision in their implementation.

RECOMMENDATIONS

Dairy producers must fully adopt and correctly implement the currently available technologies for heat abatement. These are mainly represented by the use of shade (via well-designed facilities), water cooling systems, and an emphasis on constant air movement and exchange. These practices have been proven effective in reducing heat load and, as such, can directly improve animal welfare during the summer months, maximizing the productivity of dairy cows in the State of Maryland.

Furthermore, emerging dietary management strategies for on-farm implementation (e.g., modulation of dietary concentrations of Vitamin D3, omega-3 fatty acids, dietary protein, etc.) hold promise in aiding dairy farmers in further mitigating the negative impacts of heat stress.

REFERENCES

Berkeley Earth, NOAA, UK Met Office, MeteoSwiss, DWD, SMHI, UoR, and ZAMG.

Ferreira, Fernanda C., R. S. Gennari, G. E. Dahl, and A. De Vries. 2016. "Economic Feasibility of Cooling Dry Cows Across the United States." *Journal of Dairy Science* 99 (12): 9931-9941.

Hristov, A. N., A. T. Degaetano, C. A. Rotz, E. Hoberg, R. H. Skinner, T. Felix, H. Li, P. H. Patterson, G. Roth, M. Hall, and T. L. Ott. 2018. "Climate Change Effects on Livestock in the Northeast US and Strategies for Adaptation." *Climatic Change* 146: 3-45.

McFarland, D. 2022. "Heat Stress Abatement Techniques for Dairy Cattle." Penn State Extension. <https://extension.psu.edu/heat-stress-abatement-techniques-for-dairy-cattle>.

Nigel, K., S. Sneeringer, and D. Marquardt. 2014. *Climate Change, Heat Stress, and U.S. Dairy Production*. ERR-175. U.S. Department of Agriculture, Economic Research Service.

Rotz, C. A., R. Howard Skinner, A. M. Stoner, and K. Hayhoe. 2016. "Farm Simulation Can Help Dairy Production Systems Adapt to Climate Change." *Improving Modeling Tools to Assess Climate Change Effects on Crop Response* 7: 91-124.

Salfer, I. J., C. D. Dechow, and K. J. Harvatine. 2019. "Annual Rhythms of Milk and Milk Fat and Protein Production in Dairy Cattle in the United States." *Journal of Dairy Science* 102: 742-753.

St-Pierre, Normand R., B. Cobanov, and Gary Schnitkey. 2003. "Economic Losses from Heat Stress by US Livestock Industries." *Journal of Dairy Science* 86: E52-E77.

University of Minnesota Extension. "Heat Stress in Dairy Cattle." <https://extension.umn.edu/dairy-milking-cows/heat-stress-dairy-cattle>.

POULTRY PRODUCTION SYSTEMS

Jennifer Timmons

SUMMARY

Broiler chicken production generates the highest revenue of any agricultural commodity in Maryland (USDA NASS 2021). Climate change may lead to changes in housing systems for the broiler industry. The broiler industry has been proactive in implementing technology in broiler houses to provide an optimum thermal environment to promote bird health and performance. Currently, a pooled data system that includes electricity and propane usage per pound of chicken meat in Maryland for the last 40 years is not available. In addition to housing modifications, changes to broiler genetics and dietary strategies may also offer solutions for the industry to reduce the impact of climate change on production. The incidence of disease outbreaks in the poultry industry may or may not be impacted as a result of changes to the climate in the region. Based on current reports, it is unclear how much poultry growers in the region will be impacted if current climate trends continue; however, the poultry industry is very proactive and will adapt various housing, genetic, and nutritional strategies if necessary to continue to maintain broiler health and production.

BACKGROUND AND RESULTS OF RESEARCH

Nearly 48 percent of the market value of Maryland agricultural products sold comes from poultry and eggs (USDA NASS 2021). The layer industry in Maryland is significantly smaller compared to the broiler industry. Maryland table egg production totaled 58.6 million in 2022. The total number of layer chickens raised in Maryland was 2.23 million in 2022 (USDA NASS 2023).

Birds, like mammals, are warm blooded and must maintain a fairly constant internal temperature around their core or internal organs. When it comes to maintaining their body temperature, birds have an outer shell that includes their skin and feathers, and the temperature of the shell can vary. The shell functions to protect the core from large losses or gains of heat. In hot weather, vasodilation occurs, which increases blood flow to the outer shell. This is to increase the transfer of heat from the core to the shell and then release the heat to the environment.

A bird rids itself of excess heat primarily in two ways: it loses heat to the air around it, and it loses heat through evaporation of water from its respiratory system. A bird's ability to release excess heat to the environment becomes less effective when the environmental temperature increases. As the internal temperature of birds rises, they will become heat stressed. High temperatures can cause a metabolic chain reaction that can result in reduced feed consumption, decreased weight gain, and, in some cases, damage to organs and death.

Climate change may lead to changes in housing systems, which will need to be managed differently if environmental temperatures rise or decrease. This will cause higher electricity and fuel costs (Hristov et al. 2018). Tunnel ventilation, along with evaporative cooling, is a standard practice used to keep broiler houses cool during warm weather. In a tunnel-ventilated broiler house, multiple exhaust fans are located at one end of the house to pull air from large openings (evaporative cool pad area) located at the opposite end of the house. The air pulled in from the tunnel fans creates a wind tunnel effect, and the air speed from these exhaust fans can exceed 600 feet per minute. If summer temperatures increase in the region, it would be expected that electricity and water usage would increase, resulting in higher input costs for the broiler producer. In addition, it is expected

that winter temperatures may also increase. Liang et al. (2009) reported that fuel usage decreases by 3.4% for every 1°C of ambient temperature increase and electricity use for ventilation remains fairly constant. The broiler industry may consider building future housing with more insulation and greater fan ventilation capacity to compensate for warmer temperatures. Perhaps some of the added costs for higher ventilation rates and cooling capacity in broiler houses would be offset by fuel savings during the winter months.

Due to changes in the egg industry, some companies are placing fewer hens in both cage and cage-free housing. Warming environmental temperatures will reduce fuel usage during winter months; however, it may cause heat stress for pullets and laying hens in the summer months. Raising fewer birds in the house is beneficial in the summer to keep birds comfortable; however, it does present heating challenges during the winter months.

In order to begin to determine the impact of changing temperatures on poultry production, the current energy and water usage of broiler houses must be considered. Several reports have estimated electricity, propane, and water usage in broiler houses (Table 1). Currently, a pooled data system that includes electricity and propane usage per pound of chicken meat in Maryland for the last 40 years is not available. A collection of data such as this would provide more insight into the impact of the changing climate on electricity and propane usage in broiler houses.

	Reference
Electricity Usage: 0.216667 kWh/kg body weight (BW ¹) 0.251 kWh for one broiler chicken (2.889 kg live wgt ¹) 20,000 kWh/year/house ³	Beal et al. 2023 ² Thoma and Putman 2021 Byrne et al. 2005
Propane Usage: 2,435.9 BTU/kg body weight	Beal et al. 2023 ²
Water: Consumption: 3.81 liters/kg BW Cool pad use: 1.43 liters/kg BW	Beal et al. 2023 ²

In addition to housing modifications, changes to broiler genetics and dietary strategies may also offer solutions for the industry to reduce the impact of climate change on production. Research to identify genetic solutions to improve resistance to heat stress in chickens is ongoing. Major thermotolerant genes include the naked neck, frizzle feather, and dwarf genes of indigenous chickens in tropical environments (Oke et al. 2024). The naked neck and frizzle feather genes are involved in feather coverage and quality. The dwarf genes are involved in reducing body weight. It has been reported that the naked neck gene reduces feather coverage by about 40% in homozygous chickens and 20-30% in heterozygous siblings (Lin et al. 2006; Fathi et al. 2013). The frizzle gene reduces the density of feathers allowing the birds to dissipate excess body heat more efficiently (Fathi et al. 2022). The frizzle gene reduces feather insulation through curling and decreasing the density of feathers (Lin et al. 2006; Fathi et al. 2013). The dwarf gene is associated with reduced body weight

1. In 2022, the average live weight of broiler chicken raised in Maryland was 2.9 kg (USDA NASS 2023).
2. Used baseline model of four houses (25,000 ft²/each house and placing 31,500 birds/house/flock) that raise birds to a 2.5 kg average body weight. Estimated 1,725,879 kg of live weight per year.
3. 23,880 birds per flock, 5.5 flocks per year.

by about 40% in homozygous males and 30% in homozygous females (Lin et al. 2006). The effect of the dwarf gene is more noticeable in a heavier broiler chicken compared to a lighter layer chicken. Two studies reported that the dwarf gene in fast-growing broiler chickens exposed to chronic heat stress did not improve the birds' ability to tolerate high temperatures (Deeb and Cahaner 1999; Lin et al. 2006). Currently, the application of these genetic concepts is limited, as it has been difficult to introduce these genes into commercial poultry without impacting their genetic value (Clements 2022). Another factor to consider is whether consumers will accept chicken meat products that come from a partially feathered or unfeathered bird.

Another way to prepare chickens for high environmental temperature exposure later in life is epigenetic temperature adaptation or thermal manipulation (Yahav et al. 2009). Alternative to maintaining a constant temperature throughout incubation, which results in the best hatchability and chick quality in moderate climates, increasing or decreasing the temperature during certain critical periods of embryo development may stimulate the development of different physiological control systems (Yahav et al. 2009). As a result, the ability of chickens to cope with heat stress as they reach market age might be improved. It has been suggested that intermittent thermal manipulation during embryogenesis, when applied for 12 hours per day between days 7 and 16 of incubation, can improve thermotolerance of broilers during acute post-hatching heat stress (Piestun et al. 2008, 2013). In addition to thermal manipulation during embryogenesis, other studies have exposed chicks post-hatch (3-5 days of age) to thermal manipulation temperatures (Yahav and Hurwitz 1996; Zaboli et al. 2017). These studies reported that exposure to thermal manipulation early in life may induce a tolerance to high heat exposure later in life.

In addition to developing birds that can tolerate high temperatures, there has also been work conducted to evaluate the ability to make birds more resistant to cold temperatures. Having birds that are more resistant to cold would be beneficial when they are young and fuel usage is highest to maintain bird comfort. This is accomplished not by genetics but by epigenetic temperature adaptation. During the embryonic stage of development, there is a window of time in which imprinting of physiological controls exists. It is thought that environmentally induced modifications of gene expression can occur as a result. One study reported that "cold conditioned" broiler chicks during embryonic development (pre-hatch) had improved body weight gain at 35 days of age (Schinder et al. 2011).

Dietary strategies are another adaptation tool that may provide birds the ability to deal with changing environmental temperatures. When birds consume a meal, heat is generated during digestion, which increases the birds' body temperature. It has been reported that some feed ingredients, such as fiber and protein, generate more heat during digestion than other ingredients. Research has suggested that feeding individual amino acids in place of feed protein may allow birds to digest protein more easily, which may have a positive impact on lowering body temperature. Broiler diets are formulated to contain the appropriate concentrations of limiting amino acids to optimize the economic traits of broiler chickens. Tryptophan (Trp) is considered the third most limiting amino acid in broiler diets. Trp is an essential amino acid due to its role in protein biosynthesis. Trp regulates the secretion of corticosterone, heat shock protein 70, and serotonin under normal physiological status (Bello et al. 2018), and could play a role in mitigating stress consequences in poultry due to its reported antioxidative activity (Christen et al. 1990). Tabiri et al. (2001) found that feeding 100% and 300% of NRC recommendations of Trp to 25-day-old broilers reared in a heat stress environment significantly improved body weight gain and feed efficiency compared to broilers fed a 50% Trp level reared in a heat stress environment. Prebiotics and probiotics may mitigate the negative effects of heat stress on broiler chickens by increasing the growth

of beneficial intestinal microorganisms, reducing the physiological stress response and promoting growth performance of broiler chickens (Awad et al. 2020). Wang et al. (2018) reported that broilers fed a probiotic can cope with heat stress by enhancing heat-induced behavior and inflammatory reactions through regulation of microbiota modulated immunity. A similar study (Cheng et al. 2019) reported that feeding a prebiotic to heat-stressed broilers from 0 to 42 days of age improved average daily gain and feed efficiency compared to the performance of heat-stressed broilers fed a standard diet without a prebiotic.

Biosecurity and controlling disease outbreaks are a high priority for the poultry industry. Poultry growers implement biosecurity practices daily to prevent the spread of disease to their birds or another farm's flock. It is unknown how climate change may impact the incidence of disease challenges in the poultry industry. Outbreaks of avian influenza continue to be a concern for the poultry industry in the United States. At the time of this report, there had been 1,139 confirmed flocks of avian influenza in U.S. commercial and backyard poultry from the 2022-2024 ongoing outbreak. These confirmed cases have affected over 90 million chickens and turkeys. In Maryland, there have been six affected commercial flocks and two backyard flocks, which impacted over 1.9 million birds. Gilbert et al. (2008) concluded that the biggest change in avian influenza epidemiology resulting from climate change will be brought about by the changes in distribution, composition, and migration behavior of wild bird populations that carry the virus. The impact of the environment on avian influenza transmission is not well understood and is thought to have minimal effect on the virus's epidemiology (Gilbert et al. 2008). However, climate change may influence the distribution of wild waterfowl and indirectly impact their contact with domestic poultry (Gilbert et al. 2008).

Based on current reports, it is unclear how much poultry growers in the region will be impacted if current climate trends continue. Thibeault and Seth (2014) reported that predicted warmer winter and summer temperatures, and fewer extreme cold nights in the northeastern United States would benefit broiler production by reducing fuel usage and disease challenges since ventilation rates would increase and improve the conditions inside the house.

RECOMMENDATIONS

It is unclear how much poultry growers in the region will be impacted if current climate trends continue. The broiler industry has been proactive in implementing technology in broiler houses to provide an optimum thermal environment to promote bird health and performance. Dietary strategies may provide the broiler industry with adaptation tools to mitigate the impact of changing environmental temperatures. Adding prebiotics and probiotics to broiler diets may mitigate the negative effects of heat stress on broiler chickens by increasing the growth of beneficial intestinal microorganisms, reducing the physiological stress response and promoting growth performance. In addition, higher levels of some amino acids, such as tryptophan and glutamine, in broiler diets may also offer a means for the industry to lessen the impact of changing environmental temperatures on broiler health and performance.

CHALLENGES

In order to begin to determine the impact of changing temperatures on poultry production, the current energy and water usage of broiler houses must be considered. Currently, a pooled data system that includes electricity and propane usage per pound of chicken meat in Maryland for the last 40 years is not available. A collection of data such as this would provide more insight into the impact of the changing climate on electricity and propane usage in broiler houses.

REFERENCES

- Awad, E. A., I. Zulkifli, S. K. Ramiah, E. S. Khalil, and M. E. Abdallah. 2021. "Prebiotics Supplementation: An Effective Approach to Mitigate the Detrimental Effects of Heat Stress in Broiler Chickens." *World's Poultry Science Journal* 77 (1): 135-151.
- Beal, C. M., D. M. Robinson, J. Smith, L. G. Van Doren, G. T. Tabler, S. J. Rochell, M. T. Kidd, W. G. Bottje, and X. Lei. 2023. "Economic and Environmental Assessment of U.S. Broiler Production: Opportunities to Improve Sustainability." *Poultry Science* 102: 102887.
- Bello, A. U., Z. Idrus, G. Y. Meng, E. A. Awad, and A. S. Farjam. 2018. "Gut Microbiota and Transportation Stress Response Affected by Tryptophan Supplementation in Broiler Chickens." *Italian Journal of Animal Science* 17 (1): 107-113.
- Byrne, J., L. Glover, S. Hegedus, and G. Van Wicklen. 2005. "The Potential for Solar Electricity Applications for Delaware's Poultry Farms." Final Report to a Renewable Energy Application for Delaware Yearly (READY) Project. Newark, DE: University of Delaware.
- Cheng, Y. F., C. R. Chen, Y. Su, Q. Zhang, Q. Zhang, Q. F. He, K. Wang, C. Wen, and Y. M. Zhou. 2019. "Dietary Mannan Oligosaccharide Ameliorates Cyclic Heat Stress-Induced Damages on Intestinal Oxidative Status and Barrier Integrity of Broilers." *Poultry Science* 98: 4767-4776.
- Christen, S., E. Peterhans, and R. Stocker. 1990. "Antioxidant Activities of Some Tryptophan Metabolites: Possible Implication for Inflammatory Diseases." *Proceedings of the National Academy of Sciences* 87: 2506-2510.
- Clement, M. 2022. "How Poultry Production Can Adapt to Climate Change." *Watt Poultry*. November 23. <https://www.wattagnet.com/poultry-future/new-technologies/article/15536736/how-poultry-production-can-adapt-to-climate-change>.
- Deeb, N., and A. Cahaner. 1999. "The Effects of Naked Neck Genotypes, Ambient Temperature, and Feeding Status and Their Interactions on Body Temperature and Performance of Broilers." *Poultry Science* 78: 1341-1346.
- Fathi, M. M., A. Galal, S. El-Safty, and M. Mahrous. 2013. "Naked Neck and Frizzle Genes for Improving Chickens Raised Under High Ambient Temperature: I. Growth Performance and Egg Production." *World's Poultry Science Journal* 69: 813-831.
- Fathi, M. M., A. Galal, L. M. Radwan, O. K. Abou-Emera, and I. H. Al-Homidan. 2022. "Using Major Genes to Mitigate the Deleterious Effects of Heat Stress in Poultry: An Updated Review." *Poultry Science* 101: 102157.
- Gilbert, M., J. Slingenbergh, and X. Xiao. 2008. "Climate Change and Avian Influenza." *Rev Sci Tech* 27 (2): 459-466.
- Hristov, A. N., A. T. Degaetano, C. A. Rotz, E. Hoberg, R. H. Skinner, T. Felix, H. Li, P. H. Patterson, G. Roth, M. Hall, T. L. Ott, L. H. Baumgard, W. Staniar, R. M. Hulet, C. J. Dell, A. F. Brito, and D. Y. Hollinger. 2018. "Climate Change Effects on Livestock in the Northeast US and Strategies for Adaptation." *Climatic Change* 146: 33-45.

- Liang, Y., G. T. Tabler, S. E. Watkins, H. Xin, and I. L. Berry. 2009. "Energy Use Analysis of Open Curtain vs. Totally Enclosed Broiler Houses in Northwest Arkansas." *Applied Engineering in Agriculture* 25 (4): 577-584.
- Lin, H., H. C. Jiao, J. Buyse, and E. Decuyper. 2006. "Strategies for Preventing Heat Stress in Poultry." *World's Poultry Science Journal* 62: 71-86.
- Oke, O. E., O. A. Akosile, V. A. Uyanga, F. O. Oke, A. I. Oni, K. Tona, and O. M. Onagbesan. 2024. "Climate Change and Broiler Production." *Veterinary Medicine and Science* 10: e1416.
- Piestun, Y., S. Druyan, J. Brake, and S. Yahav. 2013. "Thermal Manipulations During Broiler Incubation Alter Performance of Broilers to 70 Days of Age." *Poultry Science* 92: 1155-1163.
- Shinder, D., M. Ruzal, M. Giloh, S. Druyan, Y. Piestun, and S. Yahav. 2011. "Improvement of Cold Resistance and Performance of Broilers by Acute Cold Exposure During Late Embryogenesis." *Poultry Science* 90: 633-641.
- Tabiri, H. Y., K. Sato, K. Takahashi, M. Toyomizu, and Y. Akiba. 2002. "Effects of Heat Stress and Dietary Tryptophan on Performance and Plasma Amino Acid Concentrations of Broiler Chickens." *Asian-Australasian Journal of Animal Sciences* 15 (2): 247-253.
- Thibeault, J. M., and A. Seth. 2014. "Changing Climate Extremes in the Northeast United States: Observations and Projections from CMIP5." *Climate Change* 127: 273-287.
- Thoma, G., and B. Putman. 2021. "Broiler Production System Life Cycle Assessment: 2020 Update." National Chicken Council.
- United States Department of Agriculture, National Agriculture Statistics Service. 2020. "Maryland Agricultural Profile." December 2020. https://www.nass.usda.gov/Statistics_by_State/Maryland/Publications/Miscellaneous/Maryland-Agricultural-Profile.pdf.
- United States Department of Agriculture, National Agriculture Statistics Service. 2023. "Chicken Egg Report." January 2023. https://www.nass.usda.gov/Statistics_by_State/Pennsylvania/Publications/Survey_Results/2023/Dec22.ChickenEgg.Report.pdf.
- United States Department of Agriculture, National Agriculture Statistics Service. 2023. "Poultry Slaughter, 2022 Summary." February 2023. <https://downloads.usda.library.cornell.edu/usda-esmis/files/pg15bd88s/m613p944x/ht24xx05j/pslaan23.pdf>.
- Wang, W. C., F. F. Yan, J. Y. Hu, O. A. Amen, and H. W. Cheng. 2018. "Supplementation of *Bacillus subtilis*-Based Probiotic Reduces Heat Stress-Related Behaviors and Inflammatory Response in Broiler Chickens." *Journal of Animal Science* 96: 1654-1666.
- Yahav, S., and S. Hurwitz. 1996. "Induction of Thermotolerance in Male Broiler Chickens by Temperature Conditioning at an Early Age." *Poultry Science* 75: 402-406.
- Yahav, S., D. Shinder, M. Ruzal, M. Giloh, and Y. Piestun. 2009. "Controlling Body Temperature: The Opportunities for Highly Productive Domestic Fowl." *In Body Temperature Control*, edited by A. B. Cisneros and B. L. Goins. New York: Nova Science Publishers, Inc.

Zaboli, G., S. Rahimi, F. Shariatmadari, M. Torshizi, A. Baghbanzadeh, and M. Mehri. 2017. "Thermal Manipulation During Pre and Post-Hatch on Thermotolerance of Male Broiler Chickens Exposed to Chronic Heat Stress." *Poultry Science* 96: 478-485.

CLIMATE CHANGE AND ITS IMPACT ON CROP YIELD

Naveen Dixit

SUMMARY

The comprehensive data spanning 1974 to 2023 on yield, harvested acreage, and yield per acre of row and fruit crops across Maryland and its 23 counties reveals a significant trend: the yields of row crops (corn, soybean, wheat, barley, corn silage, hay, and hay-alfalfa) have consistently increased over these years. In stark contrast, both the yield and acreage of fruit crops (peach and apple) have experienced a marked decline. Despite gains in row crops, the absence of varieties of all crops that are tolerant to climate-related stressors has resulted in reduced yields during periods of drought and extreme temperature. A critical factor influencing these outcomes is the susceptibility of all evaluated crops—including corn, soybean, corn silage, hay, alfalfa hay, barley, wheat, peaches, and apples—to abiotic stresses such as drought and heat, exacerbated by climate change. Despite advancements in crop varieties that have led to improved yield indices, these varieties lack robust stress-resistant characteristics, and yields have been significantly reduced during periods of drought, high temperature, or other environmental conditions such as saltwater intrusion. Consequently, under the prevailing climatic conditions, abiotic stresses have caused significant yield declines in all studied crops. This phenomenon poses serious threats to Maryland's agriculture-dominated economy. It not only elevates commodity prices but also presents substantial challenges to the dairy and poultry industries, which are integral to the state's economic fabric. Every county within Maryland has exhibited adverse effects of climate change on one or more crops. The rainfed agricultural system, predominant in the state, is particularly vulnerable to climate change-induced abiotic stresses due to the lack of irrigation resources. For fruit crops, false springs are especially devastating, as they promote flower drop, leading to a consequential decline in yield. The findings underscore an urgent need for developing and deploying crop varieties with enhanced resistance to abiotic stresses. Additionally, there is a pressing need for investment in irrigation infrastructure and adaptive agricultural practices to mitigate the impacts of climate change. Without such interventions, the economic stability of Maryland's agricultural sector remains at significant risk, threatening food security and the livelihoods dependent on this critical industry.

METHODOLOGY

The dataset, encompassing state-level and county-level agricultural statistics such as production volumes, harvested areas, and crop yields covering the years 1974 to 2023, was obtained using the online Quick Stats tool. This resource is provided by the National Agricultural Statistics Service of the United States Department of Agriculture. The extensive data compilation by USDA NASS, which spans almost 50 years, offers valuable insights into agricultural trends and outputs across diverse geographical regions within Maryland.

Effect of Climate Change on Corn Yield during 1979 to 2022

Corn grain yield in Maryland has consistently increased over the last four decades, with a corresponding decrease in harvested area (USDA NASS, 1979-2022). Corn grain yield was 58.9 million bushels (m bu.) on 595,000 acres in 1979, rising to 62.7 m bu. on 380,000 acres by 2022 (Figures 1 and 2). The maximum corn grain yield was 75.3 m bu. on 430,000 acres in 2014, and the lowest was 27.3 m bu. on 420,000 acres in 1988. Similarly, the second and third greatest corn grain yields were recorded on 425,000 and 465,000 acres, respectively, in 2021 (74.4 m bu.) and 2019 (74.0 m bu.). Corn grain harvested area decreased by 40.6% from 1980 (640,000 acres) to 2022 (380,000 acres).

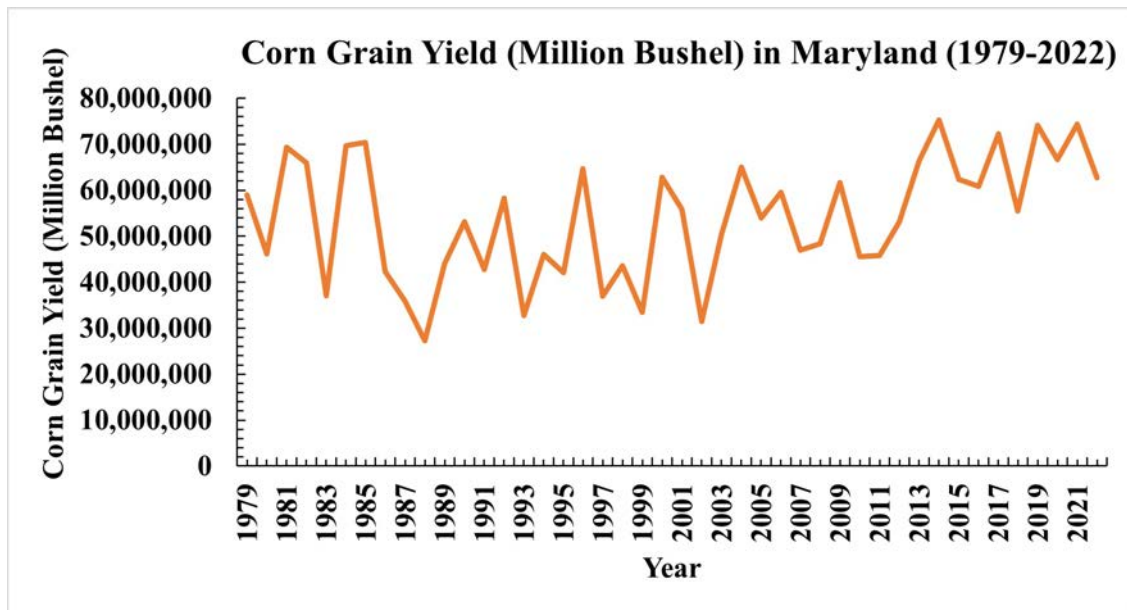


Figure 1: Corn grain yield (million bushels) in Maryland from 1979 to 2022.

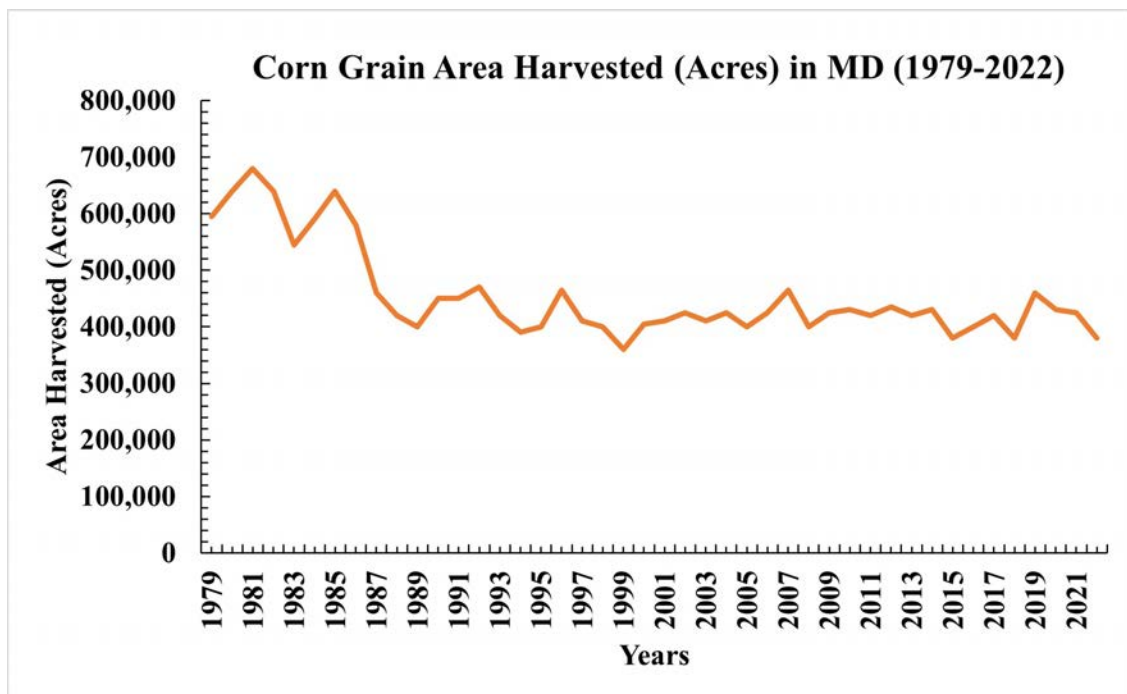


Figure 2: Corn grain area (acres) harvested from 1979 to 2022.

Multiple drought occurrences in Maryland over the previous four decades have coincided with a drop in corn grain yield (National Water Summary 1988-1989). Droughts in Maryland occurred in 1980, 1983, and 1988, coinciding with a decrease in corn grain yield. Corn grain yield fell by 21.8% in 1980 compared to 1979. Similarly, the reduction in corn production was 43.8% when compared to the 1982 yield. However, the greatest reduction in production during the four decades was found in 1988, when yield was 61.2% lower than in 1985, which was also associated with a 34.4% decrease in harvested area between 1985 and 1988. Except for the western section of Maryland, the drought from 1980 to 1983 affected the whole state. The Monocacy River basin, which includes parts of Frederick County, Carroll County, and Adams County, east of Baltimore, and the Chesapeake Bay region were all affected by the 1984-1988 drought. A federal drought emergency was declared for 40% of Maryland agricultural farmlands (Cohn and Mosses 1988).

The drought in 1993 lowered corn grain yield by 43.8% compared to the 1992 yield. Similarly, the harvested area of corn grain decreased by 10.6% between 1992 and 1993. Damage to corn crops was estimated to be between \$25 and \$30 million. Drought damage was severe in 15 counties, resulting in crop losses of more than 40%. Southern Maryland and the Eastern Shore were the hardest hit by the drought. Corn crop losses in Calvert and St. Mary's counties were 80% and 75%, respectively (The Baltimore Sun 1993a). Higher temperatures in early July disrupted pollination in maize and negatively impacted seed set (Arnold, 1993). The 1999 drought was the worst in Maryland in the last 70 years and coincided with a 48.2% decrease in corn grain yield and a 22.6% decrease in corn grain harvested area. The Northeast Region (MD and DE) experienced dry weather from April to August 1999, making it the driest period of the twentieth century (Summer [JJA] Drought Report, 1999).

In summary, over the past four decades, corn grain yield in Maryland has increased, while the harvested area has decreased (USDA NASS 1979-2022). However, frequent droughts—notably in 1980, 1983, 1988, 1993, and 1999—have significantly impacted yields. For example, in 1988, yields dropped by 61.2% from 1985 levels, with harvested areas also decreasing. Droughts particularly affected the Monocacy River basin, Southern Maryland, and the Eastern Shore, leading to substantial crop losses. To mitigate these declines, it is recommended that Maryland adopt drought-resistant corn varieties, improve irrigation infrastructure, and implement better water management practices to ensure sustainable corn production despite adverse climatic conditions.

Effect of Climate Change on Soybean Yield during 1979 to 2023

Soybean is a key oilseed commercial crop in Maryland, growing on 12,800 farms and contributing over \$200 million to the state's economy (MD Soybean Board, 2024). During 2021 and 2022, the soybean industry contributed \$160 billion to the U.S. economy and created 223,000 full-time paid jobs across the nation (National Oilseed Processors Association, 2023). In Maryland, the soybean enterprise, with average performance from 2018 to 2021, sustained 1,280 jobs, assisted 363 family farm members, disbursed \$62.5 million in wages, and generated an average revenue of \$840 million (National Oilseed Processors Association, 2023). Furthermore, the United States has supplied more than 30% of world soybean production, with an 18% rise in acreage since 2012 and a 30% increase in yield (USDA ERS, 2023). In Maryland, the soybean yield was 12.1 million bushels (m bu.) in 1979 and achieved its highest recorded yield of 25.7 m bu. in 2021, marking a 105% increase over a 44-year period (Figure 3). The harvested acreage underwent a modest shift of 19.8%, transitioning from 405,000 acres in 1979 to 485,000 acres in 2021 (Figure 4). The yield per acre exhibited a significant surge from 30 bushels per acre (bu/A) to 53 bu/A in 1979 and 2021, respectively (Figure 5). This represents a 77% increase compared to the soybean yield per acre in 1979.

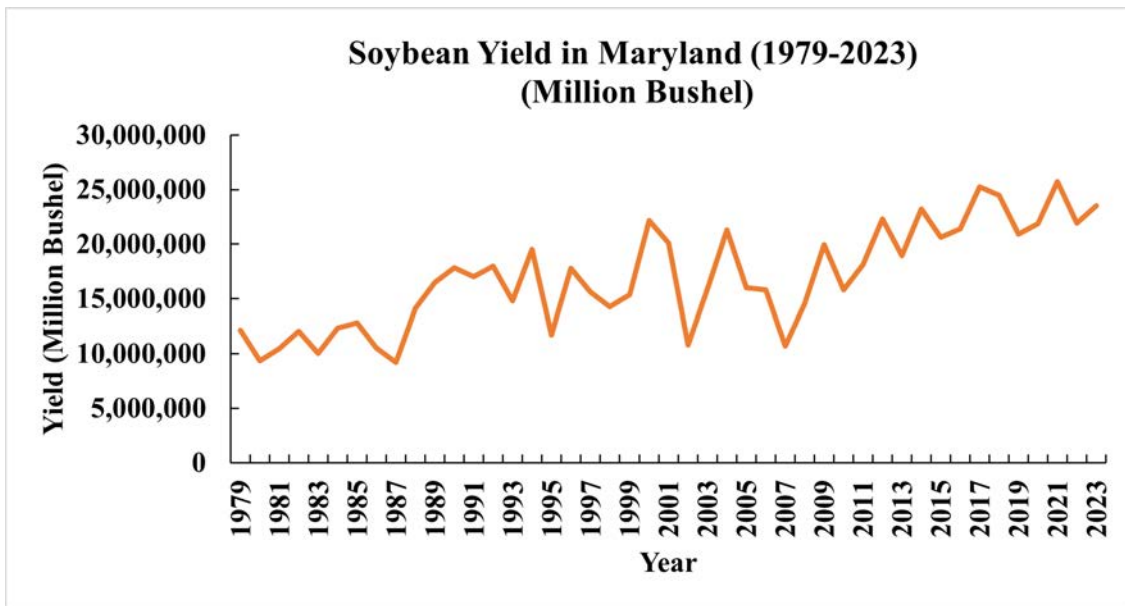


Figure 3: Soybean yield (million bushels) in Maryland from 1979 to 2023

In 1979, the top five counties with the highest soybean yield were Dorchester (1.8 m bu.), Caroline (1.6 m bu.), Queen Anne’s (1.5 m bu.), Wicomico (1.3 m bu.), and Worcester (1.2 m bu.). The lowest soybean yields were observed in Frederick County (16,000 bu.), Howard County (13,500 bu.), and Washington County (8,700 bu.). Soybean cultivation was minimal in Allegany and Garrett counties in 1979, with no available yield data. By 2021, soybean yields increased in all the top soybean-producing counties: Dorchester (2.1 m bu.), Caroline (2.0 m bu.), Talbot (2.1 m bu.), Kent (1.9 m bu.), and Worcester (1.9 m bu.). Notably, there was a remarkable increase in soybean production in Garrett County, going from negligible to 88,800 bu. by 2021. Additionally, Frederick County exhibited an increase from 16,000 bu. in 1979 to 1.8 m bu. by 2021 (USDA NASS 1979-2023).

In 1979, Carroll County led with the highest soybean yield per acre at 33 bu., while Kent, Montgomery, and Talbot followed closely with yields of 32 bu/A each. Harford, Queen Anne’s, and Worcester jointly held the third position, each recording a yield of 31 bu/A. Calvert, Howard, Prince George, and St. Mary’s counties each registered the lowest yield of 27 bu/A. The yield per acre increased significantly in 2021 across all the Maryland counties. Frederick, Worcester, Harford, and Washington were the leading counties with yields of 58, 58, 57.7, and 57.1 bu/A, respectively. Conversely, the lowest yields were observed in Garrett (5.8 bu/A), St. Mary’s (45.8 bu/A), and Calvert (47.3 bu/A). These significant increases in soybean yields are attributed to the use of genetically modified seeds, precision agriculture technologies, and sustainable applications of fertilizers, herbicides, and pesticides (USDA ERS 2023). Nevertheless, despite the integration of technology in soybean production, adverse climatic conditions such as drought, high temperatures, and saltwater intrusion have led to substantial losses in soybean yield (Teasdale and Cavigelli, 2017; Kogan, 1995; de la Reguera, 2020; Jaime, 2023). Drought commonly occurs in North America, with approximately 80% of the United States located in a climatic zone where annual water consumption surpasses annual precipitation (Gol’tsberg 1972).

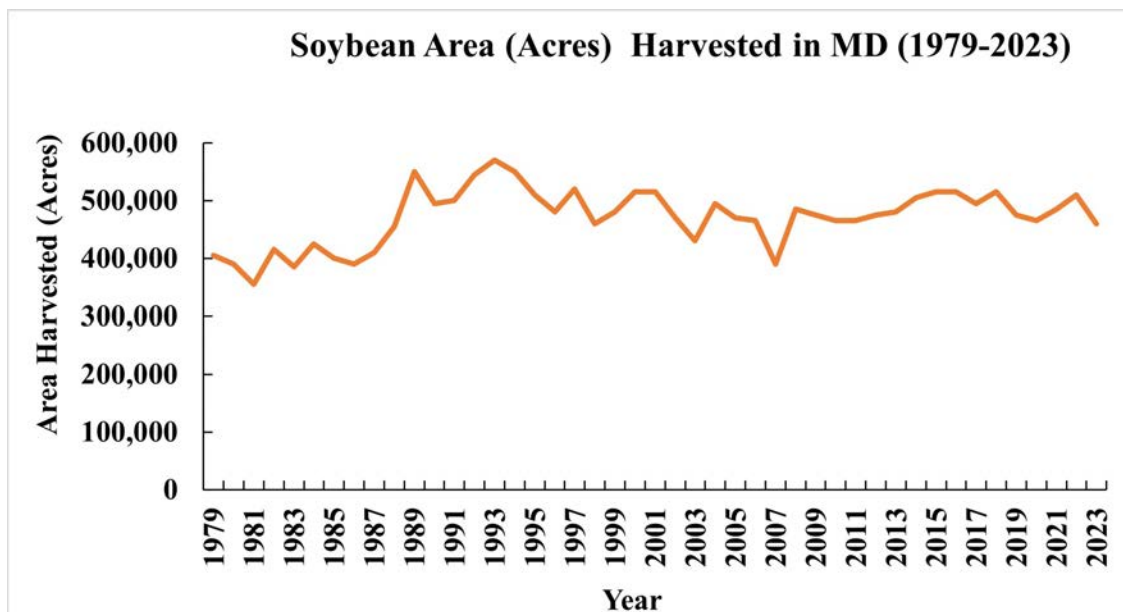


Figure 4: Soybean area (acres) harvested from 1979 to 2023.

Several instances of drought have occurred in Maryland over the last four decades. The droughts in the 1980s, specifically in 1980, 1983, and 1987, led to a significant decrease in soybean yields across several counties. The reduction in soybean yield was 23%, 18%, and 24% in 1980, 1983, and 1987, respectively, compared to the yields in 1979. The most substantial declines in soybean yield were recorded in Charles (45%), Cecil (42%), St. Mary's (39%), Caroline (28%), Kent (27%), Calvert (25%), Queen Anne's (25%), Talbot (24%), Washington (24%), and Worcester (23%) counties in 1980 when compared to the yields in 1979. Similarly, in 1983, soybean yield (bu.) declined in St. Mary's (41%), Carroll (40%), Charles (40%), Prince George (40%), Cecil (36%), Caroline (31%), Harford (31%), Baltimore (30%), Frederick (29%), and Montgomery (29%) in comparison to yields in 1982. The yield per acre also declined in St. Mary's (41%), Carroll (35%), Frederick (34%), Montgomery (32%), Charles (28%), Harford (26%), Prince George (25%), Cecil (23%), Caroline (17%), and Baltimore County (17%) compared to yields in 1982. From July 30 to August 26, 1983, most counties in the state received rainfall between 30% and 55% of their average levels (Vesey, 1983). The Delmarva Peninsula experienced temperatures reaching 105°F on August 20, 1983. The intense heat and insufficient moisture caused failure of pollination, seed set, and poor kernel growth. Low supply of crop caused a surge in soybean prices from \$5 to \$9 per bu. on the Eastern Shore of Maryland (Vesey, 1983). Maryland Agriculture Secretary Wayne A. Cawley Jr. declared his intention to request disaster aid for farmers in all 23 counties.

The second drought lasted from the fall of 1984 until the summer of 1988, impacting areas of Maryland east and south of Frederick, as well as the District of Columbia (USGS, 1988-1989). Numerous counties were designated as disaster regions due to significant agricultural losses during the summers of 1986 and 1987. Economic losses from this drought were projected to be \$89 million, \$113 million, and \$100 million in 1986, 1987, and 1988, respectively (USGS, 1988-1989). The smallest overall soybean yield (bu.) recorded from 1979 to 2023 occurred in 1987, with 922,500 bu. harvested from 410,000 acres. The soybean yield per acre dropped from 30 bu. in 1979 and 32 bu. in 1985 to 22.5 bu. in 1987, marking a 25% and 30% decline compared to the yields in 1979 and 1985, respectively. Queen Anne's County experienced the most significant decrease in total soybean yield among the counties, with a decline of 54%, followed by Caroline (53%), Talbot (50%), Kent (33%), and

Somerset (31%) in 1987 compared to 1985. Soybean yield drastically declined in 1987 in comparison to 1985. Caroline County witnessed a 50% decline, followed by Queen Anne's (45%), Talbot (45%), Kent (36%), and Somerset (19%) in 1987 compared to 1985. The harvested acreage was 400,000 in 1985 and 410,000 in 1987.

The drought in 1993 had a significant impact on soybean farmers in the Eastern Shore and Southern Maryland. Meanwhile, the drought in 1995 affected soybean farmers in the Eastern Shore, Southern Maryland, as well as in central and northeastern counties. Western Maryland counties experienced a moderate drought in 1995. The total soybean yield dropped to 14.8 m bu. in 1993 from 17.9 m bu. in 1992, and further decreased to 11.7 m bu. in 1995 from 19.5 m bu. in 1994. The harvested acreages were 545,000, 570,000, 550,000, and 510,000 acres in 1992, 1993, 1994, and 1995, respectively, while the planted acreages were 555,000, 580,000, 560,000, and 550,000 acres in the same years. In 1993, the most significant reduction in total soybean yield among the counties occurred in Montgomery (40%), followed by Charles (37%), Anne Arundel (34%), Caroline (33%), St. Mary's (33%), Kent (30%), Howard (28%), and Cecil (24%) compared to the yield in 1992. The impact of drought on yield per acre (bu.) varied significantly, ranging from 5% to 40% across these counties. The most substantial decrease in yield per acre (bu.) was documented in Charles (40%), Caroline (36%), Cecil (35%), Anne Arundel (35%), St. Mary's (34%), Kent (30%), Montgomery (22%), and Howard (5%) counties compared to the yield per acre in 1992. This data indicates the regions prone to drought in the Upper Eastern Shore, Southern, and North Central Agricultural Districts in Maryland.

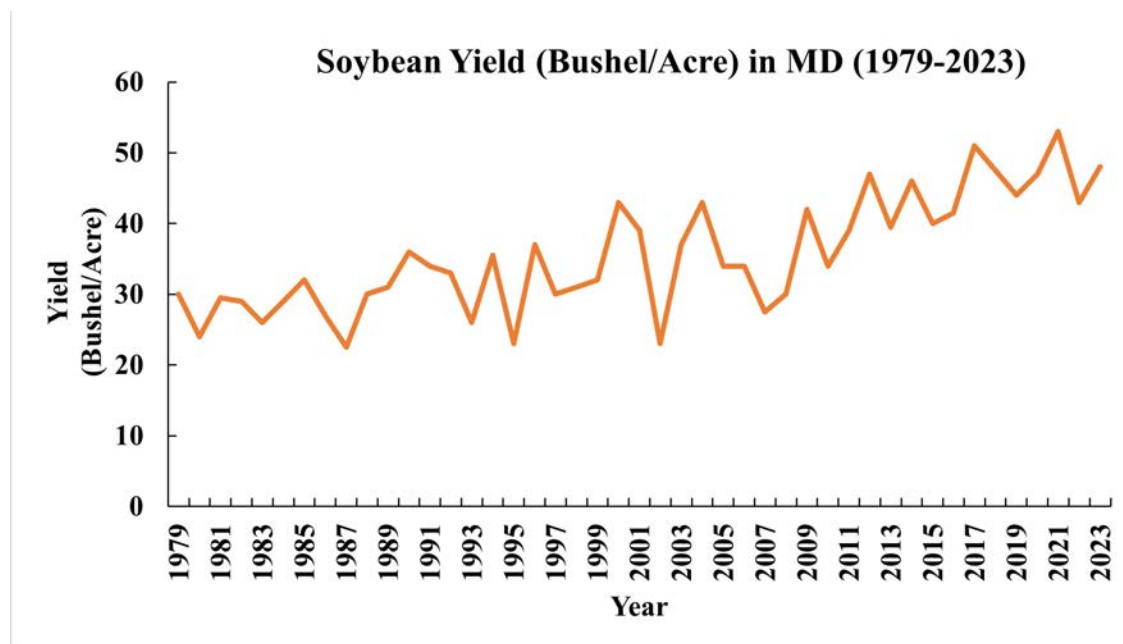


Figure 5: Soybean yield (bushels per acre) 1979 to 2023.

The situation became even more precarious during the 1995 drought, causing a 40% decline in total soybean yield compared to the yield in 1994. Planted acreages were 560,000 and 550,000 in 1994 and 1995, respectively, showing a decline of only 2% in 1995. In 1995, a 7% decline was observed between planted (550,000) and harvested acreage (510,000), likely an outcome of drought-devastated crops. Counties in the Eastern Shore and southern regions of Maryland were markedly affected by drought, leading to a significant reduction in total soybean yield (bu.). The most pronounced decline occurred in Caroline (69%), Anne Arundel (57%), Talbot (56%),

Wicomico (55%), Charles (49%), Dorchester (48%), and Calvert (46%) counties in 1995 compared to the yield in 1994. This data aligns with the decrease in yield per acre (bu.) in these counties. The most significant decline was recorded in Caroline (57%), followed by Talbot (51%), Charles (48%), Dorchester (47%), Anne Arundel (44%), Wicomico (40%), and Calvert (40%) counties in 1995 compared to 1994. The decline in harvested acreage in these counties was 14%, 2%, 8%, 12%, 5%, 8%, and 8% in Caroline, Talbot, Charles, Dorchester, Anne Arundel, Wicomico, and Calvert, respectively in comparison to planted acreage in 1995. This data showed the highest decline in harvested acreage in Caroline (14%), Wicomico (12%), and Dorchester (8%) counties, located on the Eastern Shore.

The nationwide drought of 2002, which was initiated in late 1999 and peaked in 2002, marked a severe drought event, unparalleled in the last four decades. The long-term drought, gauged through the Palmer Drought Index, encompassed 39% of the country's area, categorized as severe to extreme by July 2002. Dry conditions were evident in 2001 and persisted until February 2002 in the Eastern U.S. (NCEI 2002). Maryland Governor Parris N. Glendening issued an executive order declaring a drought emergency, imposing level one mandatory restrictions in Central Maryland. Residents were asked to limit their water consumption by 10%. Since September 1, 2001, rainfall and winter snow accumulation had been at least 10 inches below normal. The period from September 2001 to mid-August 2002 was the driest in Baltimore since record-keeping commenced in 1871 (Roylance 2002). In addition, stream flows and groundwater levels decreased significantly across the state, falling below the levels observed during the historic droughts of the 1930s and 1960s (MD Government 2002; Roylance 2002). In 2002, Baltimore encountered its eighth driest summer on record, having received only 5.54 inches of rain since June 1, 2002. The driest summer on record occurred in 1930, with a mere 3.81 inches of rainfall (Roylance 2002).

Nationally, there was a 4.5% decrease in soybean yields (Shack 2003). Maryland experienced the largest decline in soybean production across the country (Shack 2003). In 2002, soybean production (yield) in the state witnessed a 46% decline, amounting to 10.8 m bu., compared to the 20.0 m bu. recorded in 2001. The harvested acreage of 470,000 acres experienced a 4% reduction compared to the planted acreage of 490,000 acres in 2002. Similarly, there was a 9% decline in harvested acreage (470,000 acres) in 2002 compared to the area harvested (515,000 acres) in 2001. A substantial decline in yield per acre was evident, dropping from 39 bu/A in 2001 to 23 bu/A in 2002, representing a 41% decrease. Drought was most severe in Maryland's Eastern Shore and southern regions, with mild decreases in soybean yield in North Central counties. The highest decline in soybean yield was observed in St. Mary's (65%) followed by Dorchester (62%), Talbot (60%), Calvert (58%), Queen Anne's (54%), Charles (53%), Caroline (52%), Wicomico (52%), Kent (47%), Prince George (47%), Somerset (43%), and Worcester County (42%). In comparison to 2001, North Central counties experienced moderate declines in yields, including Harford (11%), Howard (16%), Montgomery (13%), and Carroll (7%) in 2002. Interestingly, Washington was the only county in Maryland with a 14% increase in soybean production in 2002, accompanied by increases in both harvestable (16%) and planted area (11%), compared to 2001. The decrease in yield per acre (bu.) was also modest in these counties compared to the Eastern Shore and southern counties. In 2002, the most significant decrease in yield per acre (bu.) occurred in St. Mary's (62%), followed by Calvert (62%), Talbot (58%), Charles (53%), Dorchester (51%), Wicomico (46%), Queen Anne's (45%), Prince George (45%), Caroline (43%), Kent (43%), Somerset (40%), and Worcester County (34%) compared to 2001.

The 2007 drought had a substantial impact on soybean production in the mid- and lower- shore, as well as in southern Maryland counties. The National Drought Mitigation Center reported unusually dry conditions throughout 97% of the state (Southern MD Online, 2007). Since May 2007,

persistent lower-than-normal rainfall levels have resulted in diminished soil moisture. A drought watch was issued for Baltimore, Caroline, Carroll, Cecil, Dorchester, Frederick, Harford, Howard, Kent, Montgomery, Queen Anne's, Somerset, Talbot, Wicomico, and Worcester counties (Maryland Government 2007). Soybean production fell 32% during the 2007 drought compared to 2006. Similarly, yield per acre decreased by 19%, from 34 bu in 2006 to 27.5 bu in 2007. Harvested acreage (390,000 acres) was down 4% compared to planted acreage (405,000 acres) in 2007. Planting and harvesting acreage fell by 14% and 16%, respectively, in 2007 compared to 2006. The most severe impact of the 2007 drought was witnessed in soybean yield with the largest decline in Calvert (65%), followed by Charles (51%), Talbot (48%), Kent (46%), St. Mary's (43%), Howard (41%), and Anne Arundel (38%) counties compared to soybean yields in 2006.

In 2010, 84% of Maryland experienced drought conditions ranging from dry regimes to extreme drought in southeastern Allegany County and southern Washington County. Additionally, abnormally dry conditions were observed in eastern Frederick County, extending into Montgomery, Prince George's, Harford, and St. Mary's counties (Lama 2010). Baltimore and the Eastern Shore suffered less severe dry conditions than Western Maryland (Lama 2010). Soybean production fell by 21% in 2010 compared to 2009. The planted and harvested acreages decreased by 2% and 3%, respectively, compared to 2009. Yield per acre fell by 19% compared to 2009. In contrast to 2009, Wicomico County experienced the greatest loss in soybean production (32%), followed by Talbot (32%), St. Mary's (29%), Frederick (29%), and Dorchester County. Yield data was unavailable for several counties in 2009, making it challenging to assess the percentage decline in soybean yield for multiple counties in 2010.

In summary, counties in Maryland are highly susceptible to drought and elevated temperatures, which significantly impact soybean production. Historical drought events in the 1980s, 1990s, 2002, 2007, and 2010 have resulted in notable yield reductions, with some counties experiencing declines of up to 65%. Critical soybean-producing regions, including the Eastern Shore, Southern Maryland, and the North Central Agricultural Districts, have been particularly affected, leading to economic losses and decreased agricultural employment. To mitigate drought and prevent yield decline, adopting drought-resistant varieties through genetically modified seeds can sustain yields, while implementing efficient irrigation systems like drip irrigation optimizes water use. Enhancing soil health with organic amendments and conservation tillage improves water retention. Employing precision technologies ensures accurate water and nutrient application, minimizing waste and enhancing crop resilience. Crop rotation and diversification reduce reliance on single crops, spreading risk. Additionally, government aid and insurance programs help mitigate financial risks for farmers facing adverse climatic conditions.

Effect of Climate Change on Corn Silage Yield from 1979 to 2023

Corn silage plays a crucial role in Maryland's agriculture because of its nutritional value for livestock, cost efficiency, effective land utilization, year-round availability, support for local economies, and potential environmental benefits. The importance of corn silage is highlighted by its ability to provide consistent and high-quality feed for dairy and beef cattle, making it a key component in the state's agricultural industry (Steinhilber et al. 2016). In 1979, corn silage production amounted to 1.50 million tons (Mt), which diminished to 0.5 Mt by 2023, reflecting a 66% reduction (Figure 6). Concurrently, the harvested acreage decreased from 97,000 acres in 1979 to 30,000 acres in 2023, signifying a 69% decline over four decades (Figure 7).

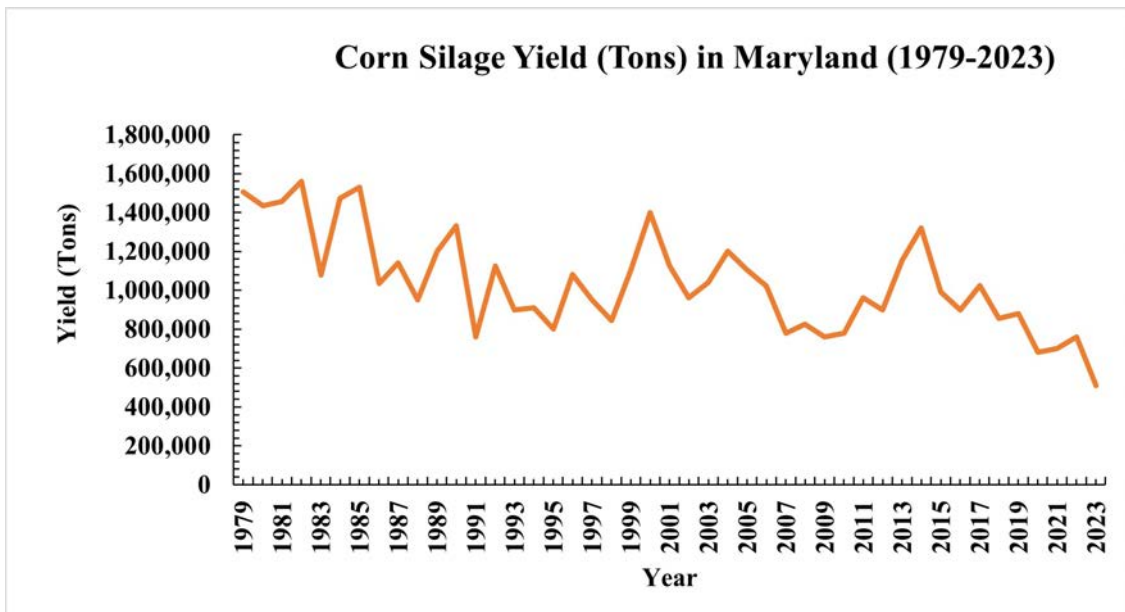


Figure 6: Corn silage production (tons) in Maryland from 1979 to 2023.

The peak corn silage yield of 1.53 Mt was documented in 1985 on 102,000 acres, whereas the maximum harvested acreage of 115,000 acres occurred in 1986. Yield per acre fluctuated between 15.5 and 17 tons per acre from 1979 to 2023 (Figure 8). The highest yield, 22 tons per acre, was recorded in 2014, 2015, and 2019, while the lowest yield, 8 tons per acre, was observed in 1991 (Figure 8). In 1979, the leading counties in corn silage production were Frederick (0.37 Mt), Washington (0.23 Mt), Carroll (0.22 Mt), Montgomery (0.11 Mt), and Harford (0.09 Mt). However, by 1992, all these top counties experienced a significant decrease in yields: Frederick saw a 12% reduction, Washington saw a 26% decline, Carroll a 19% drop, Montgomery a substantial 42% decrease, and Harford a 14% fall, compared to their 1979 production levels.

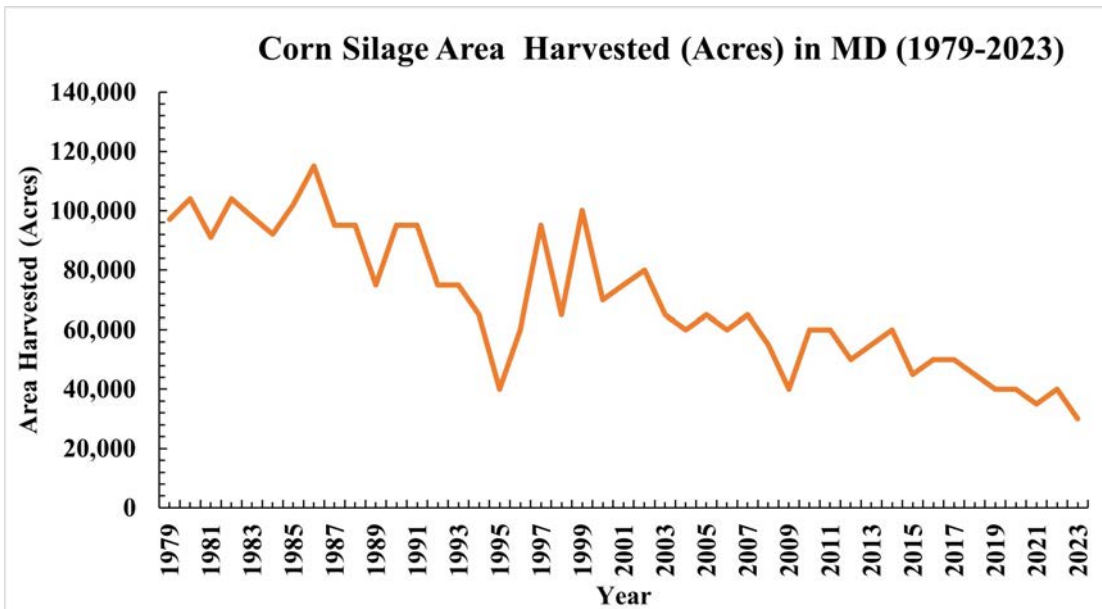


Figure 7: Corn silage area harvested (acres) from 1979 to 2023.

The 1991 drought severely impacted corn silage production in Maryland, resulting in a significant decline from 13,330,000 tons in 1990 to 7,600,000 tons—a reduction of 43%. Notably, this decrease occurred despite the harvested acreage remaining constant at 95,000 acres. The most significant reductions in yield were recorded in Queen Anne’s, Somerset, and St. Mary’s counties, with declines of 73%, 71%, and 70%, respectively. Furthermore, among the leading regions for corn silage production, Frederick, Washington, Carroll, Montgomery, and Harford counties experienced decreases of 44%, 43%, 41%, 55%, and 32%, respectively, in comparison to their 1991 yields. Similarly, the yield per acre experienced a reduction, dropping from 14 tons per acre in 1990 to 8 tons per acre in 1991. Notably, the most significant declines in yield per acre were recorded in 1991 compared to 1990 in the following counties: Charles (56%), Calvert (53%), Washington (53%), Frederick (50%), Carroll (47%), Harford (47%), and Montgomery (43%). Kent County experienced the most modest drop in corn silage output, with only an 8% reduction during the drought of 1991. Seventeen counties in Maryland, including Prince George’s and Howard, sought federal disaster aid due to the devastating impact of the drought, resulting in losses of nearly \$58 million for state farmers (O’Harrow Jr. 1991). Remarkably, this marked the fifth occurrence of drought within a mere decade. The agricultural sector has borne the brunt of this environmental crisis, with crops such as corn, hay, and pasture land suffering under the scorching heat and prolonged drought conditions. Additionally, the adverse effects of the drought were not limited to crop yield; numerous wells across multiple counties exhibited alarming signs of declining water tables, indicating the severity of the water scarcity issue (O’Harrow Jr. 1991). The meteorological data paints a grim picture, with a rainfall deficit of 5.26 inches recorded for the year leading up to May 31. These statistics underscore the severity and prolonged nature of the drought, exacerbating the challenges faced by farmers already struggling to cope with the adverse conditions. In response to the dwindling corn yields, some farmers were compelled to postpone planting schedules or switch to alternative crops such as sorghum (Young et al. 1991). This strategic adaptation reflects the pragmatic measures adopted by farmers to mitigate the impact of the drought on their agricultural operations. However, such adjustments come with their own set of challenges and uncertainties, underscoring the far-reaching repercussions of environmental crises on food production and economic stability within rural communities.

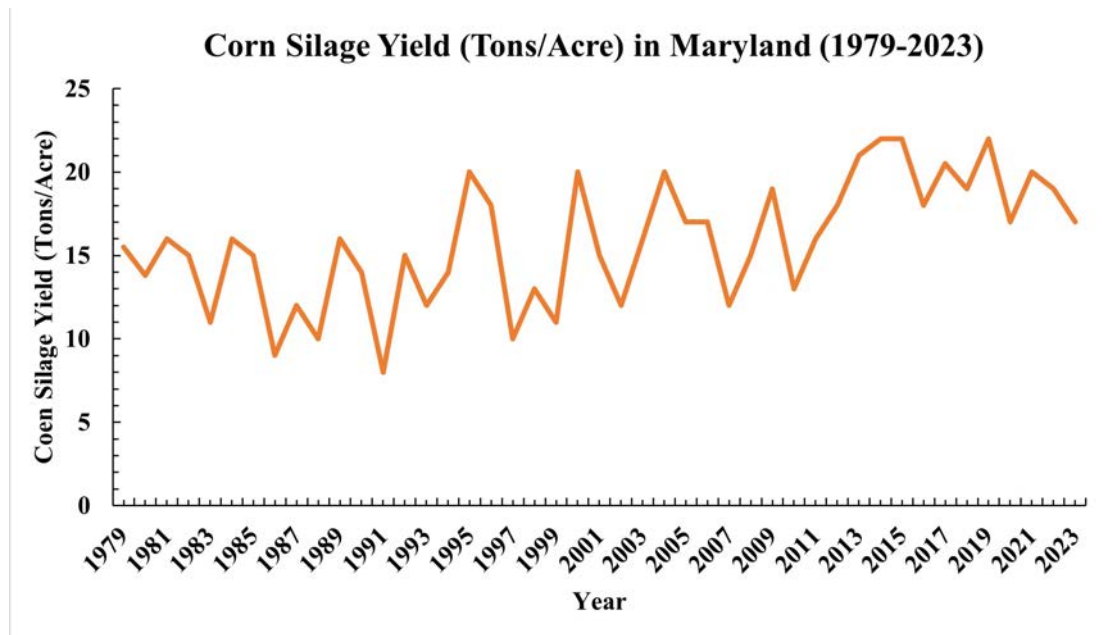


Figure 8: Corn silage yield (tons per acre) 1979 to 2023.

In 1993, 2002, and 2007, Maryland experienced several periods of drought, coinciding with notable declines in corn silage production. Despite maintaining or even expanding the acreage used for harvesting, there was a significant decrease in corn silage output by 20%, 15%, and 24% in those respective years. Furthermore, the yield per acre also suffered, dropping by 20%, 20%, and 29% in 1993, 2002, and 2007, respectively, compared to the yields of the preceding years. These figures underscore the detrimental impact of drought on corn silage farming in Maryland, both in terms of overall production and yield efficiency.

Drought significantly diminishes corn silage yield and degrades its nutritional quality. It results in reduced biomass and changes in nutrient composition, leading to lower energy and higher fiber content. This makes the silage less digestible and less effective as livestock feed. Drought-affected corn typically has a higher dry matter content, making proper fermentation and preservation more challenging and increasing the likelihood of spoilage. Moreover, drought raises the risk of mycotoxin contamination, which can harm livestock health. Consequently, farmers may face increased costs for supplemental feed and drought management efforts (Ziegler, 2023). Resop et al. (2016) delved into the potential production capacity of corn silage in the U.S. Northeastern Seaboard Region (NESR) by employing an extensive array of tools and datasets. By integrating geospatial data encompassing historical climate records, land use patterns, soil characteristics, and management practices alongside sophisticated models like SPUDSIM and MAZSIM, they projected the impact of mid-century climate change on corn silage production. Their findings unveiled a concerning trend: a projected 19% decline in corn silage output due to the effects of climate change. To counteract this decline and sustain current production levels in the face of future climate scenarios, Resop et al. underscored the necessity for a substantial increase in land allocation for corn cultivation, estimating a demanding 23% expansion in land area. However, they also highlighted a potential solution: widespread implementation of irrigation across the region. By ensuring consistent water availability, this adaptation strategy could significantly mitigate the adverse effects of climate change on corn silage yields. Crucially, the feasibility of such a strategy hinges on its economic viability, suggesting a need for further exploration of its potential costs and benefits.

Effect of Climate Change on Hay and Hay, Alfalfa Yield from 1979 to 2023

Hay plays a significant role in Maryland's agricultural sector, particularly in livestock nutrition, benefiting dairy, beef, and equine husbandry. Its cultivation across diverse geographical regions capitalizes on the state's fertile soil and varied climate. Apart from its agricultural function, hay production drives economic growth by generating income for farmers and stimulating related industries such as transportation, machinery manufacturing, and agricultural services. Additionally, hayfields contribute to soil conservation and erosion mitigation, supporting Maryland's environmental sustainability goals. Overall, hay cultivation is integral to Maryland's agricultural landscape and economic structure. In 2023, the hay industry significantly bolstered the state economy, contributing approximately \$88.5 million (USDA NASS 2023).

Historical data reveal that hay production reached 616,000 tons in 1979, decreasing to 519,000 tons by 2023. The year 2000 saw peak production at 711,000 tons, while the lowest production occurred in 2022, amounting to 409,000 tons (Figure 9). Concurrently, the harvested acreage peaked at 246,000 acres in 1979 and decreased to 205,000 acres in 2023 (Figure 10). The smallest harvest acreage was recorded in 2012, at 175,000 acres. Notably, the highest yield per acre was observed in 1994, at 3.3 tons per acre, whereas the lowest yield, 1.9 tons per acre, was recorded in 2022, marking a 44.2% decline compared to the 1994 yield (Figure 11). The leading counties for hay production in Maryland include Frederick, Carroll, Washington, Garrett, and Harford, with yields of 139,800, 67,600, 62,400, 53,500, and 47,600 tons per acre, respectively. These counties remained

at the forefront of hay production until 2008, beyond which county-specific yield data are not available. Agricultural drought frequently occurs at critical junctures during the growing season, resulting in a significant decrease in soil moisture and consequent crop failure (Lu et al. 2020). This condition not only undermines crop production but also significantly threatens the livestock sector by reducing both the availability and quality of crucial forage resources, such as hay and corn silage (Lu et al. 2020).

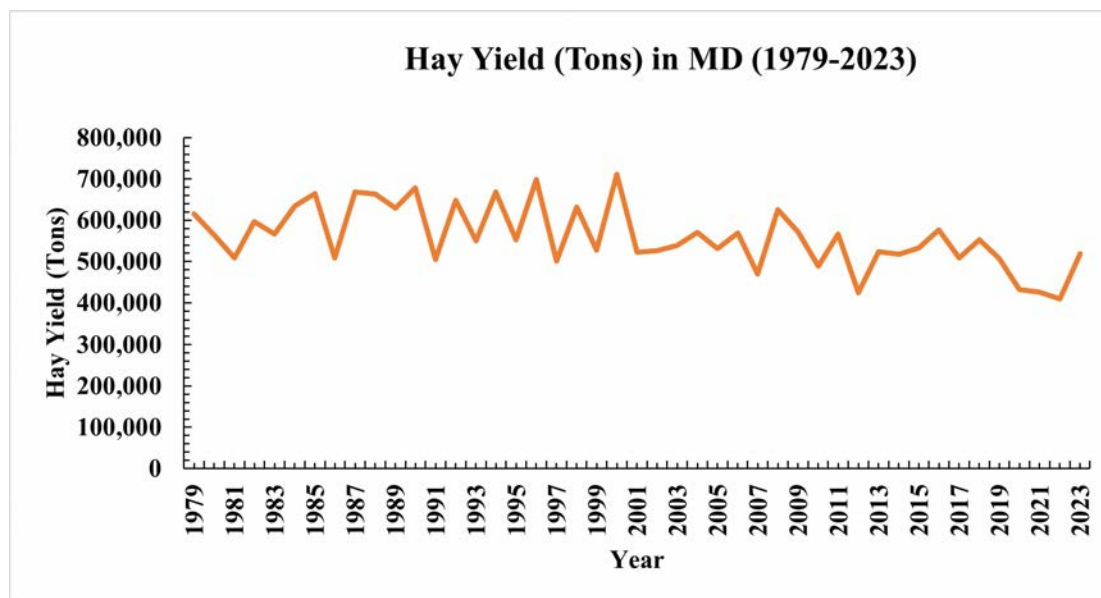


Figure 9: Hay production (tons) in Maryland from 1979 to 2023.

The combined effects of these impacts can disrupt food supply chains, elevate costs, and jeopardize the livelihoods of farmers and agricultural communities. The droughts experienced in 1991, 1995, 2007, and 2010, coupled with elevated temperatures, led to significant reductions in total hay production in Maryland, with respective declines of 26%, 17%, 17%, and 15% compared to the previous years. Notably, the harvest acreage in 1991 saw a 4.4% decrease from 1990 levels. Conversely, in 1995, 2007, and 2010, the harvested acreage increased by 2.5%, 5%, and 2%, respectively, relative to the preceding years. Despite these variations in acreage, yield per acre exhibited substantial declines of 20%, 18%, 21%, and 15% during the years 1991, 1995, 2007, and 2010, respectively, when compared to the previous years. These figures highlight the severe impact of drought conditions and high temperatures on hay productivity, underscoring the vulnerability of agricultural outputs to climatic fluctuations.

Among the various counties, St. Mary's, Anne Arundel, Allegany, Prince George's, Baltimore, Charles, Garrett, Frederick, Harford, and Carroll experienced the most severe reductions in hay production in 1991, compared to their yields in 1990. Specifically, the production declines in these counties were 61%, 56%, 50%, 42%, 39%, 36%, 37%, 33%, 29%, and 25%, respectively. These significant decreases highlight the extensive impact of adverse conditions on agricultural output. Conversely, Calvert, Talbot, and Worcester counties exhibited the least decline in hay production, with reductions of 3%, 6%, and 6%, respectively, indicating a relatively minor impact from the 1990 drought in these regions. These disparities underscore the variable resilience and vulnerability of different counties to environmental stressors, necessitating tailored agricultural and economic strategies to mitigate such impacts.

Hay Harvested Acreage(Acres) in Maryland (1979-2023)

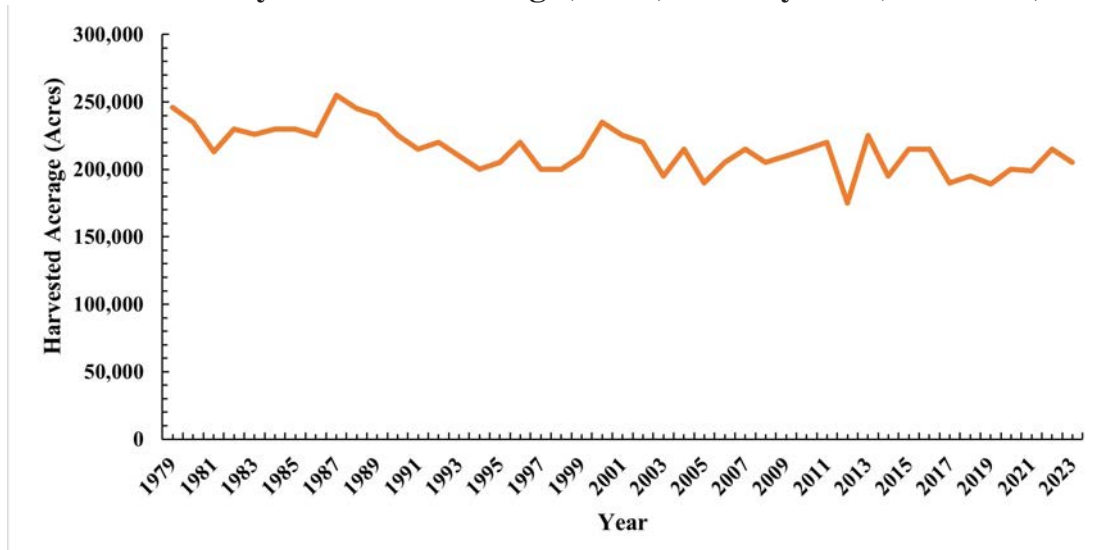


Figure 10: Hay area harvested (acres) from 1979 to 2023.

In their 2020 study, Lu and colleagues illustrated that the Standardized Precipitation Evapotranspiration Index (SPEI) for hay production exhibits its strongest correlation with the three-month SPEI calculated in July. This particular index is derived from a combination of precipitation and temperature data spanning the months of May, June, and July, underscoring the significant influence of climatic conditions during these months on hay yields. Among the various physical factors that constrain hay productivity—such as drought, pests, salt stress, and chilling—drought is recognized as the most critical (Heim, 2002). Drought stress severely impacts hay crops by reducing leaf area, stunting stem elongation, and impairing root growth. Consequently, implementing robust drought management strategies is essential to alleviate these adverse effects and ensure optimal hay production.

Hay Yield (Tons/Acre) in MD (1979-2023)

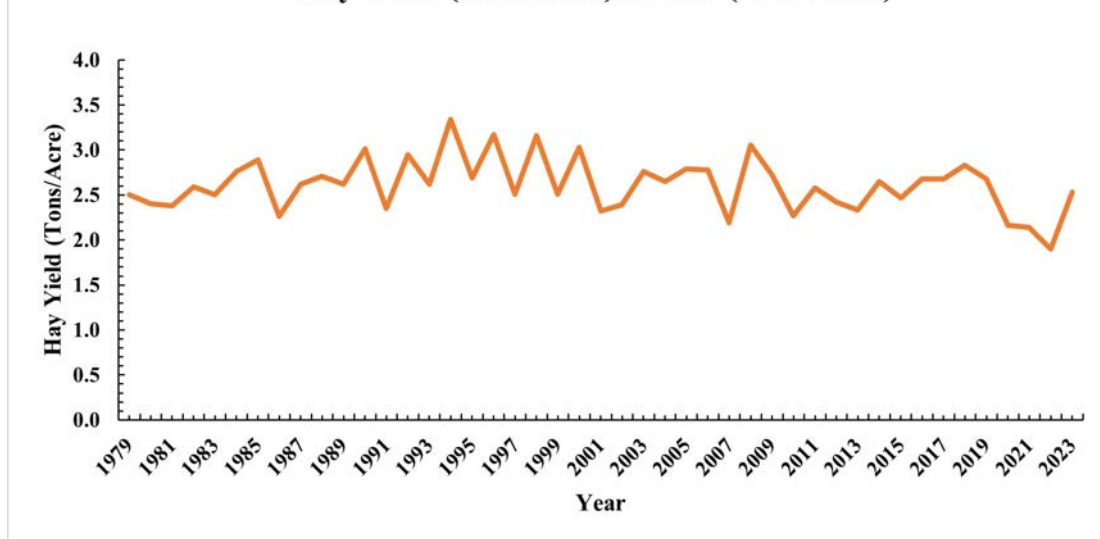


Figure 11: Hay yield (tons per acre) 1979 to 2023.

In the fiscal year 2023, Hay, Alfalfa, a vital component of the agricultural sector, made a substantial contribution of \$30.9 million to the state’s economic framework. However, despite its economic significance, the production of this crop is markedly susceptible to the adverse effects of drought conditions. A poignant illustration of this vulnerability is evidenced by the severe repercussions experienced during the 1997 drought period. Within this context, an empirical examination reveals a notable downturn in productivity, with a consequential decline in yield by 35%. This decline is starkly exemplified by a reduction in production from 282,000 tons in the preceding year of 1996 to a diminished output of 182,000 tons, as depicted in Figure 12.

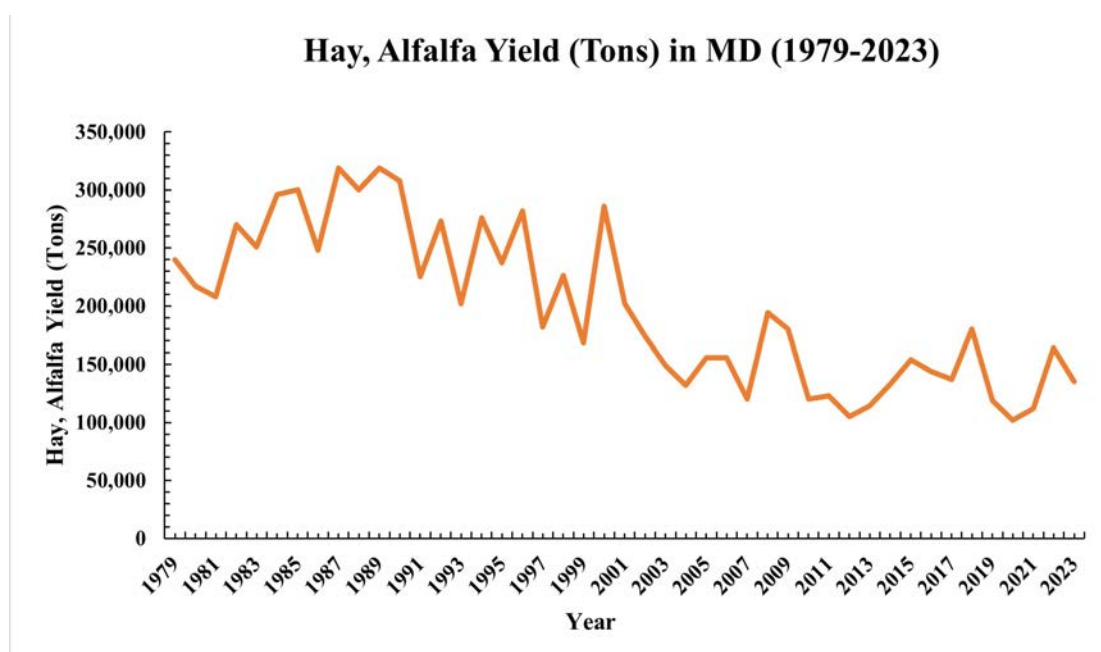


Figure 12: Hay, Alfalfa production (tons) in Maryland from 1979 to 2023.

Concurrently, the harvested acreage sustained an 8% reduction, plummeting from 60,000 acres in 1996 to a diminished expanse of 55,000 acres by the year 1997. Furthermore, the yield per acre witnessed a noteworthy decrease of 30% during the specified period, accentuating the magnitude of the adverse effects incurred. This intricate nexus between Hay, Alfalfa production and environmental exigencies underscores the imperative for strategic interventions and resilience-building measures within the agricultural domain.

Along with soy, hay, alfalfa is an important feed crop for Maryland’s cattle farmers, and decreases in these crops have significant downstream impacts on the dairy industry.

The 1997 drought severely impacted Maryland's agricultural sector, particularly dairy farmers, who faced widespread crop failures and declining milk prices. Projections indicated a 40% reduction in corn yields and a 20% decline in soybean production, worsening an already precarious situation (The Baltimore Sun, 1997a). State Agriculture Secretary Lewis R. Riley predicted a 30% drop in farm income, with adverse effects on rural economies (The Baltimore Sun, 1997a). Dairy producers, hit hardest, lost alfalfa hay crops and depleted winter reserves to feed cattle, risking livestock health. Combined with low milk prices and resource shortages, farmers struggled to sustain operations (The Baltimore Sun, 1997b).

Effect of Climate Change on Barley Yield from 1979 to 2023

Barley cultivation in Maryland serves multifaceted roles, prominently emphasizing its utility as a cover crop. Sown during autumn, barley significantly improves soil quality, mitigates erosion, and effectively reduces weed proliferation, owing to its vigorous growth and extensive root network. Moreover, barley is integral to Maryland's agricultural landscape, catering to diverse sectors such as animal husbandry, brewing, and distillation. In 2023, barley cultivation notably injected \$5.4 million into the state's economy, underscoring its economic significance. In 1979, barley production amounted to 3.8 million bushels (m bu.), cultivated across 78,000 acres, resulting in an average yield of 37 bushels per acre (Figure 13).

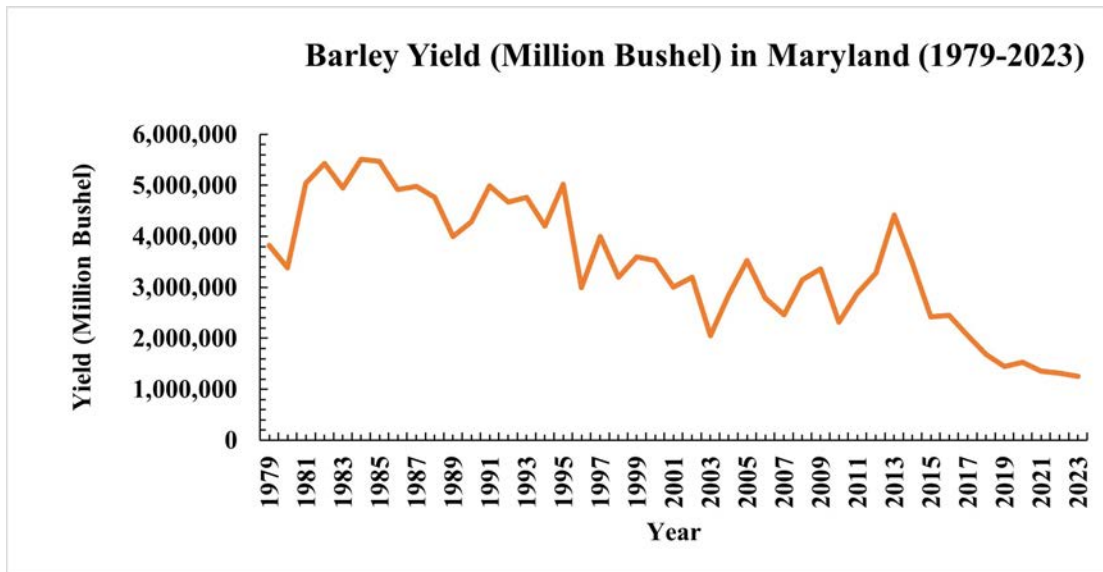


Figure 13: Barley yield (million bushels) in Maryland from 1979 to 2023

The peak of both yield and acreage was achieved in 1985, with a total production of 5.5 m bu. grown over 96,000 acres, resulting in an impressive average yield of 49 bushels per acre. Conversely, 2023 marked the year with the lowest total yield, recording a mere 1.2 m bu. on 13,000 acres, despite achieving the highest average yield per acre at 96 bushels. Over the span from 1979 to 2023, the yield per acre witnessed a substantial increase from 37 to 96 bu., reflecting a remarkable 159% enhancement attributed to advancements in barley varieties.

Assessing the influence of drought and elevated temperatures on barley yield presents considerable difficulties. This complexity arises predominantly from the fact that barley is generally sown in the fall and harvested in the spring/early summer. Furthermore, the selection of diverse cover crops by farmers, which can vary annually, adds another layer of unpredictability that may contribute to fluctuations in barley yield. This multifaceted scenario necessitates a thorough and nuanced analysis to disentangle the specific effects of climatic factors and agricultural practices on barley production.

Notably, during the drought experienced in 1997, barley yields exhibited a remarkable increase of 34%, with the harvested area expanding by 2%, and the yield per acre rising by 31%. This contrasts sharply with the performance of other crops such as corn, soybeans, hay, and others, which all suffered declines in their yields. This discrepancy underscores the unique resilience of barley under

adverse climatic conditions, highlighting its potential as a robust crop in the face of increasing environmental stressors.

Recent research underscores the detrimental impact of early spring frosts on barley production, although comprehensive data remains elusive. Small grain crops, including barley, exhibit a pronounced vulnerability to freeze damage, particularly from the booting phase through the flowering stage. During this critical period, the anthers within the flowering structure, essential for pollen production, are especially susceptible to freezing temperatures. Barley, in particular, displays heightened sensitivity to freeze injury during the boot stage, a susceptibility that surpasses that of wheat. This increased vulnerability in barley is primarily due to its distinctive characteristic of undergoing flowering while still in the boot stage (Kness, 2016). This unique phenological trait exacerbates the risk of freeze damage, highlighting the need for targeted research and adaptive agricultural practices to mitigate the adverse effects of early spring frosts on barley yields.

Effect of Climate Change on Wheat Yield from 1979 to 2023

Wheat, a fundamental winter annual crop, is sown in the autumn, facilitating the establishment of seedlings before entering dormancy during the winter months. As temperatures increase in early spring, growth resumes. In Maryland, wheat is primarily cultivated as a cover crop and for grain production, typically utilizing drills after the fall harvest, although aerial dispersal by crop dusters is also practiced. Besides its agricultural utility, wheat functions as an effective cover crop, aiding in soil protection and nitrogen uptake. Harvested from late June to July, wheat provides both grain and straw, the latter of which is used for animal bedding or compost. Soft red winter wheat, widely grown in Maryland, plays a crucial role in the production of baked goods and animal feed. A bushel, weighing approximately 60 pounds, can yield 90 pounds of bread or 210 servings of spaghetti, containing around one million kernels (Maryland Grain Producers 2024). In 2023, wheat contributed \$83.7 million to the state's economy.

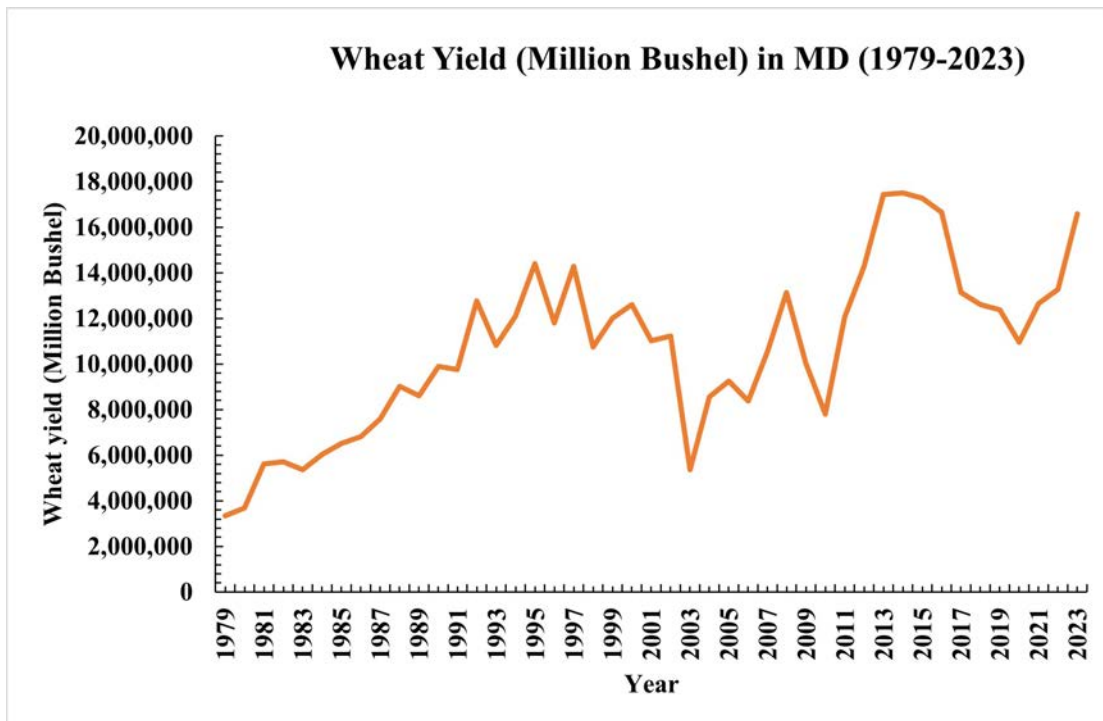


Figure 14: Wheat yield (million bushels) in Maryland from 1979 to 2023.

In 1979, wheat production amounted to 3.3 m bu., cultivated over 90,000 acres, yielding an average of 37 bushels per acre (Figures 14-16). The highest yield on record was achieved in 2014, reaching an impressive 17.5 m bu. The peak harvested acreage occurred in 2013, covering 260,000 acres. Over the period from 1979 to 2023, the yield per acre significantly increased from 37 to 85 bu. In 1979, the leading counties in wheat production were Caroline (374,000 bu.), Carroll (333,000 bu.), Frederick (328,000 bu.), Queen Anne's (328,000 bu.), and Talbot (282,000 bu.). By 2006, the foremost counties in wheat production had shifted, with Queen Anne's producing 1.9 m bu., Caroline 1.2 m bu., Frederick 1.0 m bu., Kent 0.9 m bu., and Carroll 0.5 m bu. It should be noted that county-level data post-2006 is unavailable.

Research has demonstrated that the production of winter wheat is markedly vulnerable to fluctuations in temperature (Obembe 2021). Early autumn frosts detrimentally impact yield, while late spring frosts contribute to higher rates of crop abandonment. Winter wheat exhibits particular sensitivity to freezing temperatures, which can inflict severe damage, including leaf chlorosis, death of meristematic tissue, and sterility of the reproductive structures (Balla et al. 2011). Moreover, elevated temperatures during winter exacerbate the damage from spring freezes by prematurely ceasing the hardening process, thereby leaving the crop more vulnerable (Warrick and Miller 1999). The presence of extreme heat during the grain filling stage further degrades both the quality and yield of the grain (Iizumi and Ramankutty 2015). Precipitation plays a crucial role; drought conditions during planting and critical growth phases can severely diminish productivity and quality of the crop (Iizumi and Ramankutty 2015). Effective irrigation practices are vital to mitigating the adverse effects of both drought and heat stress. Therefore, the repercussions of temperature and precipitation changes on winter wheat production are significantly influenced by regional climatic and soil conditions.

Wheat Harvested Acreage(Acres) in Maryland (1979-2023)

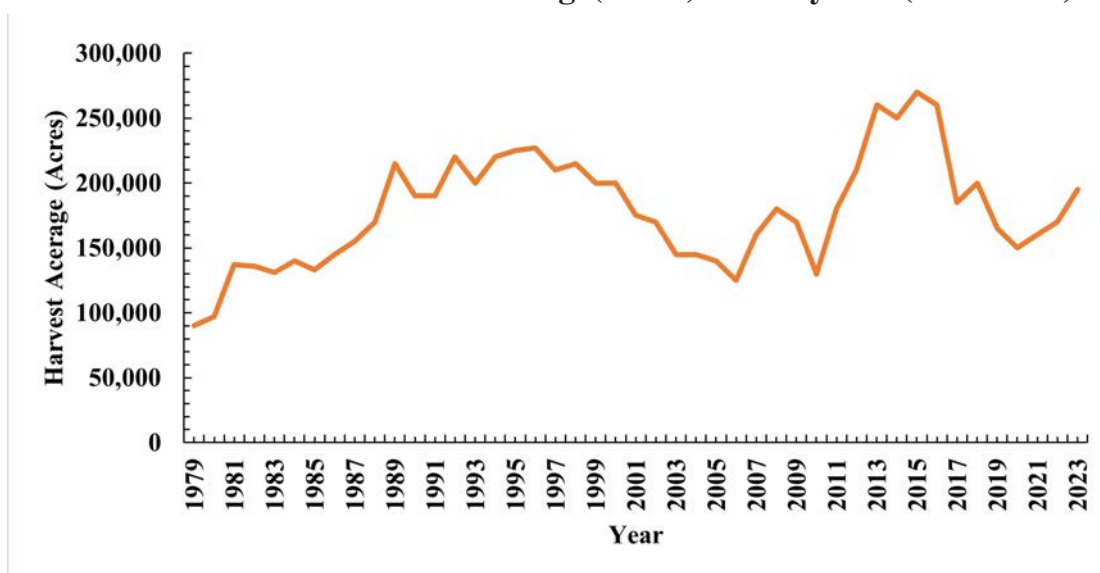


Figure 15: Wheat harvested acreage (acres) in Maryland from 1979 to 2023.

The decline in wheat yield in Maryland has been closely associated with significant drought periods, influenced by various factors including fall planting and the use of wheat as a cover crop. In 1980, a severe drought led to a 6% reduction in wheat yield, a 4% decrease in harvested area, and a 2% drop in yield per acre. Conversely, the drought of 1991 had a minimal impact, with only a 1% decline in yield and a 4% reduction in yield per acre, while the harvested area remained unchanged. The drought of 1993 had a more moderate impact, with wheat yield decreasing by 15%, harvested area by 9%, and yield per acre by 7%. Among Maryland counties, the highest yield declines in 1993 compared to 1992 were observed in Caroline (42%), Baltimore (40%), Howard (33%), Somerset (29%), and Frederick (22%). Yield per acre also fell significantly in Howard (25%), Baltimore (24%), Caroline (19.1%), Frederick (12.1%), and Somerset (7.1%) during the same period. Additionally, declines in harvested acreage were notable in Caroline (28.6%), Somerset (23.9%), Baltimore (20%), Frederick (11.9%), and Howard (11.5%) in 1993 compared to 1992. The drought of 2009 further illustrated the vulnerability of wheat yields to drought conditions, with a 24% decline in yield compared to 2008. Specifically, wheat production dropped from 13.1 m bu. in 2008 to 10 m bu. in 2009. Harvested acreage decreased by 6%, from 180,000 acres to 170,000 acres, and the average yield per acre fell from 73 bushels per acre in 2008 to 59 bushels per acre in 2009. These data highlight the significant variability in wheat yield responses to drought conditions across different periods and regions, underscoring the need for adaptive strategies in wheat farming to mitigate the adverse effects of climatic fluctuations.

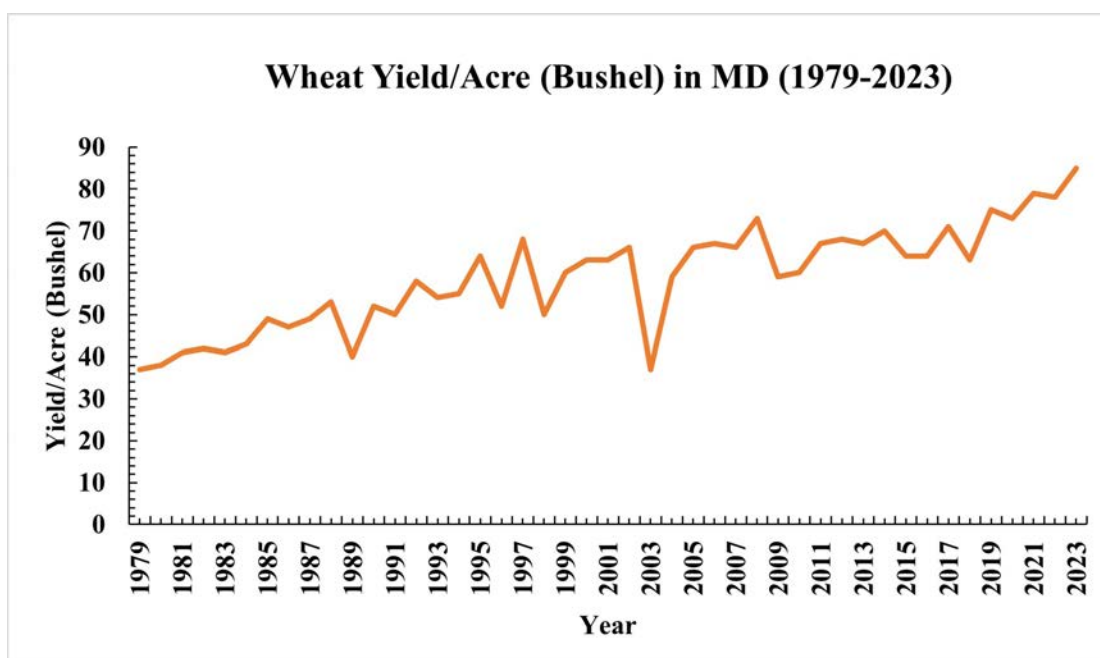


Figure 16: Wheat yield (bushels per acre) in Maryland from 1979 to 2023.

Effect of Climate Change on Peach and Apple Production from 1979 to 2023

Peach and apple cultivation in Maryland has been significant for its agricultural economy, providing both fresh produce and processed goods. However, production has declined over the past 50 years due to urbanization, reducing available farmland, economic challenges from rising production costs and external competition, increased pest and disease pressures, and the impacts of climate change. Additionally, labor shortages and market fluctuations have further complicated sustainable oper-

ations for fruit growers. Despite these issues, some farmers have adapted through diversification, technology adoption, and agritourism to maintain viability in the industry.

In 1974, peach production amounted to 22.6 million pounds, but by 2017, it had plummeted to 6.0 million pounds, marking a significant 74% decrease (Figure 17). This decline in production was accompanied by a 72% reduction in peach-growing acreage, which shrank from 2,929 acres in 1974 to 831 acres in 2017. The peak yield was recorded in 1978 at 23.0 million bushels, while the maximum acreage of 3,375 acres was noted in 1982. Furthermore, the number of peach farms experienced a dramatic reduction from 550 to 134 between 1987 and 2022. This data underscores a substantial contraction in both the scale of peach cultivation and the number of operational farms over the observed periods.

Compared to 1910, Maryland now experiences about 30 fewer days below freezing, indicating a trend of warmer winters and extended growing seasons (UME 2023). A false spring, characterized by early warmth followed by a return to freezing temperatures, can significantly reduce peach yields. Premature bud break increases the susceptibility of blossoms to frost damage, thereby decreasing flower viability and subsequent fruit set. Additionally, cold weather can disrupt pollination by limiting pollinator activity. This environmental stress can weaken tree health, increasing vulnerability to diseases and negatively impacting both current and future yields. Implementing protective measures is crucial to mitigating these risks and ensuring sustainable peach production (UME 2023). This issue was notably observed in Maryland in 2017. The Eastern U.S. has seen significant false springs in 2007, 2012, 2017, 2020, 2022, and 2023, with critical damage occurring when blooms open at 32-34°F and fruit at 28-30°F (Johnson 2023). Climate models suggest false springs will become increasingly common (Johnson 2023).

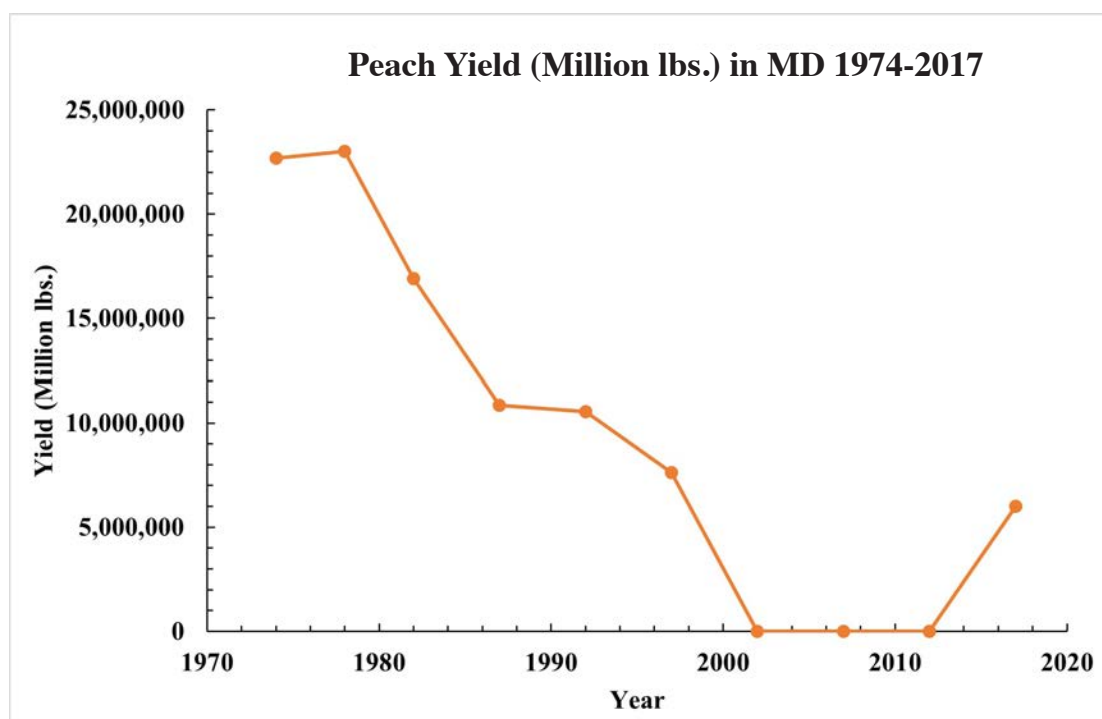


Figure 17: Peach yield (million lbs.) in Maryland from 1974 to 2017. Data for the years 2002, 2007, and 2012 is not available.

Apple production in Maryland experienced a significant decline between 1974 and 2017, as illustrated in Figure 18. In 1974, apple production peaked at 74.7 million pounds, but by 2017, it had decreased to 43.0 million pounds, representing a 42.4% reduction. Concurrently, the acreage dedicated to apple cultivation plummeted by 74%, from 6,973 acres in 1974 to just 1,793 acres in 2017. The number of farms engaged in apple production also saw a reduction, dropping from 250 farms in 1974 to 205 farms in 2017, an 18% decline over the period. These trends reflect a marked contraction in both the scale and scope of apple farming in Maryland over the studied years. The rapid and varied climate changes, encompassing heat waves in the Pacific Northwest, rising temperatures in the South, and condensed, warmer cool seasons in the North and East, pose significant challenges to apple farming in Maryland (Cutlip, 2023). Orchards, traditionally acclimatized to cooler environments, now face uncertainties stemming from elevated temperatures and shifting seasonal patterns, which impact crucial factors such as fruit quality, yield, and vulnerability to pests and diseases. Vital strategies for maintaining viable apple production include the introduction of heat-tolerant apple cultivars, enhancement of irrigation systems to alleviate water-related stress, and implementation of comprehensive integrated pest management protocols to combat escalating pest pressures.

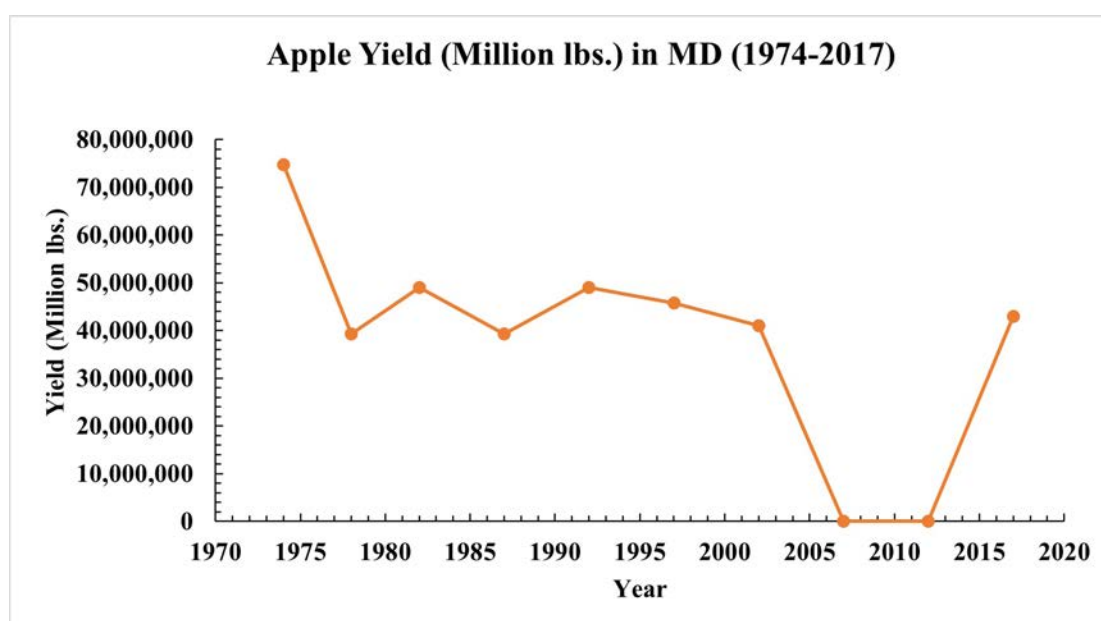


Figure 18: Apple yield (million pounds) in Maryland from 1974-2017. Data for the years 2007 and 2012 is not available.

RECOMMENDATIONS

To address the adverse effects of climate change on crop yield and survival in Maryland, particularly in light of comprehensive data from 1979 to 2023, several detailed recommendations are proposed to mitigate these impacts:

- Invest in research and development to breed crop varieties that exhibit greater resistance to abiotic stresses such as drought, heat, and false springs. This effort should include the use of genetic engineering and biotechnology to introduce traits that enhance stress tolerance in both row and fruit crops.

- Support collaborations between universities, agricultural research institutes, and private sector companies to leverage advanced breeding techniques and share resources and knowledge.
- Provide critical funding for the development and expansion of irrigation systems across Maryland, especially in areas most vulnerable to drought. Implementing modern irrigation technologies, such as drip and sprinkler systems, will ensure efficient water usage.
- Promote water-saving practices, including rainwater harvesting and soil moisture monitoring, and develop policies that encourage sustainable water management practices among farmers.
- Encourage crop rotation and diversification to improve soil health and reduce the risk of crop failure due to climate stress. Introducing cover cropping will protect soil and enhance its water retention capacity. Promoting no-till or reduced-till farming practices will maintain soil structure and moisture levels.
- Provide farmers with training on climate-resilient farming techniques and the use of new stress-resistant crop varieties. Outreach programs should be developed to disseminate information on best practices for managing abiotic stress.
- Offer subsidies or financial incentives for adopting climate-smart agricultural practices, invest in irrigation infrastructure, and create insurance schemes to protect farmers against crop losses due to extreme weather events.
- Advocate for state and federal policies that support agricultural adaptation to climate change, including funding for research, infrastructure, and farmer support programs. Developing regional climate action plans that address the specific needs and vulnerabilities of different counties within Maryland, and implementing and enforcing agricultural sustainability standards will promote the long-term health and productivity of Maryland's agricultural lands.
- Enhance monitoring systems to track climate impacts on crop yields and identify emerging trends. Utilizing satellite imagery and remote sensing technologies to gather real-time data on soil moisture, crop health, and weather conditions will provide valuable insights. Developing early warning systems for extreme weather events, such as droughts and heat waves, will provide timely alerts to farmers, enabling proactive measures.

By adopting a comprehensive approach that includes developing stress-resistant crop varieties, improving irrigation infrastructure, adopting adaptive agricultural practices, enhancing farmer support, advocating for supportive policies, and implementing robust monitoring systems, Maryland can effectively mitigate the effects of climate change on its agricultural sector. This strategy will help safeguard the state's economic stability, food security, and the livelihoods of those dependent on agriculture.

CHALLENGES

A critical obstacle in examining the historical ramifications of climate change on crop production in Maryland lies in the scarcity of accessible data pertaining to crop yields and acreage, with a particular dearth noted in fruit and vegetable crops. This challenge is compounded by the absence of information regarding reductions in acreage and yield attributed to abiotic stresses. The paucity

of such data presents significant hurdles for conducting comprehensive agricultural analyses and formulating effective strategies to mitigate the adverse impacts of these stresses on crop production. Without precise and comprehensive datasets, grasping the full extent of yield losses becomes arduous, hindering the development of targeted interventions aimed at bolstering the agricultural sector's resilience and productivity under adverse environmental conditions.

REFERENCES

Arnold, M. S. 1993. "In MD and VA, Drought Has Dried Up Crops and Spirits." *The Washington Post*. Accessed September 22, 2023. <https://www.washingtonpost.com/archive/politics/1993/08/18/in-md-and-va-drought-has-dried-up-crops-and-spirits/a382aba3-d1ea-4c7e-b247-c043a3b6bc14/>.

Balla, K., Rakszegi, M., Li, Z., Bekes, F., Bencze, S., and Veisz, O. 2011. "Quality of Winter Wheat in Relation to Heat and Drought Shock After Anthesis." *Czech Journal of Food Sciences* 29 (2): 117-128.

Cohn, D., and Mosses, J. 1988. "The Drought." *The Washington Post*. Accessed September 22, 2023. <https://www.washingtonpost.com/archive/politics/1988/07/08/the-drought/7b4a9a15-32f7-44c1-b64f-a2cb316f5cea/>.

Cutlip, K. 2023. "Adapting Apples to the Times: New Fruit from UMD Could Weather Changing Climate and Labor Shortages to Boost Grower Profits." Accessed May 29, 2024. <https://agrn.umd.edu/news/adapting-apples-times/>.

de la Reguera, E., Veatch, J., Gedan, K., and Tully, K. L. 2020. "The Effects of Saltwater Intrusion on Germination Success of Standard and Alternative Crops." *Environmental and Experimental Botany* 180: 104254.

Gol'tsberg, I. A., ed. 1972. *Agroclimatic Atlas of the World*. Hydrometizdat.

Heim, R. R. 2002. "A Review of Twentieth Century Drought Indices Used in the United States." *Bulletin of the American Meteorological Society* 83 (8): 1149-1165.

Iizumi, T., and Ramankutty, N. 2015. "How Do Weather and Climate Influence Cropping Area and Intensity?" *Global Food Security* 4: 46-50.

Jaime, K. 2023. "Farmer Battle Climate Change, Sea Level Rise with New Assist from UMES Research." *Salisbury Daily Times*. Accessed January 23, 2024. <https://www.delmarvanow.com/story/news/local/maryland/2023/07/31/farmers-facing-climate-change-look-to-resilient-crops-new-strategies/70486892007/>.

Johnson, G. 2023. "Potential for Another False Spring and Long-Term Seasonal Shifts." Accessed May 29, 2024. <https://sites.udel.edu/weeklycropupdate/?p=21657>.

Kness, A. 2016. "Early May Freeze: What's the Risk to Our Grain Crops?" Accessed May 28, 2024. <https://blog.umd.edu/agronomynews/2017/05/30/late-may-freeze-whats-the-risk-to-our-grain-crops/>.

Kogan, F. N. 1995. "Droughts of the Late 1980s in the United States as Derived from NOAA Polar-Orbiting Satellite Data." *Bulletin of the American Meteorological Society* 76 (5): 655-668.

- Lama, D. 2010. "Dry Spell Has Maryland Bordering on Drought." *Capital News Service*. Accessed January 26, 2024. <https://thedailyrecord.com/2010/09/22/dry-spell-has-maryland-bordering-on-drought/>.
- Lu, J., Carbone, G. J., Huang, X., Lackstrom, K., and Gao, P. 2020. "Mapping the Sensitivity of Agriculture to Drought and Estimating the Effect of Irrigation in the United States, 1950-2016." *Agricultural and Forest Meteorology* 292-293: 1-11.
- Maryland Government. 2002. "Governor's Press Release." Accessed January 25, 2024. <https://mde.maryland.gov/programs/pressroom/Pages/462.aspx>.
- Maryland Government. 2007. "Governor's Press Release." Accessed January 26, 2024. <https://mde.maryland.gov/programs/pressroom/Pages/1048.aspx>.
- Maryland Grain Producers. 2024. Accessed May 29, 2024. <https://marylandgrain.org/wheat/#:~:text=Maryland%20typically%20grows%20soft%20red,or%20210%20servings%20of%20spaghetti>.
Maryland Soybean Board. 2024. Accessed January 23, 2024. <https://www.mdsoy.com/>.
- USDA NASS 2023. "2023 State Agriculture Overview." Accessed May 28, 2024. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=MARYLAND.
- National Oilseed Processors Association. 2023. "The Economic Impact of US Soybean and End Products on the US Economy—2023 Update." Accessed January 23, 2024. <https://www.nopa.org/resources/economic-impact-of-u-s-soybeans-end-products-on-the-u-s-economy/>.
- NCEI. 2002. "Annual 2002 Drought Report: US Drought." Accessed January 25, 2024. <https://www.ncei.noaa.gov/access/monitoring/monthly-report/drought/200213>.
- Obembe, O. S., Hendricks, N. P., and Tack, J. 2012. "Decreased Wheat Production in the USA from Climate Change Driven by Yield Losses Rather than Crop Abandonment." *PLoS One* 16 (6): e0252067.
- O'Harrow Jr., R. 1991. "Drought Claims \$93 Million Worth of Md., Va. Crops." *The Washington Post*. Accessed May 28, 2024. <https://www.washingtonpost.com/archive/local/1991/09/08/drought-claims-93-million-worth-of-md-va-crops/6448cb90-f5e5-4a30-a5fe-e16c64bd9616/>.
- Resop, J. P., Fleisher, D. H., Timlin, D. J., Mutibwa, D., and Reddy, V. R. 2016. "Climate, Water Management, and Land Use: Estimating Potato and Corn Production in the US Northeastern Seaboard Region." *Transactions of the ASABE* 59 (6): 1539-1553.
- Roylance, F. D. 2002. "Maryland Drought Deepens, No Relief in Sight." *The Baltimore Sun*. Accessed January 25, 2024. <https://www.baltimoresun.com/2002/08/21/md-drought-deepens-no-relief-in-sight/>.
- Shack, E. A. 2003. "State's Corn, Soybean Harvests Slashed by Drought." *Capital News Service*. Accessed January 25, 2024. <https://cnsmaryland.org/2003/01/10/states-corn-soybean-harvests-slashed-by-drought/>.
- Southern MD Online. 2007. "U.S. Dept. of Agriculture to Declare Drought Disaster Designation for Entire State." Accessed January 26, 2024.

Steinhilber, P., Shipley, P., and Vvedenskaya, A. 2016. "Estimating Corn Silage (NM-1)." Accessed May 28, 2024. https://extension.umd.edu/sites/extension.umd.edu/files/publications/NM-1%202016%20Estimating_Corn_Silage_Yield.pdf.

Summer (JJA) Drought Report. 1999. National Centers for Environmental Information. Accessed September 22, 2023. [https://www.ncei.noaa.gov/access/monitoring/monthlyreport/drought/199916#:~:text=The%20Northeast%20region%20\(which%20includes,have%20been%20drier%20than%20normal](https://www.ncei.noaa.gov/access/monitoring/monthlyreport/drought/199916#:~:text=The%20Northeast%20region%20(which%20includes,have%20been%20drier%20than%20normal).

Teasdale, J. R., and Cavigelli, M. A. 2017. "Meteorological Fluctuations Define Long-Term Crop Yield Patterns in Conventional and Organic Production Systems." *Scientific Reports* 7: 688. <https://doi.org/10.1038/s41598-017-00775-8>.

The Baltimore Sun. 1993a. "All of MD Can Qualify for Farm Aid Drought Damage Put at \$50 Million." Accessed September 22, 2023. <https://www.baltimoresun.com/1993/08/18/all-of-md-may-qualify-for-farm-aid-drought-damage-put-at-50-million-name-not-applicable-2/>.

The Baltimore Sun. 1997a. "Drought Has Dairy Farmers in Md. Seeking Federal Aid: Low-Interest Loans Could Be 2 Weeks Away." Accessed May 28, 2024. <https://www.baltimoresun.com/1997/08/07/drought-has-dairy-farmers-in-md-seeking-federal-aid-low-interest-loans-could-be-2-weeks-away/>.

The Baltimore Sun. 1997b. "Double Whammy for State Farmers: Drought, Low Prices—Federal Disaster Program Offers Little Consolation for Parched Fields." Accessed May 28, 2024. <https://www.baltimoresun.com/1997/08/19/double-whammy-for-state-farmers-drought-low-prices-federal-disaster-program-offers-little-consolation-for-parched-fields/>.

UME. 2023. "The Effects of Climate Change in Maryland." Accessed May 29, 2024. <https://extension.umd.edu/resource/effects-climate-change-maryland/>.

USDA ERS. 2023. "U.S. Soybean Production Expands Since 2002 as Farmers Adopt New Practices, Technologies." Accessed January 23, 2024. <https://www.ers.usda.gov/amber-waves/2023/july/u-s-soybean-production-expands-since-2002-as-farmers-adopt-new-practices-technologies/#:~:text=With%20the%20expansion%20of%20soybean,combined%20to%20support%20yield%20gains>.

USDA NASS. 1979-2023. "Quick Stats." Accessed January 23, 2024. <https://quickstats.nass.usda.gov/#3FF2AE19-7FE8-35D3-BA17-67915AB26D49>.

USDA NASS. 1979-2022. "Quick Stats." Accessed September 22, 2023. <https://quickstats.nass.usda.gov/>.

USGS. 1988-89. *Maryland and the District of Columbia: Floods and Droughts*. U.S. Geological Survey Water-Supply Paper 2375, 319-326.

Vesey, T. 1983. "Area Farmer Facing Disaster as Drought Damages Crop." *The Washington Post*. Accessed January 24, 2024. <https://www.washingtonpost.com/archive/politics/1983/09/05/area-farmers-facing-disaster-as-drought-damages-crops/47003772-b70b-4073-b15f-9f280d143dec/>.

Warrick, B. E., and Miller, T. D. 1999. *Freeze Injury on Wheat*. Texas Agricultural Extension Service, The Texas A and M University System, San Angelo, Texas.

Young, L., Clark, M. J., and Lyons, S. 1991. "Md. Farmers' Hope for Wet Spring Withers in Face of Drought." *The Baltimore Sun*. Accessed May 28, 2024. <https://www.baltimoresun.com/1991/06/12/md-farmers-hope-for-wet-spring-withers-in-face-of-drought/>.

Ziegler, B. 2023. "Drought-Stressed Corn Silage: What You Can Expect." Accessed May 28, 2024. https://www.hubbardfeeds.com/sites/default/files/2023-07/Hubbard%20Forage%20Blog_Drought%20Stressed%20Corn%20Silage_Jul2023.pdf.

INSECTS

Alan Leslie

SUMMARY

A review of existing literature has identified some of the documented responses of insect pests to climate change factors, which have been compared against climate model predictions for Maryland. Temperature, precipitation, and extreme weather have emerged as the climate factors that are most often studied in relation to their expected or documented impact on insect species. *Northward expansion of overwintering ranges of insects in response to milder winter temperatures will allow new pests with historically southern ranges to invade Maryland* (Lawton et al. 2022; Liu et al. 2002; Musolin 2012). Likewise, an increased number of generations due to more rapid accumulation of growing degree days will result in increases in pest populations and additional pest outbreaks for multivoltine species (Deutsch et al. 2018). Extreme weather events may create asynchrony between insect pests and plant hosts if planting dates or plant growth are delayed, while abnormally warm days will create heat stress for vulnerable insect stages (Bodlah et al. 2023; Menzel et al. 2006). Periods of heat stress may benefit pest species if they have physiological or behavioral adaptations to tolerate heat stress better than their predators and parasitoids (Bodlah et al. 2023; Spahn and Lill 2022). Developing and implementing a consistent and widespread monitoring program of key pests will provide invaluable data on actual changes in pest phenology and abundance as the climate continues to change. Maryland farmers should continue to adapt to changes in insect pest pressure by implementing integrated pest management strategies and by using conservation biological control strategies to create a more resilient crop environment.

INTRODUCTION

Insect herbivory can reduce agricultural crop yields in a variety of ways. Root-feeding insects such as wireworms (Coleoptera: Elateridae) can cause severe stunting or even kill young seedling plants, reducing the overall stand of crops. Chewing insects such as beetles and caterpillars directly consume plant material and relatively low amounts of feeding damage can render crops unmarketable due to cosmetic appearance, while high amounts of damage can reduce photosynthesis or even directly kill the crop. Insects adapted to piercing-sucking feeding, such as aphids and stink bugs, can reduce plant growth and yield by consuming sugars and amino acids in the phloem or xylem, while causing relatively little physical damage to the plant. Stem boring insects, such as the European corn borer, can cause additional problems for crop yields by weakening stems and causing plant lodging. In some cases, boring insects can show up as a contaminant of harvested products, resulting in crops being rejected by processing plants.

Understanding how insect pest pressure will respond to climate change in Maryland will be important to help farmers adapt their management strategies to mitigate potential losses. By some estimates, insects and other arthropod pests reduce global crop production by 18-20% through feeding damage (Sharma et al. 2017). Across the U.S., approximately 14% of corn and 23% of soybean fields received an insecticide, while 82-85% of fruit and 54-73% of vegetable fields received an insecticide application to control pests (USDA NASS). Maryland farmers use a range of non-chemical pest management tactics, including crop rotation and planting resistant varieties; however, increased insecticide use is expected in response to increased pest pressure (Delcour et al. 2015). Insects are the most diverse group of multicellular organisms on the planet, and therefore their responses to human-induced climate change are expected to be equally diverse (Meglitsch 1972). The specific goals for this objective were (1) to compile historical records of insect pest abundance in Maryland to relate to available historical weather data; (2) to conduct a literature review to determine climate change factors that will impact pest insect abundance; and (3) to assess likely responses of representative pest species to climate change factors based on literature and climate models for Maryland. Results from these three objectives will be used to draw conclusions about the expected pattern in insect pest pressure under different climate change scenarios in Maryland and to make recommendations for mitigation strategies.

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METHODS

Historical Data on Insect Abundance

The most extensive historical record of insect pest abundance in Maryland comes from a network of blacklight traps that were deployed to monitor moth (Lepidoptera) pests of vegetable crops. This network was originally started by Professor Galen Dively in the Department of Entomology at the University of Maryland and was eventually taken over by Dick Bean at the Maryland Department of Agriculture. The network of traps was run from 1973 to 2008, with approximately 60 traps deployed across the state each year. Blacklight traps provide relative abundance data on night-flying

insects, such as moths, and were a useful tool for informing farmers on when to apply insecticide sprays to control lepidopteran pests of sweet corn and other important vegetable crops. This dataset also provides the most comprehensive record of insect pests of importance to Maryland agriculture.

Sixteen species of moth were identified from samples collected by blacklight trapping, representing species of economic importance as well as other minor pests (Table 1). The dataset has been described in detail in Walter et al. (2020). To account for differences in sampling intensity from year to year across the state, the abundances of different moth species were normalized by the number of traps deployed for any given night in any given area. Traps were located across the state, but the abundances are grouped by USDA crop reporting regions within the state, each of which encompasses two to three individual counties, for a total of eight different regions (Table 2). Data have been analyzed and published elsewhere with respect to the spatial synchrony of pest abundance (Walter et al. 2020) and the regional suppression of European corn borer by transgenic Bt crops (Venugopal and Dively 2017). The current analysis will use the relationships between moth abundances and historical weather to predict future pest abundance patterns using data generated from climate models predicting future weather patterns under different greenhouse gas emissions scenarios.

Species	Common Name	Crops
Beet Armyworm	<i>Spodoptera exigua</i>	vegetable, grain, forage
Black Cutworm	<i>Agrotis ipsilon</i>	vegetable, grain, forage
Biololed Looper	<i>Megalographa biloba</i>	vegetable
Bristly Cutworm	<i>Lacinipolia renigera</i>	vegetable
Celery Looper	<i>Anagrapha falcifera</i>	vegetable
Corn Earworm	<i>Helicoverpa zea</i>	vegetable, grain, alfalfa
Cabbage Looper	<i>Trichoplusia ni</i>	vegetable
Dingy Cutworm	<i>Feltia jaculifera</i>	grain
European Corn Borer	<i>Ostrinia nubilalis</i>	vegetable, grain
Fall Armyworm	<i>Spodoptera frugiperda</i>	vegetable, grain, forage
Forage Looper	<i>Caenurgina erechtea</i>	forage
Green Cloverworm	<i>Hypena scabra</i>	grain
Hornworms	<i>Manduca</i> spp.	vegetable
Spotted Cutworm	<i>Xestia</i> spp.	vegetable, grain
True Armyworm	<i>Mythimna unipunctata</i>	grain
Variiegated Cutworm	<i>Peridroma saucia</i>	vegetable, grain
Yelloiow Striped Armyworm	<i>Spodoptera ornithogalli</i>	vegetable, grain, forage

Table 1. List of species of moth collected by blacklight traps in Maryland and the types of crops that their larvae feed on.

Region	Name	Counties
1	Lower Shore	Somerset, Worcester, Wicomico
2	Mid Shore	Dorchester, Talbot, Caroline
3	Upper Shore	Queen Anne's, Kent, Cecil
4	Baltimore/Harford	Baltimore, Harford
5	Lower Central	Montgomery, Anne Arundel, Prince George's
6	Southern	Charles, St. Mary's, Calvert
7	Central	Howard, Carroll, Frederick
8	Western	Washington, Allegany, Garrett

Table 2. Maryland counties represented in each of the USDA crop reporting regions.

Literature Review of Climate Change Impacts on Insect Pests

A literature review was conducted to retrieve information from published peer-reviewed articles on the expected impacts of different climate change factors on populations of agricultural pest insects. Searches were conducted through the online database ScienceDirect (<https://www.sciencedirect.com/>) using the keywords “climate change” and “insects” and “agriculture” to narrow the results to papers specific to the intended subject. Initially, Google Scholar was also used as a search engine but was ultimately abandoned in favor of the quality of results returned by ScienceDirect. Results from the initial keyword search were screened by article type, retaining only review and research articles. Additional screening further selected only papers that had a direct mention of a pest insect and climate impact in the title. After searching and screening, the resulting papers were read, and the specific climate factors and the nature of the effect on the pest insect were recorded.

To complement the broad literature search, we also compiled a comprehensive list of major agricultural insect pests in Maryland and recorded key aspects of their biology. Biological factors include diet breadth, life stage causing damage, plant part damaged, voltinism, and overwintering stage. This information was primarily collected from extension sources, including production guides for different commodity groups and individual fact sheets. This list of species and biological traits will be used in relation to the reports from the literature review to determine the extent of insect pests in Maryland that may be affected by different climate change factors.

Assess Likely Response of Representative Insect Pests of Concern in Maryland

To determine specific impacts of climate change on insect pests of concern in Maryland, a subset of insect pests was chosen for a second literature review. This group of twelve pests represents some of the most common and/or economically important pests in the state. Pest species were chosen to provide representation of all potential cropping systems in Maryland, as well as a range in pest taxonomy and biological traits. This literature review was performed to find published papers with specific relationships between climate change factors and the pest species. Studies could be a combination of field observations, laboratory experiments, and modeling approaches to determine or document direct impacts of climate change factors on these representative pests.

Pest	Order	Common Name
Helicoverpa zea	Lepidoptera	Corn Earworm
Ostrinia nubilalis	Lepidoptera	European Corn Borer
Pentatomidae	Hemiptera	Stink Bugs
Plutella xylostella	Lepidoptera	Diamondback Moth
Tetranychus urticae	Trombidiformes	Two-Spotted Spider Mite
Trichoplusia ni	Lepidoptera	Cabbage Looper
Diabrotica undecimpunctata	Coleoptera	Spotted Cucumber Beetle
Acalymma vittatum	Coleoptera	Striped Cucumber Beetle
Spodoptera spp.	Lepidoptera	Armyworm
Leptinotarsa decemlineata	Coleoptera	Colorado Potato Beetle
Empoasca fabae	Hemiptera	Potato Leafhopper
Frankliniella spp.	Thysanoptera	Flower Thrips

Table 3. List of Representative Arthropod Pests for Maryland Crops.

This literature search was performed similarly to the previous literature review in terms of title screening and data retrieval. Searches were conducted using ScienceDirect for publications accessible through UMD libraries using the following keywords: pest name and “climate change,” as well as pest name and “climate change” and either “pest damage” or “pest management.” Papers returned using these search parameters were further screened for research and review articles, and then again for specific mention of pest species and climate change factors in the title. For papers that were retained following the search and screening, specific climate change factors and the impact on pest biology were recorded. Specific examples of climate change impacts were further analyzed along with the climate model data for Maryland to make specific predictions about changes in pest insect biology under different emissions scenarios.

RESULTS/DISCUSSION

From the initial literature search, nearly 27,000 papers were found. Of these, 4,894 met the criteria of being listed as review and research articles. These titles were further screened to 182 papers with relevant content on climate impacts on insect pests of agriculture. These papers were read to retrieve data on specific climate impacts as they relate to different insect pests. If a paper did not include relevant information, such as a discussion of an agricultural system, or if there was no further mention of insects, it was removed from consideration. Overall, a total of 127 papers provided useful information from this literature review.

From the 127 papers analyzed, 17 different climate change impacts were identified (Table 4). Temperature, extreme climate events, precipitation, and increased CO₂ were the four climate change factors most frequently reported to affect pest insect biology. This initial literature review was done on a broad scale, considering publications from all over the world and including a diverse range of

insects, including those identified as beneficial and as pests. These climate change factors were grouped across multiple publications mentioning their importance; however, the specific impact on pest insects varied depending on the publication.

Climate Change Factor	Total
Temperature	84
Extreme Weather Events	39
Precipitation	30
Increased Carbon Dioxide	21
Tropospheric Ozone	4
Humidity	4
Climate Variability	3
Nutrient Availability	3
Seasonality	2
Radiation	2
Wind Speed	2
Early Snowmelt	1
Elevated Ground-Level Ozone	1
Light Intensity	1
Soil Moisture	1
Soil Salinization	1
Soil Temperature	1

Table 4. Summary of Climate Change Factors Found to Affect Pest Insects from Literature Search.

Finding that temperature was reported in 84 of the 127 papers under review is not surprising, since temperature directly affects many aspects of insect physiology. As poikilothermic animals, insects have very little ability to regulate their own body temperature; thus, their metabolic processes are directly related to the temperature of their environment. This means that insect developmental rates, feeding, reproduction, and movement are all limited by environmental temperature. With a warmer climate, Maryland can expect to see more southern species move into the state and a greater abundance of migratory pest species as milder winters allow greater overwintering success (Aidoo et al. 2023; Bale and Hayward 2010; Chain-Guadarrama et al. 2019; Chen et al. 2011; Gno-Solim Ela et al. 2023). Warmer growing seasons may also result in the production of additional generations and greater late-season abundance of some multivoltine insect species (Hong et al. 2019; Jha et al. 2024; Liu et al. 2002). Accumulation of growing degree days earlier in the year may also result in phenological mismatches between pests and host plants or between pests and beneficial insects (Menzel et al. 2006; Milevovic et al. 2023; Porter et al. 1991). The

climate models for Maryland predict a continued increase in average annual temperature through the rest of the century and an extension of the growing season with growing degree days accumulated earlier and for a longer duration. These predictions vary in terms of severity under different emissions scenarios, but increases in temperature are expected under all scenarios.

The second most frequently reported climate change factor impacting insect populations was the frequency of extreme weather events. These extreme events cover a broad range of weather phenomena, such as drought, flood, wind, precipitation, and heat waves. However, the common thread among the different events is that they are transient, unpredictable, and disruptive to normal patterns of growth and development of both insects and crops. Extreme weather events create strong selection pressure for insects that are adapted to those transient conditions and may facilitate

new pest invasions while increasing mortality rates for other species (Filazzola et al. 2021; Garrett et al. 2013; Nyamukondiwa et al. 2022). Disturbances caused by extreme weather events can delay or otherwise alter the normal timeline of crop planting and development, with cascading effects on the development of pests and their natural enemies (Castex et al. 2018; Christmann 2020; Subedi et al. 2023; Van Espen et al. 2023). Historical weather data for Maryland show a significant increase in the frequency of extreme precipitation events over the last 40 years and a trend toward increasing frequency of warm spells during summer months. The effect that these types of temporary extreme weather events will have on different insect species is difficult to predict, and largely depends on timing as well as intensity (Yang et al. 2021).

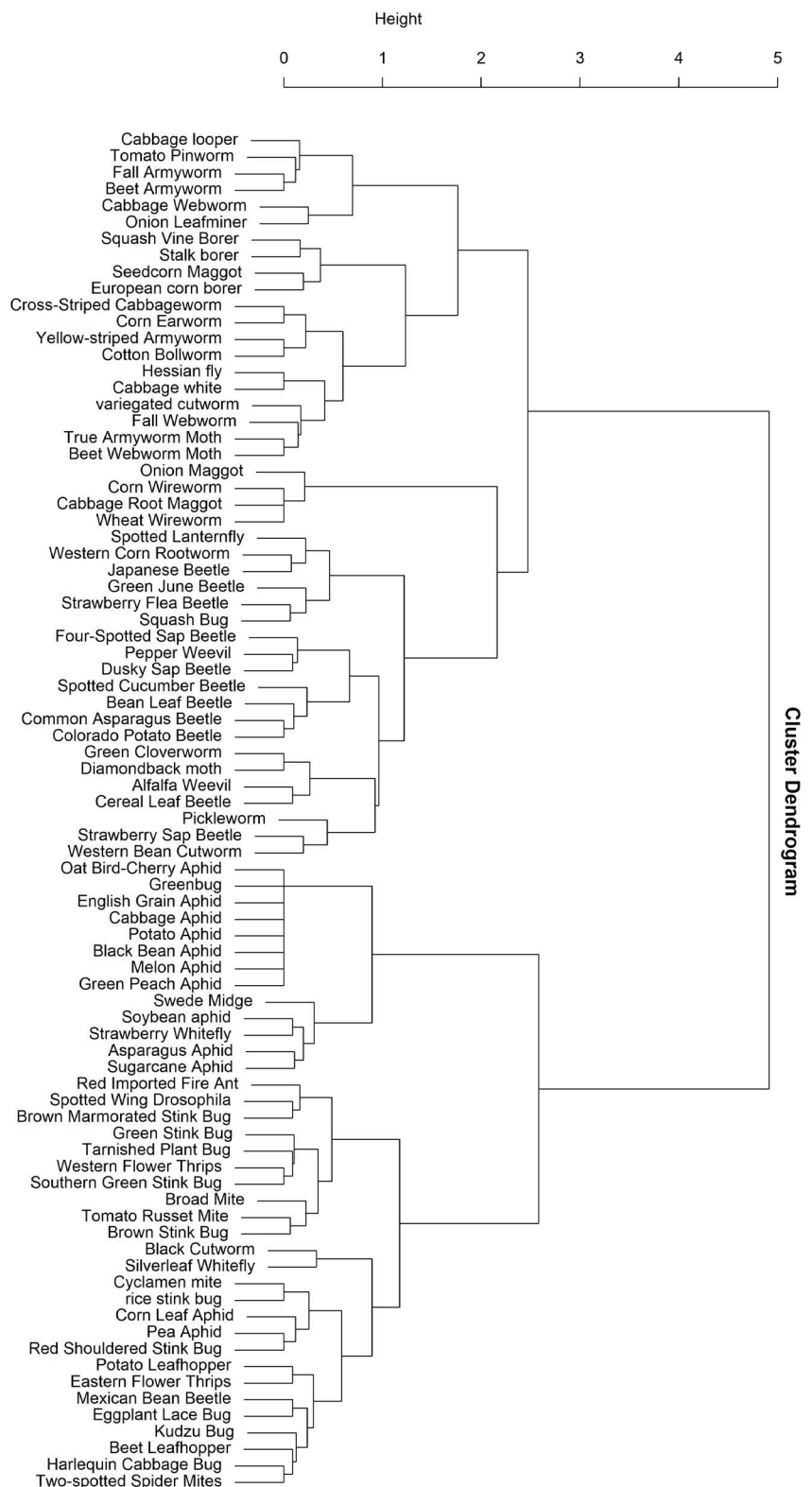
Precipitation was the third most frequently reported factor influencing insect populations, though most papers report precipitation having an indirect effect on insects through direct effects on plant hosts. The majority of grain crops (corn, wheat, soybean) and many important fruit and vegetable crops (pumpkins, apples, grapes) are grown without supplemental irrigation in Maryland. Therefore, plant growth, development, and yield are largely determined by having adequate rainfall at appropriate times during the growing season. Additionally, planting annual crops and harvesting forage crops depend on having conditions that are dry enough to allow vehicle traffic in fields. Delays in planting can alter crop phenology throughout the growing season and potentially disrupt timing of pest abundance and natural enemies that provide biological control (Castex et al. 2018; Chain-Guadarrama et al. 2019; Kamdi et al. 2023). Furthermore, stress from too much or too little rainfall can change the quality of crop plants as hosts to insects and affect their ability to resist or tolerate insect feeding damage (Morshed et al. 2023; Roy et al. 2020; Schneider et al. 2022). Analyses of historical weather in Maryland show a significant increase in annual precipitation over the last 40 years, with an increase in the frequency of measurable rain events. Ultimately, the timing of precipitation will determine the effects on the insect community through possible delays in planting and harvest or through changes in crop growth and plant health.

The fourth most frequently cited climate change factor impacting insect populations was increased atmospheric CO₂ levels, and similar to precipitation, its effects on insects tend to be mediated by the direct response of the host plant. Elevated atmospheric CO₂ concentrations can alter the levels of secondary metabolites and the carbon to nitrogen ratio (C:N) of plants, potentially decreasing the quality of the plants as a food source for herbivorous insects (Facey et al. 2014; Jamieson et al. 2017; Pokharel et al. 2021). Beneficial effects of CO₂ enrichment on plant growth and quality are more likely to be seen in C₃ plants than in C₄ plants (Fuhrer 2003). However, some studies also report that environmental stress to plants predicted by climate models will not be offset by potential benefits from CO₂ enrichment (Kang et al. 2022).

Other climate change factors that were reported to affect insects were mentioned much less frequently than temperature, extreme weather, precipitation, and elevated CO₂. Some of these factors, such as humidity, wind speed, and snowmelt are expected to have significant effects on insect populations, but their effects are likely much more difficult to generalize broadly across large groups of insects (Gno-Solim Ela et al. 2023; Karuppiah and Sujayanad 2012). In reality, none of these climate factors impact insects independently of the others, and multiple climate factors will be interacting simultaneously to affect different species in unique ways (Fuhrer 2003). Making predictions about how individual pest species will respond to future climatic conditions will have to take into account multiple interacting climate factors as well as specific aspects of the pest's biology.

A total of 82 pest insect species were identified from production guides for grain, forage, fruit, and vegetable crops for Maryland. Life history characteristics were determined from various extension publications to establish voltinism, overwintering behaviors and life stages, type of feeding damage, diet breadth, and the life stages causing pest damage. Hierarchical cluster analysis was used to visualize differences in the life history characteristics of these diverse pests. The cluster dendrogram shows that species generally group according to taxonomic order, with most Lepidoptera, Coleoptera, and Hemiptera clustering with each other. This analysis suggests that if different climate change factors act on similar life history traits in a similar manner, then we can expect pests with similar taxonomy to respond similarly. However, if the ultimate impacts of climate change are mediated by interactions with host plants or with natural enemies, then even closely related pests may respond very differently to changes in climate factors.

Figure 1. Cluster dendrogram of Maryland agricultural insect pests by life history characteristics. Clustering was done using Ward's method and a Bray-Curtis distance matrix.



The second literature review of a subset of the most important agricultural insect pests in Maryland returned 6,282 papers, of which 416 were retained after initial title screening. Of these papers, 93 were found to contain relevant information regarding specific responses of pest species to climate change factors. Three of the pest species did not return any published papers: the potato leafhopper (*Empoasca fabae*), the striped cucumber beetle (*Acalymma vittatum*), and the cabbage looper (*Trichoplusia ni*). Similar to the previous literature search, the top three most frequently reported climate factors were temperature, precipitation, and extreme weather (Table 6). Information collected from papers was also categorized by the specific biological impact that the climate change factors had on the pest species, with the top five categories of biological impact being voltinism, survival, distribution, overwintering, and fitness (Table 7). Information collected on this group of pest species can create “case studies” exemplifying how a particular pest species might be impacted by different climate change factors in the future.

Life History Trait	% of Species
Univoltine	17.1
Overwinter as Adults	53.7
Overwinter in Maryland	85.4
Fruit Feeding	36.6
Defoliating	63.4
Sap Feeding	40.2
Root Feeding	9.8
Stem Borer/Leaf Miner	13.4
Lodging	3.7
Stem Cutting	2.4
Disease Vector	20.7
Generalist Diet Breadth	54.9
Pest Stage Immature	97.6
Pest Stage Adult	58.5

Table 5. Life History Traits Analyzed for Cluster Analysis of Maryland Pest Insect Species.

Climate Change Factor	Total
Temperature	72
Precipitation	15
Extreme Weather	10
Humidity	9
Increased CO ₂	7
Wind Speed	6
Solar Radiation	3
Climate Variability	3
Nutrient Availability	2

Table 6. Summary of Climate Change Factors Reported from Literature Search on Insect Pests Specific to Maryland Crops.

Biological Impact on Pest

Climate Factor	Voltinism	Survival	Distribution	Overwintering	Fitness
Temperature	20	43	26	2	31
Precipitation	4	7	5	0	5
Extreme Weather	1	8	0	0	4

Table 7. Summary of Specific Biological Impacts Reported in Papers Retrieved in the Second Literature Search for the Top Three Most Reported Climate Change Factors.

Diamondback Moth

The diamondback moth (*Plutella xylostella*) is a pest of cabbage, broccoli, kale, and other *Brassica* crops in Maryland, and is the most destructive pest of cruciferous crops worldwide. It does not tolerate cold temperatures and therefore does not overwinter in Maryland; rather, it migrates northward each year through the growing season. Currently, the moth is limited to Florida and the Gulf Coast for suitable overwintering sites in the U.S., but under a warmer climate, diamondback moths may be able to persist and overwinter further north. Ma et al. (2021) found that under laboratory conditions, diamondback moths showed exponentially higher survival when exposed to chilling conditions under 500 low-temperature degree days, with a base of 11°C (LTDD₁₁). Model projections for Maryland climate data show that under the highest emissions scenario, the state may be able to support overwintering populations of diamondback moth, with LTDD values well below the threshold of 500 (Figure 2). These authors also show that areas where diamondback moths overwinter are more likely to develop pesticide resistance, as more generations are exposed to similar chemistries, and there is greater selection for resistance in those populations.

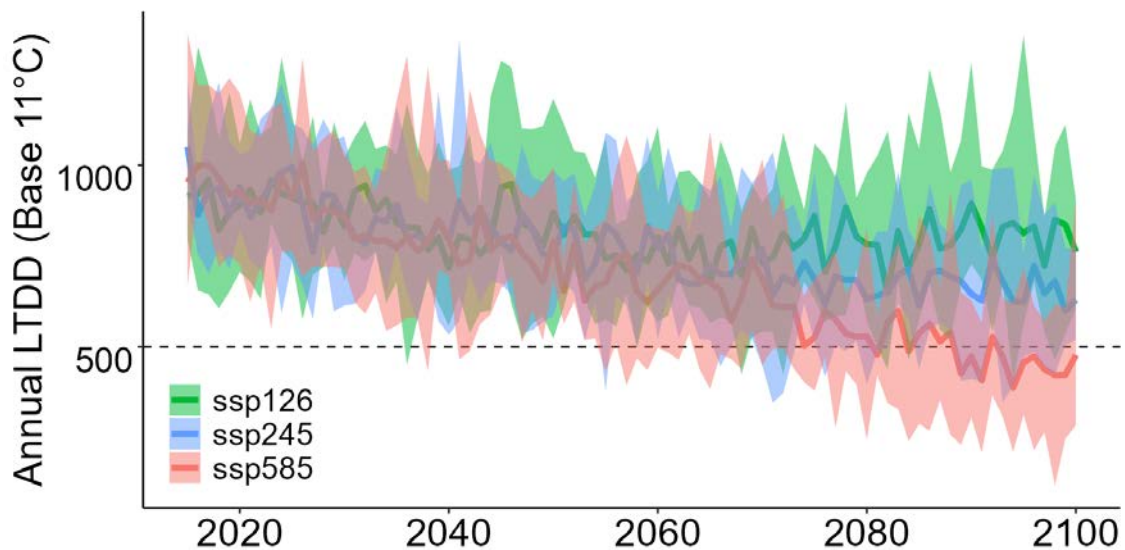


Figure 2. Climate Model Predictions for Average LTDD in Maryland. Colored lines represent different emissions scenarios, and shaded regions show maximum and minimum estimates across different Earth systems models. The dashed line represents the threshold under which the diamondback moth has exponentially greater winter survival.

Warmer temperatures during the growing season can also result in faster development times for diamondback moths, resulting in the development of more generations (Spahn and Lill 2022). This insect has shown behavioral adaptations to high temperatures, selecting cooler microclimates to lay eggs to help protect vulnerable first-instar larvae from heat stress (Bodlah et al. 2023). Laboratory experiments also show that diamondback moths can tolerate higher temperatures better than *Diadegma insulare*, a hymenopteran parasitoid that provides natural biological control of this pest (Spahn and Lill 2022). Therefore, under a warming climate, the diamondback moth may appear earlier in vegetable crops, reproduce faster, escape chemical control through the evolution of resistance, and evade biological control due to differences in heat tolerance.

Pentatomid Stink Bugs

Stink bugs represent a group of insects that tend to be generalists, feeding on a wide range of grain, fruit, and vegetable crops, they are pests at all life stages, and are highly mobile as adults. All cause damage through a piercing-sucking feeding behavior. In the mid-to-late 2000s, Maryland farmers had to adapt to the invasion of the brown marmorated stink bug (*Halyomorpha halys*), which was especially devastating to vegetable and tree fruit industries. Laboratory analyses of developmental thresholds of this insect found that immature stages experience heat stress and reduced growth above 33.5°C (Baek et al. 2017). Climate models show that under the highest emissions scenario, Maryland is expected to have nearly double the number of days where maximum daily temperatures are at or above that developmental threshold by the end of the century (Figure 3).

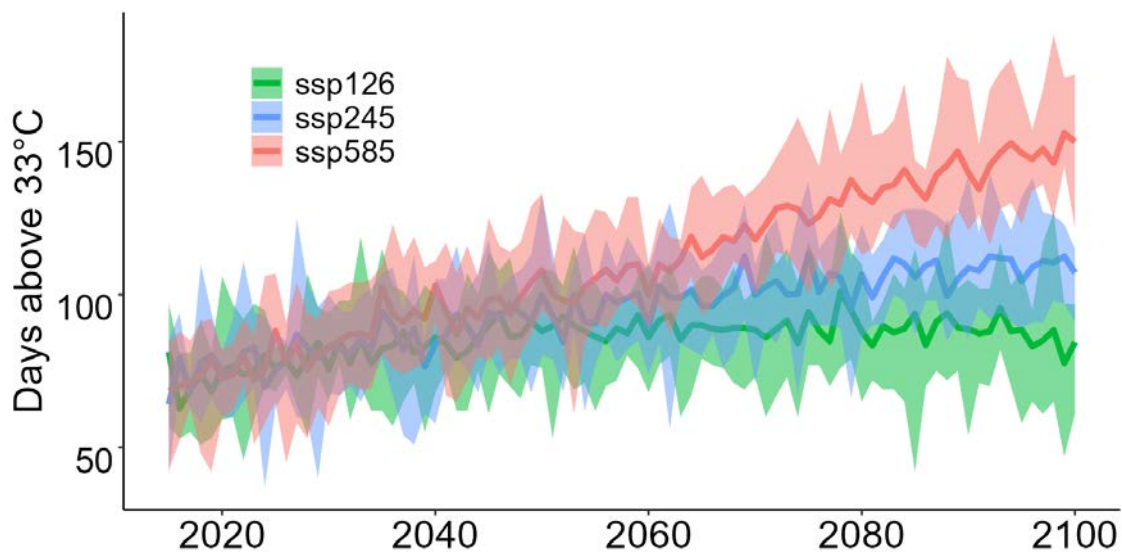


Figure 3. Number of Days Per Year with Maximum Temperatures Above the Optimum Developmental Threshold for *H. halys* Nymphs. Colored lines represent different emissions scenarios, and shaded regions show maximum and minimum estimates across different Earth systems models.

Heat stress from future climate warming may become limiting for populations of the brown marmorated stink bug in Maryland, but it may also produce conditions favoring the invasion of other stink bug species. The southern green stink bug (*Nezara viridula*) is a polyphagous crop pest in states south of Virginia. It occasionally migrated as far north as Maryland but does not survive the winter.

Kiritani (2011) found that in its introduced range in Japan, the northern limit of this species coincides with the isotherm for mean January temperatures greater than or equal to 5°C. Historical weather data show that mean January temperatures are rarely above the 5°C threshold in Maryland (Figure 4). However, climate models show that under medium and high emissions scenarios, mean January temperature across the state will regularly be at or above that threshold by the latter half of the century (Figure 5). This analysis also does not take into account the variability in weather across the state, so southern counties may exceed this threshold well ahead of the rest of the state.

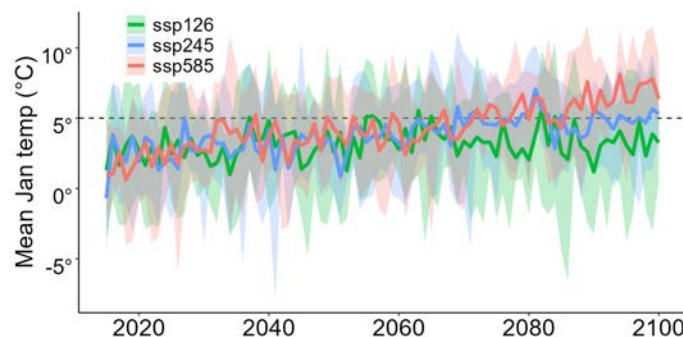
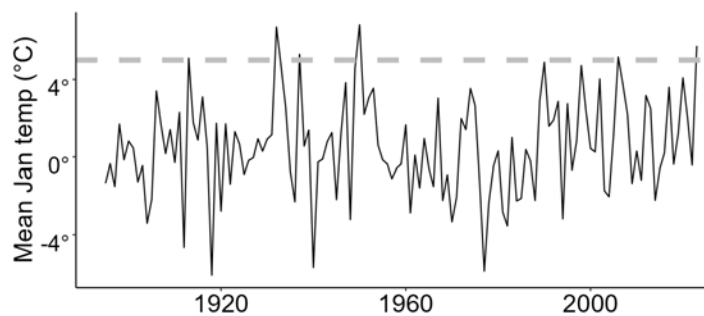


Figure 4. Historical Mean January Temperatures Averaged Across the Entire State of Maryland. The dashed line represents the threshold where *N. viridula* would theoretically be able to survive overwinter.

Figure 5. Climate Model Predictions for Mean January Temperature in Maryland Through the End of the Century. Colored lines represent different emissions scenarios, and shaded regions show maximum and minimum estimates across different Earth systems models. The dashed line represents the threshold above which *N. viridula* can survive the winter.

Armyworms

The genus *Spodoptera* includes several moth species that are major agricultural pests in Maryland and are collectively referred to as “armyworms.” The fall armyworm (*S. frugiperda*) has received considerable research attention recently, as it has become invasive across several countries in Africa (2016) as well as China (2018). These studies of habitat characteristics in its introduced range in other countries provide some insights into potential range shifts here in the U.S., where fall armyworm overwinters in the South and migrates northward during the growing season. As a result, fall armyworm is a sporadic pest of vegetable, grain, and forage crops in Maryland, and its pest status largely depends on the timing of invasion from the South. Similar to the diamondback moth, fall armyworm is limited by cold temperatures during the winter (Jiang et al. 2022), and general warming may create more suitable overwintering habitat in Maryland. Increased total annual precipitation also increases the habitat suitability for fall armyworm (Abdel-Rahman et al. 2023; Jiang et al. 2022), though extreme precipitation events can increase the mortality of young instars (Lowry et al. 2022). Climate models for Maryland show similar trends across all emissions scenarios for total annual precipitation (Figure 6) and for heavy rainfall events, so precipitation is not likely to be a limiting factor for armyworm invasion in the future. Studies of a closely related species (*S. eridania*) show that under a warming climate, additional degree days may allow a shift from 9 to 12 generations per year (Sampaio et al. 2021). Climate models show that growing degree day accumulation in Maryland is expected to increase approximately 50% by the end of the century under the highest emissions scenario (Figure 7). Multivoltine species like fall armyworm that invade from southern areas each year will potentially have more time to build up larger populations in Maryland, provided they are not limited by other diapause cues, such as photoperiod.

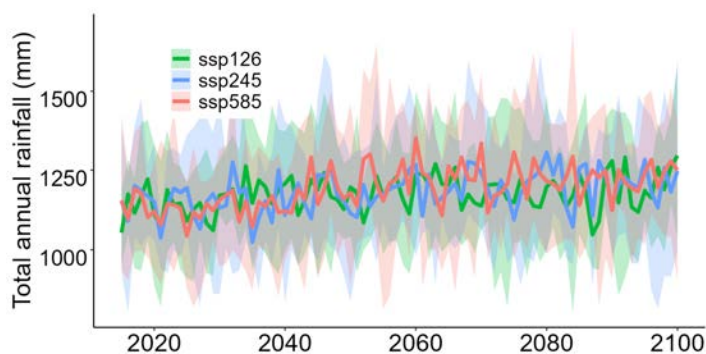


Figure 6. Total Annual Rainfall for Maryland Predicted by Different Climate Models. Colored lines represent different emissions scenarios, and shaded regions show maximum and minimum estimates across different Earth systems models.

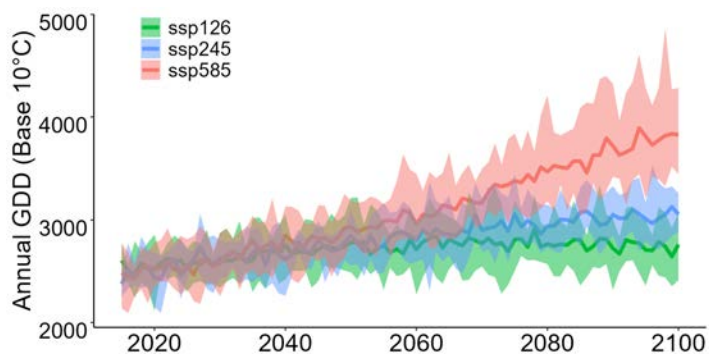


Figure 7. Growing Degree Day Accumulation in Maryland Predicted by Different Climate Models. Colored lines represent different emissions scenarios, and shaded regions show maximum and minimum estimates across different Earth systems models.

Habitat modeling for predicting invasive ranges of fall armyworm also highlights some of the limitations of using climate model data for predicting future abundance and distribution of insect species. Although climate variables are important in these models, other variables such as land use/land cover and area of host crop planted also play important roles in predicting future distributions of pests (Abdel-Rahman et al. 2023; Jiang et al. 2022). Many of these models also oversimplify the landscape when determining habitat suitability, while fine-scale microclimates may exist within a matrix of inhospitable habitat (Ma and Ma, 2022). We found no papers that provided any predictions for the interaction of different climate factors on the long-range dispersal of this insect in the future, and whether it will be aided or hindered under different climate models.

CONCLUSION

Our review of published scientific literature on insect response to climate change found that the three most reported factors influencing insect populations are temperature, precipitation, and extreme weather. In Maryland, we expect to see higher average annual temperatures under all emissions scenarios, resulting in an extension of the growing season and milder winter temperatures. For insects, this will result in greater overwintering survival for cold-sensitive species, and development of additional generations during the growing season with the accumulation of additional degree days. For some insects, the higher summer temperatures will introduce chronic heat stress that may result in lower populations for some species. Heat stress will likely affect species differently and may disrupt natural biological control between pests and beneficial insects if one species is more heat tolerant than the other. Milder winters may also result in the northward expansion of species that currently have a southern distribution or only arrive in Maryland as seasonal migrants. Precipitation is not predicted to change as drastically as temperature, so specific predictions regarding future insect responses to precipitation are unclear. Similarly, extreme weather events take on multiple forms and are by nature difficult to predict with any accuracy. Extreme weather has the potential to affect insect populations by delaying planting dates and changing the timing of when crop plants are available to pest insect species. All of these factors will be affecting insect species simultaneously, so although these predictions can provide guidance on expectations, future insect populations will be the result of multiple interacting factors.

RECOMMENDATIONS

The blacklight trapping data collected between 1973 and 2008 have provided an extremely useful resource for tracking historical insect populations and their responses to multiple factors, including climate change (Dively et al. 2018; Venugopal and Dively 2017; Walter et al. 2020). This analysis has compiled and summarized findings and predictions from many different studies to provide general predictions on how insect pests will change under future climatic conditions. *In order to test whether these predictions are correct and make appropriate recommendations for mitigation, monitoring for key insect pests is needed. There is currently no statewide monitoring program for agricultural insect pests that provides a long-term dataset that can be used to benchmark and track abundances of different pest insects.*

The general prediction from among the many published studies is that pest pressure is expected to increase in Maryland in the future. In order to be prepared for additional pest pressure in the future, *we need to return to an [integrated pest management] IPM approach for pest management now to preserve efficacy of limited chemical controls and delay insecticide resistance development as long as possible. This includes good stewardship of the transgenic insecticidal traits in Bt corn, judicious application of systemic insecticidal seed treatments, and rotating insecticide modes of action and/or tank-mixing multiple modes of action within single applications.*

Conservation biological control will become increasingly important to reduce pest pressures as hotter summer temperatures have the potential to create conditions that are more stressful to beneficial organisms than they are to pests. Reduced tillage, cover cropping, vegetated buffer strips, and intercropping are all methods that can help agroecosystems to become more resilient to pest outbreaks by creating habitat that is more hospitable to predators and parasitoids.

CHALLENGES

One of the main limitations of this analysis is that many of the large-scale changes in insect pest populations over the last several decades have been driven by factors other than climate change. For example, the widespread adoption of transgenic Bt corn expressing insecticidal proteins has resulted in the areawide suppression of European corn borer across all crops in Maryland and has greatly shifted pest control strategies for field corn (Dively et al. 2018). The widespread adoption of winter cover cropping and no-till agriculture in Maryland has drastically changed the soil habitat and disturbance regime for soil-dwelling arthropods. This has led to increases in some soil dwelling pests, while at the same time improving biological control by predaceous ground beetles (Coleoptera: Carabidae) and other beneficial epigeal arthropods (Hatten et al. 2007; Stinner and House, 1990).

The universal application of systemic insecticides as seed treatments in corn and other grain crops has represented a fundamental shift in the way insecticides are applied and generally abandons the integrated pest management (IPM) approach for a cheap, convenient application method (Tooker et al. 2017).

Invasive species continue to be an additional threat to Maryland agriculture and will disrupt production systems and IPM in new and unpredictable ways (Paini et al. 2016). *Future similar changes to the agricultural landscape will likely interact with the changing climate in new and unpredictable ways, making specific predictions of future pest abundance difficult.*

REFERENCES

- Abdel-Rahman, E. M., Kimathi, E., Mudereri, B. T., Tonnang, H. E. Z., Mongare, R., Niassy, S., and Subramanian, S. 2023. "Computational Biogeographic Distribution of the Fall Armyworm (*Spodoptera frugiperda* J.E. Smith) Moth in Eastern Africa." *Heliyon* 9: e16144. <https://doi.org/10.1016/j.heliyon.2023.e16144>.
- Aidoo, O. F., Souza, P. G. C., Silva, R. S., Júnior, P. A. S., Picanço, M. C., Heve, W. K., Duker, R. Q., Ablormeti, F. K., Sétamou, M., and Borgemeister, C. 2023. "Modeling Climate Change Impacts on Potential Global Distribution of *Tamarixia radiata* Waterston (Hymenoptera: Eulophidae)." *Science of the Total Environment* 864: 160962. <https://doi.org/10.1016/j.scitotenv.2022.160962>.
- Baek, S., Hwang, A., Kim, H., Lee, H., and Lee, J.-H. 2017. "Temperature-Dependent Development and Oviposition Models of *Halyomorpha halys* (Hemiptera: Pentatomidae)." *Journal of Asia-Pacific Entomology* 20: 367-375. <https://doi.org/10.1016/j.aspen.2017.02.009>.
- Bale, J. S., and Hayward, S. A. L. 2010. "Insect Overwintering in a Changing Climate." *Journal of Experimental Biology* 213: 980-994. <https://doi.org/10.1242/jeb.037911>.
- Bodlah, M. A., Iqbal, J., Ashiq, A., Bodlah, I., Jiang, S., Mudassir, M. A., Rasheed, M. T., and Fareen, A. G. E. 2023. "Insect Behavioral Restraint and Adaptation Strategies Under Heat Stress: An Inclusive Review." *Journal of the Saudi Society of Agricultural Sciences* 22: 327-350. <https://doi.org/10.1016/j.jssas.2023.02.004>.
- Castex, V., Beniston, M., Calanca, P., Fleury, D., and Moreau, J. 2018. "Pest Management Under Climate Change: The Importance of Understanding Tritrophic Relations." *Science of the Total Environment* 616-617: 397-407. <https://doi.org/10.1016/j.scitotenv.2017.11.027>.
- Chain-Guadarrama, A., Martínez-Salinas, A., Aristizábal, N., and Ricketts, T. H. 2019. "Ecosystem Services by Birds and Bees to Coffee in a Changing Climate: A Review of Coffee Berry Borer Control and Pollination." *Agricultural Ecosystems & Environment* 280: 53-67. <https://doi.org/10.1016/j.agee.2019.04.011>.
- Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B., and Thomas, C. D. 2011. "Rapid Range Shifts of Species Associated with High Levels of Climate Warming." *Science* 333: 1024-1026. <https://doi.org/10.1126/science.1206432>.
- Christmann, S. 2020. "Climate Change Enforces to Look Beyond the Plant - The Example of Pollinators." *Current Opinion in Plant Biology* 56: 162-167. <https://doi.org/10.1016/j.pbi.2019.11.001>.
- Delcour, I., Spanoghe, P., and Uyttendaele, M. 2015. "Literature Review: Impact of Climate Change on Pesticide Use." *Food Research International* 68: 7-15. <https://doi.org/10.1016/j.foodres.2014.09.030>.
- Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B., and Naylor, R. L. 2018. "Increase in Crop Losses to Insect Pests in a Warming Climate." *Science* 361: 916-919. <https://doi.org/10.1126/science.aat3466>.
- Dively, G. P., Venugopal, P. D., Bean, D., Whalen, J., Holmstrom, K., Kuhar, T. P., Doughty, H. B., Patton, T., Cissel, W., and Hutchison, W. D. 2018. "Regional Pest Suppression Associated with Widespread Bt Maize Adoption Benefits Vegetable Growers." *Proceedings of the National Academy of Sciences* 115: 3320-3325. <https://doi.org/10.1073/pnas.1720692115>.

- Facey, S. L., Ellsworth, D. S., Staley, J. T., Wright, D. J., and Johnson, S. N. 2014. "Upsetting the Order: How Climate and Atmospheric Change Affects Herbivore-Enemy Interactions." *Current Opinion in Insect Science* 5: 66-74. <https://doi.org/10.1016/j.cois.2014.09.015>.
- Filazzola, A., Matter, S. F., and Maclvor, J. S. 2021. "The Direct and Indirect Effects of Extreme Climate Events on Insects." *Science of the Total Environment* 769: 145161. <https://doi.org/10.1016/j.scitotenv.2021.145161>.
- Fuhrer, J. 2003. "Agroecosystem Responses to Combinations of Elevated CO₂, Ozone, and Global Climate Change." *Agricultural Ecosystems & Environment* 97: 1-20. [https://doi.org/10.1016/S0167-8809\(03\)00125-7](https://doi.org/10.1016/S0167-8809(03)00125-7).
- Garrett, K. A., Dobson, A. D. M., Kroschel, J., Natarajan, B., Orlandini, S., Tonnang, H. E. Z., and Valdivia, C. 2013. "The Effects of Climate Variability and the Color of Weather Time Series on Agricultural Diseases and Pests, and on Decisions for Their Management." *Agricultural and Forest Meteorology* 170: 216-227. <https://doi.org/10.1016/j.agrformet.2012.04.018>.
- Gno-Solim Ela, N., Olago, D., Akinyi, A. D., and Tonnang, H. E. Z. 2023. "Assessment of the Effects of Climate Change on the Occurrence of Tomato Invasive Insect Pests in Uganda." *Heliyon* 9: e13702. <https://doi.org/10.1016/j.heliyon.2023.e13702>.
- Hatten, T. D., Bosque-Pérez, N. A., Labonte, J. R., Guy, S. O., and Eigenbrode, S. D. 2007. "Effects of Tillage on the Activity Density and Biological Diversity of Carabid Beetles in Spring and Winter Crops." *Environmental Entomology* 36: 356-368. <https://doi.org/10.1093/ee/36.2.356>.
- Hong, J., Lee, G.-S., Park, J.-J., Mo, H., and Cho, K. 2019. "Risk Map for the Range Expansion of Thrips palmi in Korea Under Climate Change: Combining Species Distribution Models with Land-Use Change." *Journal of Asia-Pacific Entomology* 22: 666-674. <https://doi.org/10.1016/j.aspen.2019.04.013>.
- Jamieson, M. A., Burkle, L. A., Manson, J. S., Runyon, J. B., Trowbridge, A. M., and Zientek, J. 2017. "Global Change Effects on Plant-Insect Interactions: The Role of Phytochemistry." *Current Opinion in Insect Science* 23: 70-80. <https://doi.org/10.1016/j.cois.2017.07.009>.
- Jha, P. K., Zhang, N., Rijal, J. P., Parker, L. E., Ostojica, S., and Pathak, T. B. 2024. "Climate Change Impacts on Insect Pests for High Value Specialty Crops in California." *Science of the Total Environment* 906: 167605. <https://doi.org/10.1016/j.scitotenv.2023.167605>.
- Jiang, C., Zhang, X., Xie, W., Wang, R., Feng, C., Ma, L., Li, Q., Yang, Q., and Wang, H. 2022. "Predicting the Potential Distribution of the Fall Armyworm *Spodoptera frugiperda* (J.E. Smith) Under Climate Change in China." *Global Ecology and Conservation* 33: e01994. <https://doi.org/10.1016/j.gecco.2021.e01994>.
- Kamdi, P. J., Swain, D. K., and Wani, S. P. 2023. "Developing Climate Change Agro-Adaptation Strategies Through Field Experiments and Simulation Analyses for Sustainable Sorghum Production in Semi-Arid Tropics of India." *Agricultural Water Management* 286: 108399. <https://doi.org/10.1016/j.agwat.2023.108399>.
- Kang, X., Qi, J., Li, S., and Meng, F.-R. 2022. "A Watershed-Scale Assessment of Climate Change Impacts on Crop Yields in Atlantic Canada." *Agricultural Water Management* 269: 107680. <https://doi.org/10.1016/j.agwat.2022.107680>.

- Karuppaiah, V., and Sujayanad, G. K. 2012. "Impact of Climate Change on Population Dynamics of Insect Pests."
- Kiritani, K. 2011. "Impacts of Global Warming on *Nezara viridula* and Its Native Congeneric Species." *Journal of Asia-Pacific Entomology* 14: 221-226. <https://doi.org/10.1016/j.aspen.2010.09.002>.
- Lawton, D., Huseeth, A. S., Kennedy, G. G., Morey, A. C., Hutchison, W. D., Reisig, D. D., Dorman, S. J., Dillard, D., Venette, R. C., Groves, R. L., Adamczyk, J. J., Barbosa Dos Santos, I., Baute, T., Brown, S., Burkness, E., Dean, A., Dively, G. P., Doughty, H. B., Fleischer, S. J., Green, J., Greene, J. K., Hamilton, K., Hodgson, E., Hunt, T., Kerns, D., Leonard, B. R., Malone, S., Musser, F., Owens, D., Palumbo, J. C., Paula-Moraes, S., Peterson, J. A., Ramirez, R., Rondon, S. I., Schilder, T. L., Seaman, A., Spears, L., Stewart, S. D., Taylor, S., Towles, T., Welty, C., Whalen, J., Wright, R., and Zuefle, M. 2022. "Pest Population Dynamics Are Related to a Continental Overwintering Gradient." *Proceedings of the National Academy of Sciences* 119: e2203230119. <https://doi.org/10.1073/pnas.2203230119>.
- Liu, S.-S., Chen, F.-Z., and Zalucki, M. P. 2002. "Development and Survival of the Diamondback Moth (Lepidoptera: Plutellidae) at Constant and Alternating Temperatures." *Environmental Entomology* 31: 221-231. <https://doi.org/10.1603/0046-225X-31.2.221>.
- Lowry, A., Durocher-Granger, L., Oronje, M., Mutisya, D., Mfuno, T., Gitonga, C., Musesha, M., Taylor, B., Wood, S., Chacha, D., Beale, T., Finch, E. A., and Murphy, S. T. 2022. "Optimizing the Timing of Management Interventions Against Fall Armyworm in African Smallholder Maize: Modelling the Pattern of Larval Population Emergence and Development." *Crop Protection* 157: 105966. <https://doi.org/10.1016/j.cropro.2022.105966>.
- Ma, C.-S., Zhang, W., Peng, Y., Zhao, F., Chang, X.-Q., Xing, K., Zhu, L., Ma, G., Yang, H.-P., and Rudolf, V. H. W. 2021. "Climate Warming Promotes Pesticide Resistance Through Expanding Overwintering Range of a Global Pest." *Nature Communications* 12: 5351. <https://doi.org/10.1038/s41467-021-25505-7>.
- Ma, G., and Ma, C.-S. 2022. "Potential Distribution of Invasive Crop Pests Under Climate Change: Incorporating Mitigation Responses of Insects into Prediction Models." *Current Opinion in Insect Science* 49: 15-21. <https://doi.org/10.1016/j.cois.2021.10.006>.
- Meglitsch, P. A. 1972. *Invertebrate Zoology*. 2nd ed. Oxford University Press.
- Menzel, A., Sparks, T. H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O., Briede, A., Chmielewski, F. M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatczak, K., Måge, F., Mestre, A., Nordli, Ø., Peñuelas, J., Pirinen, P., Remišová, V., Scheffinger, H., Striz, M., Susnik, A., Van Vliet, A. J. H., Wielgolaski, F.-E., Zach, S., and Züst, A. 2006. "European Phenological Response to Climate Change Matches the Warming Pattern." *Global Change Biology* 12: 1969-1976. <https://doi.org/10.1111/j.1365-2486.2006.01193.x>.
- Milenovic, M., Ripamonti, M., Eickermann, M., Rapisarda, C., and Junk, J. 2023. "Changes in Longevity, Parasitization Rate and Development Time of the Whitefly Parasitoid *Encarsia formosa* Under Future Climate Conditions." *Biological Control* 186: 105354. <https://doi.org/10.1016/j.biocontrol.2023.105354>.
- Morshed, M. N., Mamun, M. A. A., Nihad, S. A. I., Rahman, Md Mahfuzur, Sultana, N., and Rahman, Md Mezanur. 2023. "Effect of Weather Variables on Seasonal Abundance of Rice Insects in Southeast Coastal Region of Bangladesh." *Journal of Agricultural and Food Research* 11: 100513. <https://doi.org/10.1016/j.jafr.2023.100513>.

- Musolin, D. L. 2012. "Surviving Winter: Diapause Syndrome in the Southern Green Stink Bug *Nezara viridula* in the Laboratory, in the Field, and Under Climate Change Conditions." *Physiological Entomology* 37: 309-322. <https://doi.org/10.1111/j.1365-3032.2012.00846.x>.
- Nyamukondiwa, C., Machezano, H., Chidawanyika, F., Mutamiswa, R., Ma, G., and Ma, C.-S. 2022. "Geographic Dispersion of Invasive Crop Pests: The Role of Basal, Plastic Climate Stress Tolerance and Other Complementary Traits in the Tropics." *Current Opinion in Insect Science* 50: 100878. <https://doi.org/10.1016/j.cois.2022.100878>.
- Paini, D. R., Sheppard, A. W., Cook, D. C., De Barro, P. J., Worner, S. P., and Thomas, M. B. 2016. "Global Threat to Agriculture from Invasive Species." *Proceedings of the National Academy of Sciences* 113: 7575-7579. <https://doi.org/10.1073/pnas.1602205113>.
- Pokharel, S. S., Shen, F., Parajulee, M. N., Wang, Y., and Chen, F. 2021. "Effects of Elevated Atmospheric CO₂ Concentration on Tea Quality and Insect Pests' Occurrences: A Review." *Global Ecology and Conservation* 27: e01553. <https://doi.org/10.1016/j.gecco.2021.e01553>.
- Porter, J. H., Parry, M. L., and Carter, T. R. 1991. "The Potential Effects of Climatic Change on Agricultural Insect Pests." *Agricultural and Forest Meteorology* 57: 221-240. [https://doi.org/10.1016/0168-1923\(91\)90088-8](https://doi.org/10.1016/0168-1923(91)90088-8).
- Roy, S., Barooah, A. K., Ahmed, K. Z., Baruah, R. D., Prasad, A. K., and Mukhopadhyay, A. 2020. "Impact of Climate Change on Tea Pest Status in Northeast India and Effective Plans for Mitigation." *Acta Ecologica Sinica* 40: 432-442. <https://doi.org/10.1016/j.chnaes.2019.08.003>.
- Sampaio, F., Krechemer, F. S., and Marchioro, C. A. 2021. "The Hotter the Better? Climate Change and Voltinism of *Spodoptera eridania* Estimated with Different Methods." *Journal of Thermal Biology* 98: 102946. <https://doi.org/10.1016/j.jtherbio.2021.102946>.
- Schneider, L., Rebetez, M., and Rasmann, S. 2022. "The Effect of Climate Change on Invasive Crop Pests Across Biomes." *Current Opinion in Insect Science* 50: 100895. <https://doi.org/10.1016/j.cois.2022.100895>.
- Sharma, S., Kooner, R., and Arora, R. 2017. "Insect Pests and Crop Losses." In *Breeding Insect Resistant Crops for Sustainable Agriculture*, edited by R. Arora and S. Sandhu, 45-66. Singapore: Springer. https://doi.org/10.1007/978-981-10-6056-4_2.
- Spahn, R., and Lill, J. T. 2022. "Higher Temperatures Reduce the Efficacy of a Key Biocontrol Parasitoid." *Biological Control* 176: 105079. <https://doi.org/10.1016/j.biocontrol.2022.105079>.
- Stinner, B., and House, G. 1990. "Arthropods and Other Invertebrates in Conservation-Tillage Agriculture." *Annual Review of Entomology* 35: 299-318.
- Subedi, B., Poudel, A., and Aryal, S. 2023. "The Impact of Climate Change on Insect Pest Biology and Ecology: Implications for Pest Management Strategies, Crop Production, and Food Security." *Journal of Agricultural and Food Research* 14: 100733. <https://doi.org/10.1016/j.jafr.2023.100733>.
- Tooker, J. F., Douglas, M. R., and Krupke, C. H. 2017. "Neonicotinoid Seed Treatments: Limitations and Compatibility with Integrated Pest Management." *Agricultural and Environmental Letters* 2: ael2017.08.0026. <https://doi.org/10.2134/ael2017.08.0026>.

Van Espen, M., Williams, J. H., Alves, F., Hung, Y., de Graaf, D. C., and Verbeke, W. 2023. "Beekeeping in Europe Facing Climate Change: A Mixed Methods Study on Perceived Impacts and the Need to Adapt According to Stakeholders and Beekeepers." *Science of the Total Environment* 888: 164255. <https://doi.org/10.1016/j.scitotenv.2023.164255>.

Venugopal, P. D., and Dively, G. P. 2017. "Climate Change, Transgenic Corn Adoption and Field-Evolved Resistance in Corn Earworm." *Royal Society Open Science* 4: 170210. <https://doi.org/10.1098/rsos.170210>.

Walter, J. A., Sheppard, L. W., Venugopal, P. D., Reuman, D. C., Dively, G., Tooker, J. F., and Johnson, D. M. 2020. "Weather and Regional Crop Composition Variation Drive Spatial Synchrony of Lepidopteran Agricultural Pests." *Ecological Entomology* 45: 573-582. <https://doi.org/10.1111/een.12830>.

Yang, L. H., Postema, E. G., Hayes, T. E., Lippey, M. K., and MacArthur-Waltz, D. J. 2021. "The Complexity of Global Change and Its Effects on Insects." *Current Opinion in Insect Science* 47: 90-102. <https://doi.org/10.1016/j.cois.2021.05.001>.

CROP DISEASE AND PATHOGENS

Nidhi Rawat

SUMMARY

Soybean, corn, and winter wheat are the major agronomic crops of Maryland. Soybean and corn are used for feed (grains and silage) and commercial products like lubricants and oils. Wheat is used as a food crop and as a cover crop in the state. These crops have specific pathogens causing different diseases, resulting in significant yield losses. Over recent years, some new diseases as well as changing patterns of disease severity have been reported from Maryland for these crops, which correlates with observations of increasing temperatures and irregular precipitation patterns. For example, tar spot disease of corn, which was first reported from Illinois and Indiana in 2015, has been recently reported from Maryland in 2022 and is being increasingly reported in multiple Maryland counties since then. Similarly, new races of soybean cyst nematodes are emerging, which are resistant to the resistance genes used in cultivars. Wheat Fusarium Head Blight is a major challenge, reducing crop yield and contaminating grains with mycotoxins. With the predicted climate changes over the next decades, these diseases are expected to increase in their severity, and thus it is critical for farmers to adopt strategies to minimize losses due to them in a timely manner.

METHODS

Disease Data

For analyzing the effect of diseases in these crops, we used the Crop Protection Network (Crop Protection Network 2024) database to categorize the approximate yield and dollar losses in these crops. The data on soybean was available from 1996 onward, for corn it was available from 2017 onward, and for wheat it was available from 2018 onward. It is important to note that diseases in field crops do not occur in isolation, and it is very difficult to accurately measure the losses caused by a specific disease.

The contributors of the data include the Corn Disease Working Group (CDWG), the North Central Research and Extension Activity (NCERA) 137 Soybean Disease Committee, and the North Central Regional Committee on Management of Small Grain Diseases (NCERA 184). Estimates may be based on statewide surveys; feedback from university extension, industry, government, and farmer representatives; and personal experiences. It is important to note the limitations of this data, including the fact that loss values here are expert estimates and not actual loss values.

How Loss Estimates Are Determined

Yield losses have been calculated as the expert percentage estimate of a particular disease in that year times the yield or dollar value estimated without any loss. Production without estimated disease or invertebrate pest loss is used to formulate values. Inflation has NOT been accounted for in reported U.S. dollar (USD) values. Per acre USD loss values are derived by dividing losses in USD by the reported number of acres planted in the state. Disease losses have been reported in the following categories: % Yield Loss, USD (\$) Loss, and Per acre USD (\$) loss. Because data was obtained from differing sources (extension personnel, previously published papers, and government reporting agencies), unaccountable discrepancies among years and locations may exist. Finally, it is important to remember that the data presented here are estimates only.

RESULTS

Soybean Diseases

Most soybean data were back calculated from reported yield reductions to percent losses using production reports from USDA NASS and OMAFRA. Cercospora leaf blight and purple seed stain losses have been combined into one value. From 1996 to 2010, losses from root knot nematode and other nematodes (excluding soybean cyst nematode) were contained in a single category; from 2011 onward, root knot nematode data were separated from the other nematodes category; from 2014 onward, Reniform nematode data were separated from the other nematodes category. From 1996 to 2022, diseases and nematodes caused an average yield loss of 3.7% in soybean (Figure 1). The minimum yield loss of 0.69% during this period was reported in 2010, and the maximum yield loss of 9.3% was reported in 2013. On average, over USD 6.2 million were lost every year in Maryland due to pathogens and pests, which ranged from \$1.3 million to \$24.8 million in 2010 and 2013, respectively.

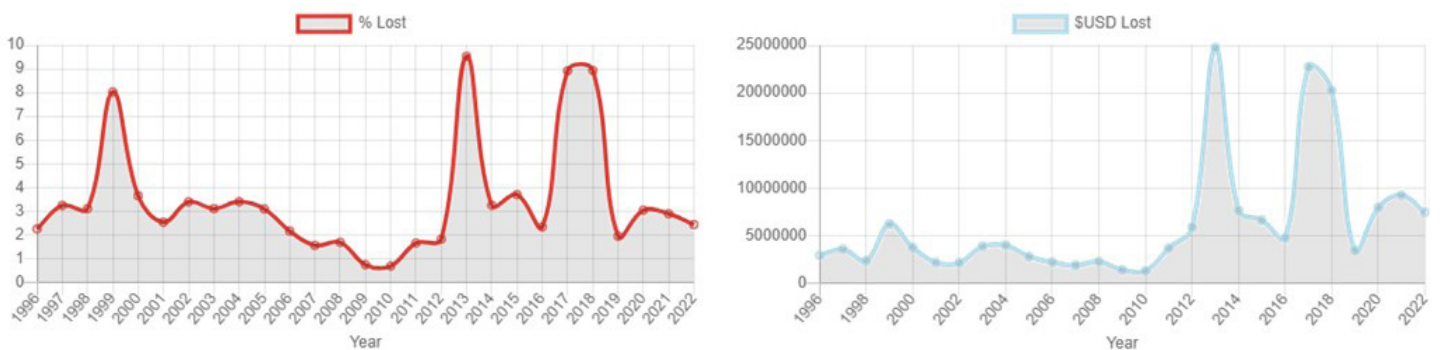


Figure 1. Disease Losses in Soybean in Maryland 1996 to 2022. Left: Percent yield losses, Right: Losses in USD

Figure 2 depicts the individual pests and pathogens of concern in soybean in Maryland. Soybean cyst nematode was the most important pest over most of the years in this period, followed by stem and pod blight caused by the *Phomopsis*/*Diaporthe* complex and charcoal rot caused by *Macrophomina phaseolina*. Root knot nematode and *Cercospora* leaf blight were other pests and pathogens of concern in soybeans. Other seedling diseases, such as damping off, were reported in years with high precipitation. With the predicted warmer weather, these diseases and nematodes are predicted to further increase in severity and incidence. Soybean cyst nematode has been consistently rising, and this trend is predicted to continue over the next few decades. Importantly, the increase in the rate of growth and reproduction in the pathogens and pests will lead to the evolution of new races, which may overcome the genes deployed in cultivars for resistance against these pests and pathogens.

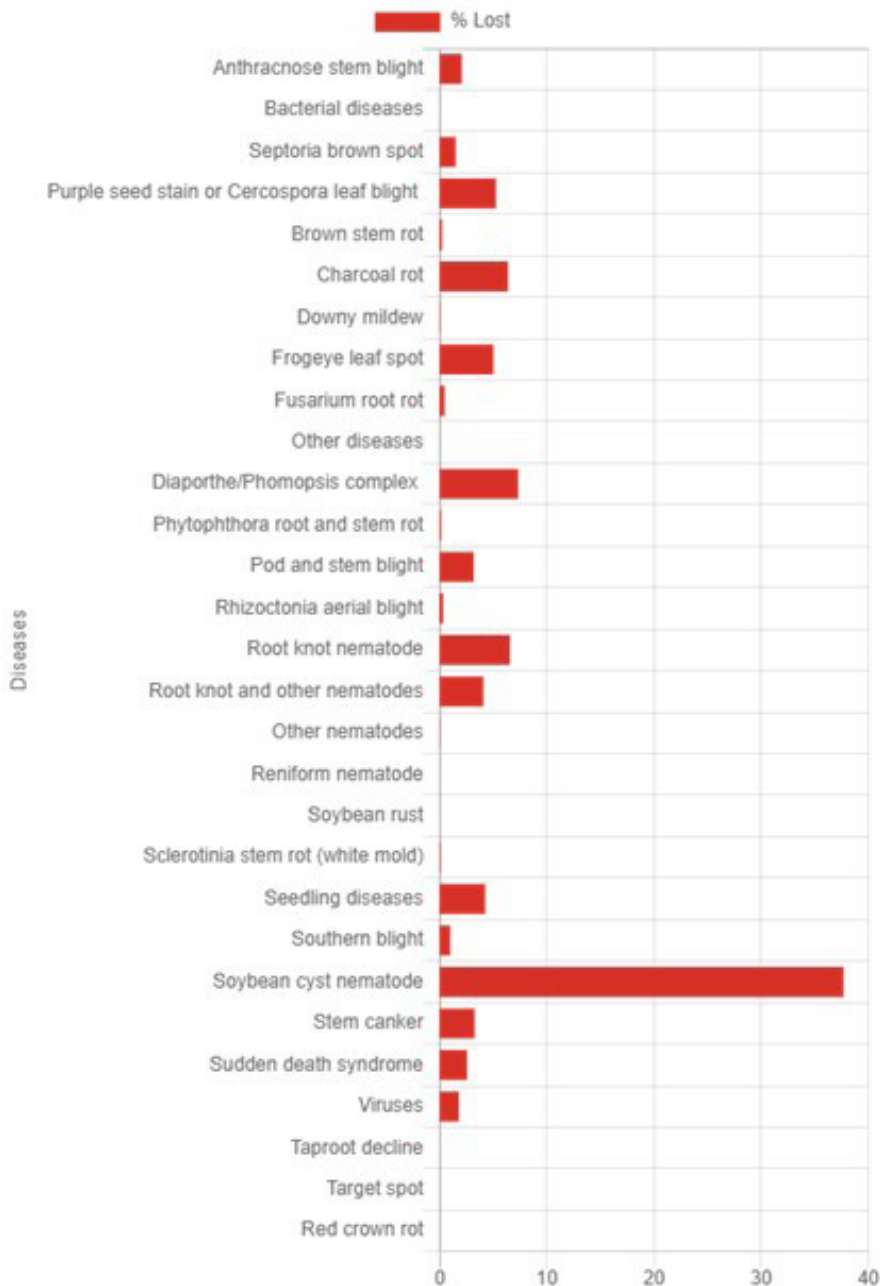


Figure 2. Specific Pathogens of Significance in Soybean and the Corresponding Yield Losses

Corn Diseases

Data on corn diseases for Maryland was available from 2017 to 2023. The average yield loss in this period due to diseases was 1.98% (Figure 3). A maximum yield loss of 5.01% was reported in 2018. The USD losses in this period have been reported to range from \$1,944,732 to \$24,005,561. On average, \$5,545,050 was lost in this period due to diseases of corn in the state.

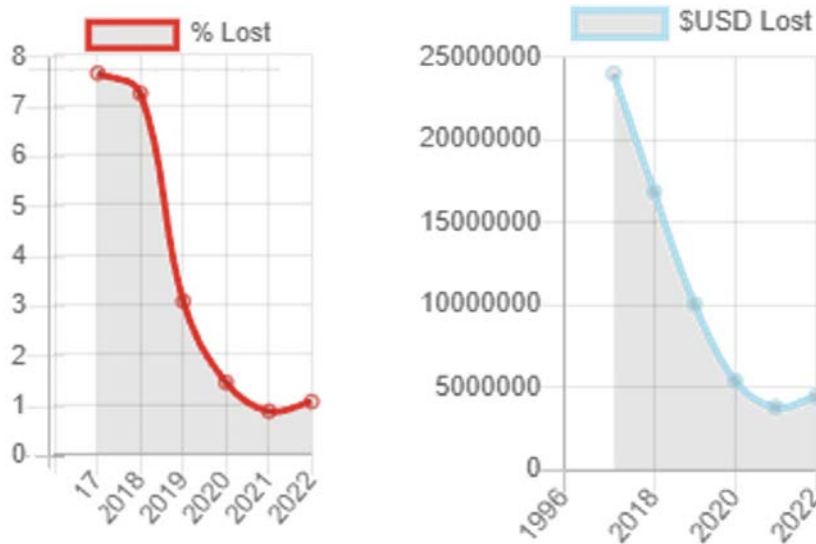
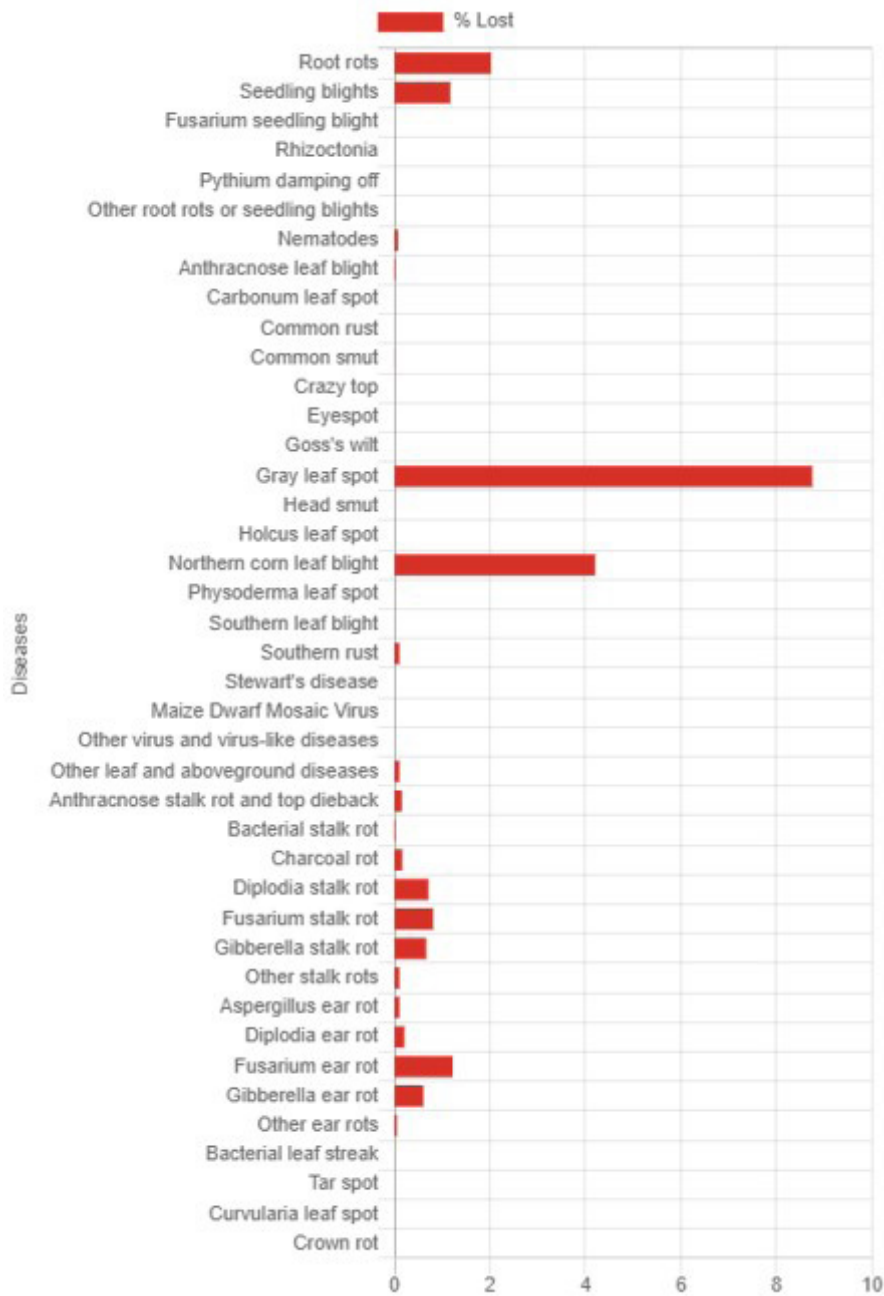


Figure 3. Overall Disease Losses in Corn in Maryland 2017 to 2022. Left: Percent yield losses, right: Losses in USD

Gray leaf spot and Northern corn leaf blight were reported to be major foliar diseases of concern. 2018 was a warm and wet year, and poor seedling emergence due to root rot and seedling blight diseases was a major issue. Other diseases of concern including fungal rots such as Diplodia stalk rot, Fusarium stalk rot, Fusarium ear rot, and Giberella ear rot have been reported in years specifically with high temperatures and humidity. In addition, the emergence of a new disease, tar spot, in 2022 poses a challenge for the corn growers in the state and is predicted to increase in economic significance in the future. It was increasingly reported in 2023 from different counties of the state (Valle-Torres et al. 2020; Kness 2022). Being a new disease, no well-characterized genetic resistance in varieties is available yet.



Wheat Diseases

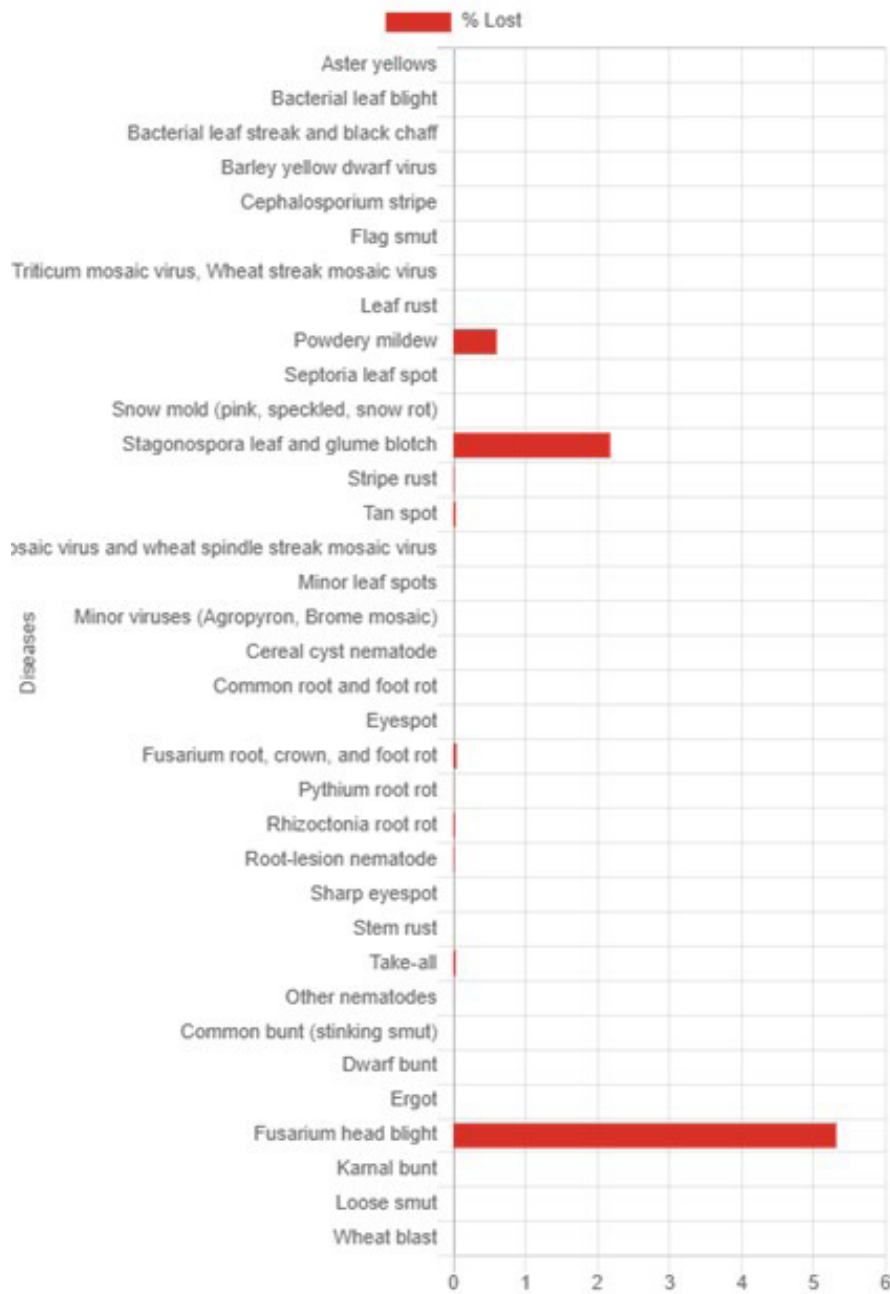
Wheat is the third most important crop in Maryland. It is grown not only as food and feed crop, but around 40% of the crop acreage is planted as a cover crop. Data on wheat diseases was available from 2017 onward. 2018 was a wet and warm year for wheat, and maximum disease losses (1.08 %) were reported in this year. Losses of \$651,510 were reported in this year due to different diseases.



Figure 5. Overall Disease Losses in Wheat in Maryland 2017 to 2022. Left: Percent yield losses, Right: Losses in USD

Fusarium head blight (FHB) is the biggest challenge for wheat growers in the state. FHB not only reduces the grain yield but also contaminates grain with associated mycotoxins such as Deoxynivalenol (DON). DON is regulated for human and feed consumption to levels as low as 1 part per million and 5 parts per million, respectively. In 2018, FHB was the major issue for wheat growers, who faced not only low yield but rejection of their grain for sales at the elevators due to the high DON content. Other diseases of concern include *Stagonospora nodorum* leaf and glume blotch. These diseases reduce the photosynthetic efficiency of the plants, thereby reducing grain yield. Other diseases include powdery mildew, rusts, and Fusarium crown rot and root rot.

It is important to note that all these diseases are expected to increase in their incidence and severity with warmer temperatures and high humidity conditions. With warm weather conditions, the rates of evolution of pathogen races are very high, and they are increasingly being reported to overcome resistance genes and fungicide treatments.



RECOMMENDATIONS

- Use of genetic resistant varieties: It has been found that genetic resistance is still the most effective and sustainable approach to fighting crop diseases.
- Practicing effective crop rotation: Corn and wheat are both host plants for Fusarium species. Therefore, alternating crops such as soybean or other non-host crops is an effective way to manage diseases caused by Fusarium.

CHALLENGES

Based on recent trends and future weather predictions, crop diseases are expected to increase in their severity and incidence. With warming temperatures being conducive to pathogen evolution, new pathogen races are emerging that defeat the deployed genes of resistance. This trend is also evident in the emergence of fungicide resistance in pathogens. Although the trends are overwhelmingly supportive of the conclusions, the data used in making predictions by the Crop Protection Network are based on expert estimates of the losses and are subject to differences in individual approximations.

As diseases in fields do not occur in isolation, it is often difficult to accurately predict the losses caused by specific diseases. Another challenge is the availability of accurate long-term historical data for corn and wheat. For these crops, data was available only from 2017 onward. However, as accidental weather events are becoming pretty frequent in recent times, the trends observed for these crop diseases, although short-term, are quite informative.

REFERENCES

Crop Protection Network. 2024. "Estimates of Crop Yield Losses Due to Diseases and Invertebrate Pests: An Online Tool." <https://loss.cropprotectionnetwork.org/>. <https://doi.org/10.31274/cpn-20191121-0>.

Kness, A. 2022. "Tar Spot of Corn Confirmed in Maryland." *Agronomy News* 13: 6. <https://extension.umd.edu/resource/tar-spot-corn-confirmed-maryland>.

Valle-Torres, J., T. J. Ross, D. Plewa, M. C. Avellaneda, J. Check, M. I. Chilvers, A. P. Cruz, et al. 2020. "Tar Spot: An Understudied Disease Threatening Corn Production in the Americas." *Plant Disease* 104 (10): 2541-50. <https://doi.org/10.1094/PDIS-02-20-0449-FE>.

WATER RESOURCE

Majid Mirzaei, Negahban-Azar, & Shirmohammadi

SUMMARY

This comprehensive study examines agricultural water withdrawal trends, extreme precipitation events, and water deficits in Maryland, offering critical insights and recommendations for sustainable water management in agriculture. From 1980 to 2022, agricultural water withdrawals from the Aquia Aquifer during growing seasons have shown a significant upward trend, peaking at 3.1 billion gallons in 2019. The Aquia Aquifer is a significant source of water supply in Anne Arundel, Calvert, Queen Anne's, Kent, St. Mary's, and Talbot counties, and to a lesser extent in Caroline, Cecil, Charles, Dorchester, and Prince George's counties.

This increase underscores the growing reliance on high-quality freshwater to meet agricultural demands, driven by the expansion of irrigated lands and increasing water needs. The analysis of extreme precipitation events reveals that these events are becoming more frequent and intense,

particularly from 2003 onward. Traditional water availability assessments often overlook these extreme events, which can lead to overestimations of water availability due to rapid runoff.

The probability of extreme precipitation events is projected to increase even if global CO₂ emissions are reduced, according to projected data from the Shared Socioeconomic Pathways (SSP) scenarios, which describe different development paths society may take with respect to their impacts on climate change. This highlights the necessity of incorporating extreme event projections into water management strategies. Historical data on water deficits, calculated as the difference between evapotranspiration (ET) and precipitation, show an increasing trend driven by rising temperatures and ET. However, recent years have seen a reduction in water deficits, primarily due to significant increases in precipitation. Future projections suggest that higher temperatures and increased ET will likely result in greater water deficits, particularly under the high CO₂ emissions SSP585 scenario, despite slight increases in precipitation. These findings emphasize the need for improved water management practices to ensure sustainable agricultural production.

Recommendations include investing in efficient irrigation systems, promoting water conservation strategies, and developing drought-resistant crop varieties. Policymakers and farmers in Maryland must integrate these insights into their planning and decision-making processes to mitigate the impacts of climate change on water resources and maintain agricultural resilience. By understanding these trends and implementing adaptive strategies, Maryland can ensure sustainable agricultural productivity and resilience against the impacts of climate change. With respect to water resources data, Maryland faces data gaps, insufficient monitoring, and limited accessibility and integration of critical groundwater and water use data. It is recommended that future work should focus on developing a regional groundwater-flow model, expanding monitoring networks, improving data accessibility, quantifying smaller withdrawals, enhancing water quality data management, and transitioning the aquifer information system to a web-based and user-friendly platform.

BACKGROUND AND METHODS

Heavy freshwater withdrawals from confined aquifers and declines in groundwater levels as large as 72 feet (about 22 m), even in humid regions like Maryland, are truly alarming for future freshwater sustainability in Maryland (Shirmohammadi et al. 2020). As such, we have been using modeling tools to assess both the benefits of irrigation versus rain-fed crop production and the potential use of treated wastewater from wastewater treatment plants (WWTP) as supplemental irrigation water in order to conserve freshwater in the aquifers (Rahman et al. 2024). Our results indicate that irrigation increases crop yield for corn and soybean in Maryland and the use of treated wastewater can supplement irrigation requirements by as much as 56%, depending upon the field size and proximity of the WWTP to the field parcels. The findings further reveal that the treated water supply from nearby WWTPs can meet crop water requirements during wet years and partially fulfill needs during average and dry years by 56% and 30%, respectively. The framework aims to enhance crop yields while preserving freshwater in confined aquifers. Implementing this model as a decision support tool will empower stakeholders to assess the feasibility of using recycled water for supplemental irrigation and quantify potential reductions in water extractions from confined aquifers. This effort was followed after our reported historical groundwater withdrawal trends and extreme precipitation patterns during the second quarter, as presented in the following paragraphs.

RESULTS

Analysis of Agricultural Water Withdrawal Trends and Influencing Factors in Maryland

Figure 1 illustrates growing season water withdrawals for agricultural use from the Aquia Aquifer in Maryland from 1980 to 2022. The data reveal significant fluctuations and an overall increasing trend in water withdrawals over this period. During the initial years (1980 to 1986), water use was relatively moderate, ranging from approximately 400 to 636 million gallons per year in the growing season. A marked surge began in 1988, with withdrawals escalating rapidly into billions of gallons per year, reflecting a substantial increase in agricultural water demand. Throughout the late 1980s and 1990s, water usage displayed an erratic pattern, oscillating between several million gallons to a peak of approximately 2.4 billion gallons in 1999. From the 2000s onward, withdrawals remained high, fluctuating annually but maintaining an upward trajectory. This trend culminated in the highest recorded usage in 2019, with about 3.1 billion gallons per year in the growing season. This pattern indicates an increasing reliance on high-quality freshwater from the Aquia Aquifer to meet agricultural demands, likely due to the expansion of irrigated lands and the growing needs of other agricultural water uses. The sustained upward trend in water withdrawals underscores the critical importance of managing aquifer resources to ensure sustainable agricultural practices in Maryland.

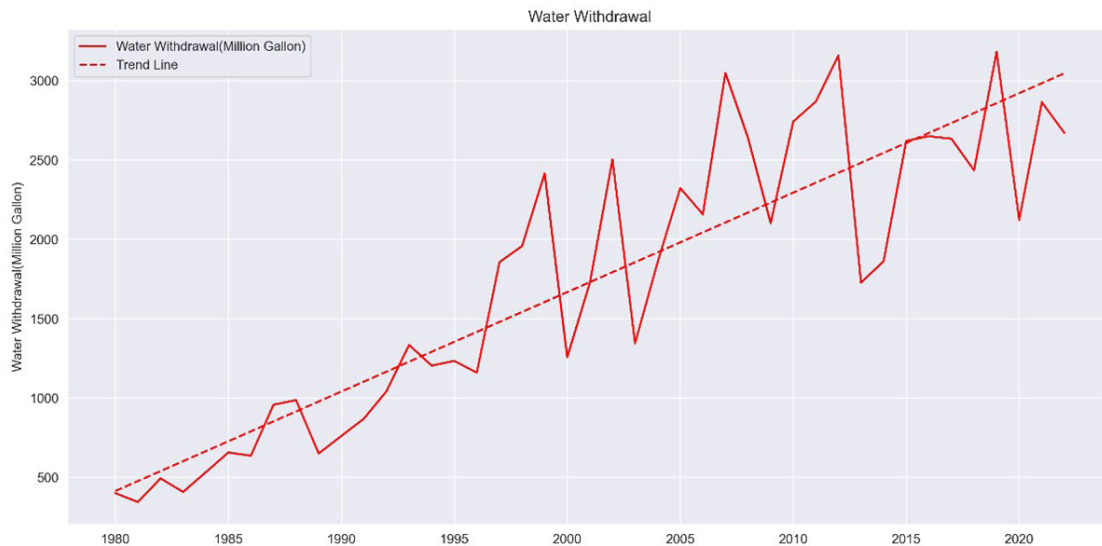


Figure 1. Water Withdrawals for Agriculture (irrigation, livestock, etc.) from Aquia Aquifer in Maryland in Growing Seasons (Data Source: Water Supply Division of the Maryland Department of the Environment, 2023).

Extreme Precipitation Events Analysis in Maryland

Extreme precipitation events are a critical factor in agriculture (Vogel et al. 2019), particularly during the growing season, yet they are often not carefully considered in water availability analyses. Typically, total rainfall during the growing season is summed and considered the primary water source for agriculture. However, it is essential to account for the timing and intensity of rainfall—soil needs sufficient time to absorb and store water for plant use, and the infiltration rate of the soil plays a crucial role in this process. When rainfall intensity is lower than the soil's infiltration capacity, water is absorbed and stored effectively in the soil zone. However, extreme precipitation events, characterized by high intensity and short duration, often exceed the soil's infiltration capacity. As a result, a significant portion of the rainfall during such events runs off the surface, rather than

infiltrating the soil, and is lost as stream water. This runoff reduces the actual amount of water available for crops, leading to an overestimation of water availability if extreme events are not properly accounted for.

To analyze extreme precipitation patterns in all Maryland counties, we utilized climate data from the National Oceanic and Atmospheric Administration (NOAA) (NOAA 2023), which includes daily records of precipitation and measurements of minimum, maximum, and mean daily temperatures. This data was used to identify historical patterns and trends at both state and county levels, analyzed across yearly, seasonal, and monthly resolutions. In this phase of analysis, we examined extreme precipitation data by defining extreme events as any daily precipitation exceeding the 95th percentile (i.e., threshold for extreme events) of the data. The Chi-square goodness of fit test was employed to identify data points that exceeded this threshold, providing a statistical measure of how well the observed data fit a specific distribution.

After applying the Chi-square goodness of fit test, we determined that the Generalized Logistic (GLO) distribution is the most suitable for fitting our precipitation data to establish a threshold for extreme events (Zakaria et al. 2012). By fitting the GLO distribution to county-level data across Maryland, we identified distinct threshold values for extreme precipitation events in each county. Using these thresholds, we counted the number of extreme events each year from 1951 to 2022, and we calculated the average magnitude of these events to assess changes over time.

A comprehensive analysis of the data revealed an overall negative trend in the number of extreme events from 1950 to 2000. However, a reversal occurred after 2000, with an increasing trend in the number of extreme events persisting to the present for most counties. Figure 2 shows the ten-year moving average for extreme precipitation events for Anne Arundel County. The moving average was calculated as follows: first ten-year segment was from 1953 through 1962, the second ten-year segment was considered to be from 1954 to 1963, and then the third ten-year segment was considered to be from 1955 to 1964, and so on. Due to space limitation, the labels on the x-axis in Figure 2 do not show all the labels for all ten-year segments. However, data are reflected for all ten-year segments with the bar graphs.

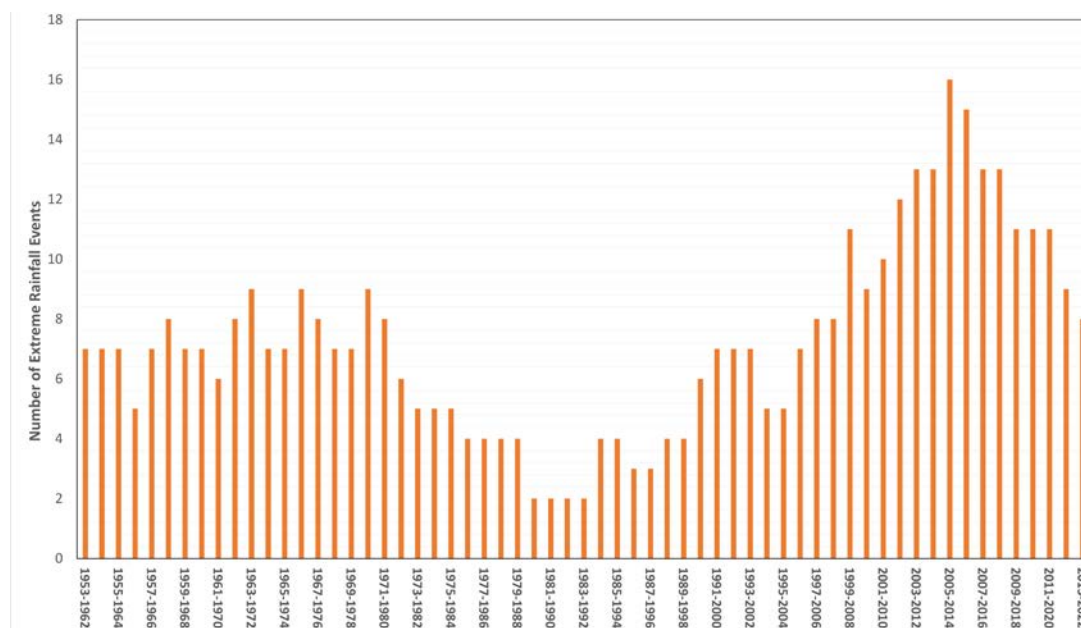


Figure 2: Ten-Year Moving Average for Extreme Precipitation Events, Illustrated for Anne Arundel County, Maryland (Data Source: NOAA 2023).

Figure 3 shows that, in addition to the ongoing upward trend in the number of extreme events for most counties, there has been a notable increase in the average magnitude of precipitation for these extreme events over the past two decades across all counties.

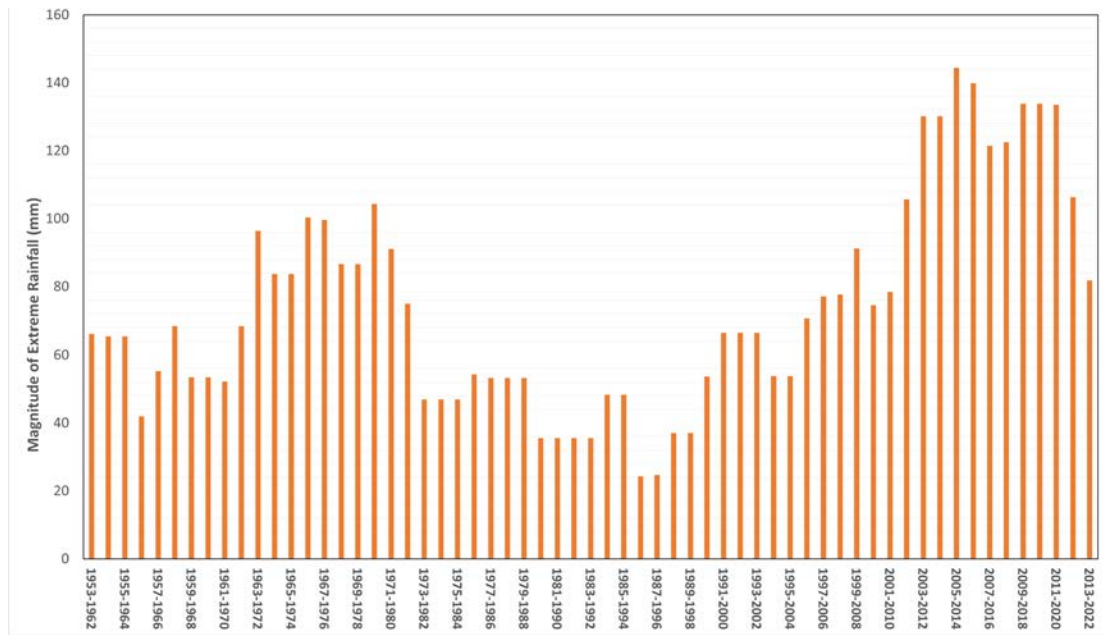


Figure 3: Ten-Year Moving Average for Magnitude of Extreme Precipitation Events, Illustrated for Anne Arundel County, Maryland (Data Source: NOAA 2023).

In Figure 4, we present the state-level analysis of extreme precipitation events in Maryland. This figure illustrates the probability of an extreme event occurring on any given day of the year. The red line represents the average probability of extreme events over the observation period (1951 to 2022). The results reveal that from 1951 to 1970, the probability of extreme events was consistently below the long-term average. However, between 1970 and 1980, there was a notable surge, with probabilities exceeding the average. From 1980 to 2002, most years again saw probabilities below the average, but from 2003 onward, there has been a significant increase in the probability of extreme events. The overall trend from 1951 to 2022 indicates a positive trajectory, suggesting an increasing likelihood of extreme precipitation events. Regarding the magnitude of extreme events, Figure 5 shows the average magnitude of extreme precipitation events for each year. This analysis reveals a positive trend from 1951 to 2022, indicating that not only are extreme events becoming more frequent, but their intensity is also increasing.

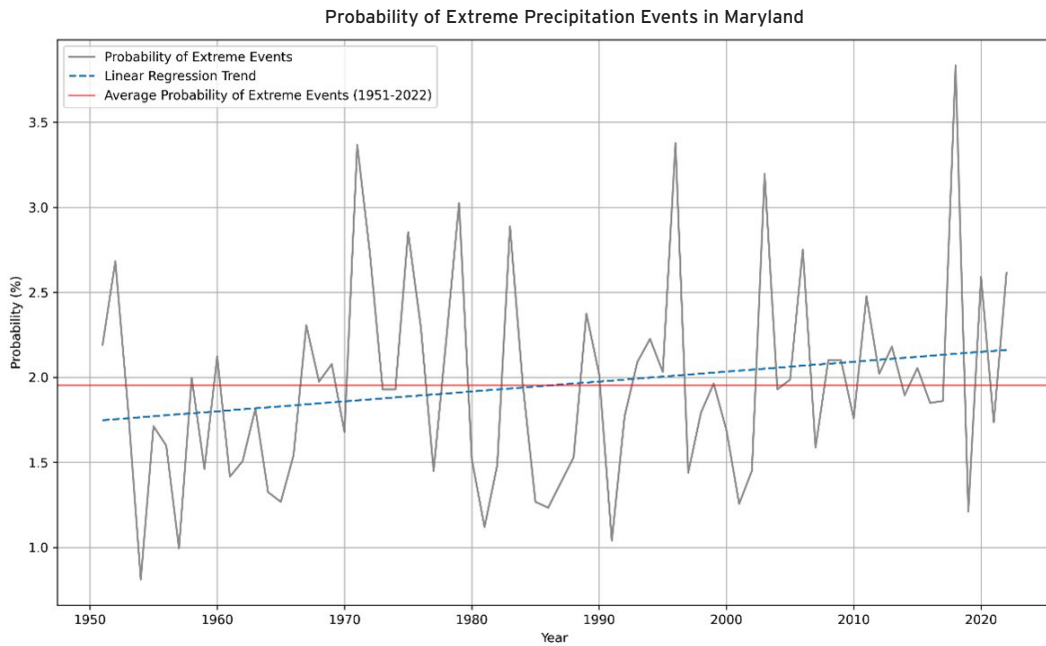


Figure 4: Probability of Extreme Precipitation Events in Maryland (1951 to 2022) (Data Source: NOAA 2023).

These findings underscore the importance of considering extreme precipitation events in agricultural water management. Traditional analyses that sum seasonal rainfall may overestimate the water available for agriculture, as they do not account for the rapid runoff associated with extreme events. By incorporating these extreme events into our water availability assessments, we can develop more accurate and resilient agricultural strategies. This is crucial for Maryland, where changing precipitation patterns and increasing extreme events necessitate proactive measures to ensure sustainable water use and agricultural productivity.

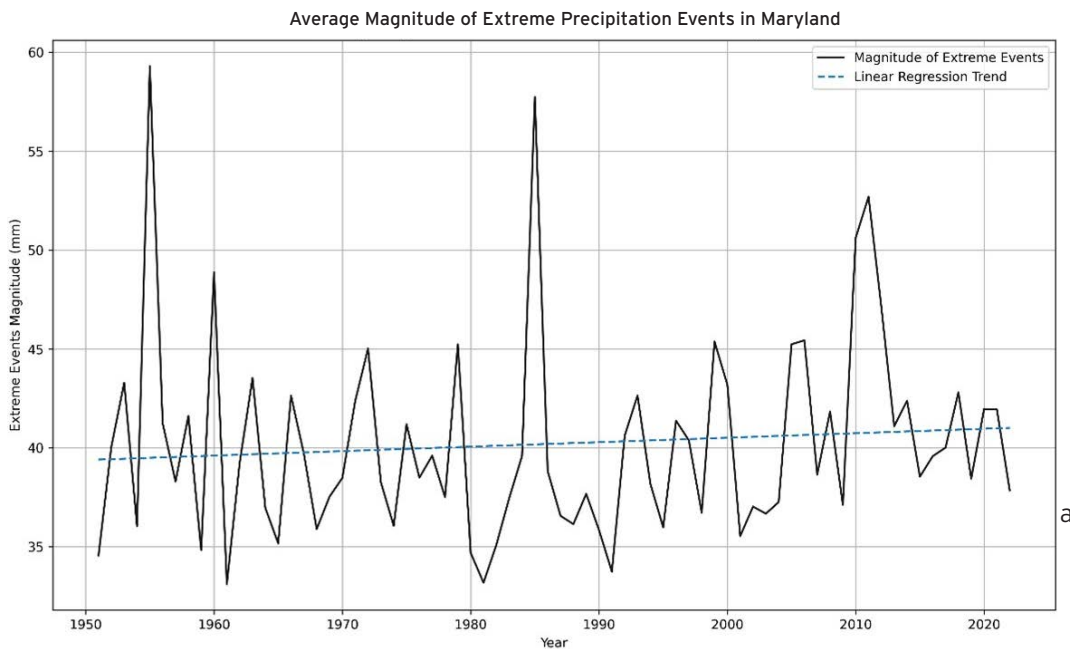


Figure 5: Average Magnitude of Extreme Precipitation Events in Maryland (1951 to 2022) (Data Source: NOAA 2023).

Analysis of Projected Extreme Precipitation Events in Maryland Across Climate Scenarios

In this section, we discuss the analysis of projected extreme precipitation events using data from three Shared Socioeconomic Pathways (SSP) scenarios in CMIP6: SSP126, SSP245, and SSP585. The same method applied to historical observational data was used to analyze the projected data. We evaluated the data over eight decades, spanning from 2021 to 2100, and compared the probability of extreme events in each SSP scenario against historical data. Figure 6 displays the probability of extreme precipitation events by decade and scenario for Maryland. The historical data is shown alongside the projections for SSP126, SSP245, and SSP585. Each bar represents the probability of extreme events for a given decade, allowing us to observe trends and compare different scenarios. The analysis reveals that the probability of extreme events varies across different scenarios and decades. For the period from 2021 to 2030, the probabilities are relatively similar across all scenarios, with SSP245 showing a slightly higher probability compared to historical data. Moving forward, each scenario demonstrates a distinct pattern. The SSP126 scenario (blue bars) generally shows a moderate increase in the probability of extreme events compared to the historical baseline, with fluctuations across decades. The SSP245 scenario (orange bars) often shows higher probabilities of extreme events compared to SSP126, particularly noticeable in the mid-century decades (2041 to 2050 and 2051 to 2060). The SSP585 scenario (green bars) consistently shows the highest probability of extreme events among all scenarios, indicating a significant increase in extreme precipitation events as we move toward the end of the century.

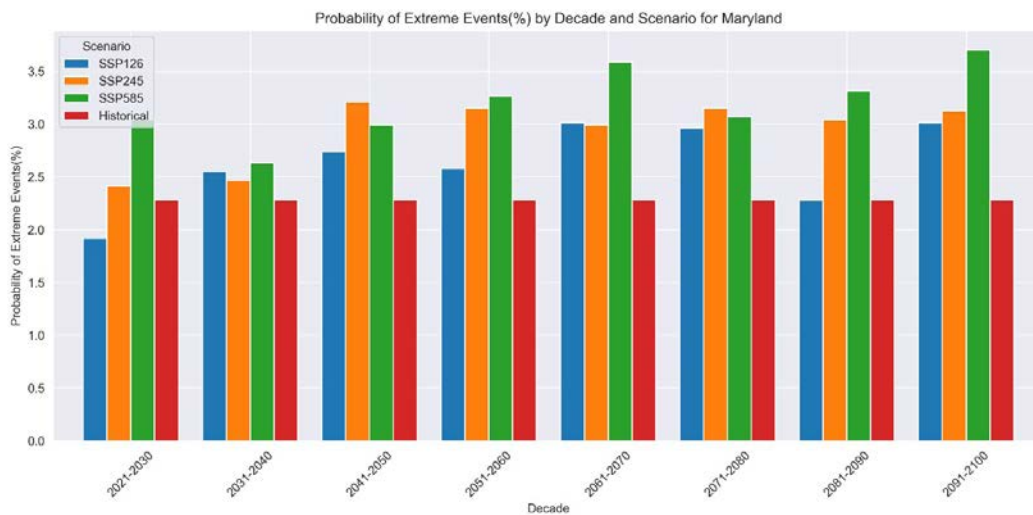
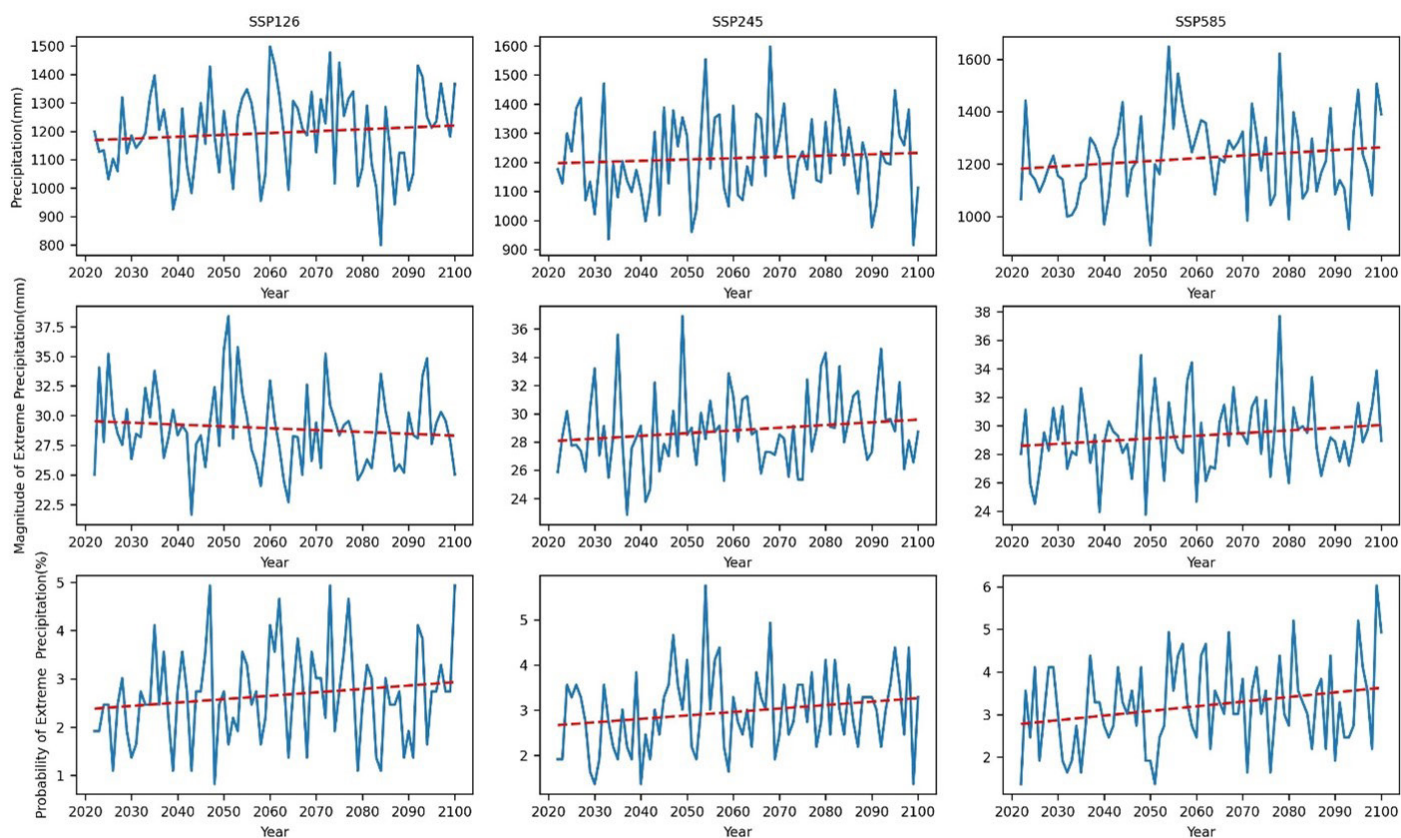


Figure 6: Projected Probability of Extreme Precipitation Events by Decade and Scenario in Maryland (2021 to 2100)

Figure 7 displays the projected annual precipitation, magnitude of extreme precipitation events, and probability of extreme precipitation events for the periods 2022 to 2100 under three different SSP scenarios (SSP126, SSP245, and SSP585) in Maryland. The top row of plots shows a slight increase in annual precipitation across all scenarios. SSP585 exhibits the highest variability and overall increase in precipitation, followed by SSP245 and SSP126. The middle row of plots indicates the magnitude of extreme precipitation events. Notably, while SSP245 and SSP585 show stable

or slightly increasing trends, SSP126 reveals a decreasing trend in the magnitude of these events. The bottom row presents the probability of extreme precipitation events, which increases across all scenarios, with SSP585 showing the most significant rise. This indicates a higher likelihood of extreme precipitation events occurring as we progress through the century, particularly under the more severe climate change scenario, SSP585.

These projections suggest that while overall precipitation and the probability of extreme events are expected to increase, the magnitude of these extreme events may not follow the same trend uniformly across all scenarios. Specifically, the decrease in the magnitude of extreme events under SSP126 contrasts with the increasing trends in probability and total precipitation. This divergence highlights the complexity of predicting future climatic impacts and underscores the need for tailored adaptation strategies. In particular, understanding these nuanced trends is crucial for water resource management and agricultural planning in Maryland, ensuring resilience against the varied impacts of climate change. Consequently, adaptation measures must be flexible and responsive to both the frequency and intensity of future climatic changes.



Annual Precipitation, Magnitude of Extreme Precipitation, and Probability of Extreme Precipitation across scenarios SSP126, SSP245, SSP585 for Maryland. Red dashed line represents the trend line.

Figure 7: Projected Annual Precipitation, Magnitude, and Probability of Extreme Precipitation Events in Maryland (2022 to 2100) Across SSP Scenarios

Analyzing Water Deficit Trends in Maryland's Agriculture

Water deficit, the difference between evapotranspiration (ET) and precipitation, is a critical factor in agricultural planning and resource management, especially during the growing season. Understanding water deficit is vital as it directly impacts crop growth, irrigation needs, and yield outcomes (Zhang and Cai 2013). This analysis becomes even more significant when considering varied geographical and climatic zones, as water needs can significantly differ across regions. In Maryland, for instance, agricultural practices and water management strategies can vary greatly from one county to another due to differences in rainfall patterns and crop choices. To provide a comprehensive view of the state's water balance, we have conducted an extensive analysis covering all counties in Maryland. As an example, Figure 8 represents the overall water deficit trend for the entire State of Maryland, but similar detailed studies have been carried out for each county, offering localized insights crucial for effective agricultural and environmental management. The data used in this study is sourced from the NOAA database for precipitation, and the ET is estimated using the Penman-Monteith method. This method is recommended by the United Nations Food and Agricultural Organization (UN-FAO) for its accuracy and reliability in estimating ET (Allen et al. 1998, Cai et al. 2007, Zotarelli et al. 2010).

Figure 8 illustrates the historical trends in key parameters influencing water deficit from 1980 to 2022 during the growing season (June-August). The parameters include average temperature, precipitation, evapotranspiration, and water withdrawal, each plotted with their respective trend lines to highlight long-term changes.

- **Average Temperature (°C):** The first subplot shows a clear increasing trend in average temperature over the period (June-August). This rise in temperature contributes to higher evapotranspiration rates, thereby increasing the potential for water deficit.
- **Precipitation (mm):** Precipitation in the plot is calculated by summing the total daily precipitation during the growing season, which spans from June to August, for each year. The second subplot displays the variability and slight increasing trend in precipitation. While there are fluctuations year by year, the overall trend suggests a modest rise in precipitation levels, which partially offsets the increasing ET.
- **Evapotranspiration (mm):** Evapotranspiration is calculated daily and then summed to represent the total evapotranspiration for each growing season, which is the cumulative daily ET from the start to the end of the growing season each year. The third subplot highlights the trend in ET, which also shows an increasing pattern. This increase is driven by the rising temperatures, indicating higher water demand from crops.
- **Water Deficit (mm):** The fourth subplot presents the water deficit, calculated as the difference between ET and precipitation. Water deficit is determined by calculating the difference between daily evapotranspiration (ET) and daily precipitation. The sum of daily water deficit is then accumulated to represent the total water deficit for the growing season each year. Interestingly, the data reveal a decreasing trend in the deficit in recent years, particularly noticeable in the latter part of the time series. This reduction in deficit is primarily attributed to a significant increase in precipitation and only a slight rise in ET, as observed in the last decade.

This trend shift is essential for understanding changing climatic conditions and their implications for water resource management and agricultural practices. Such insights are invaluable for devising adaptive strategies to ensure sustainable agriculture and water conservation in Maryland's diverse agricultural landscape. The increasing water deficit highlights the need for improved water management practices, such as efficient irrigation systems and better water conservation strategies, to ensure sustainable agricultural production in the face of changing climatic conditions. By understanding these trends, policymakers and farmers can make informed decisions to mitigate the impacts of water scarcity and enhance agricultural resilience. Additionally, proactive planning and investment in innovative water-saving technologies will be crucial to adapt to these evolving conditions.

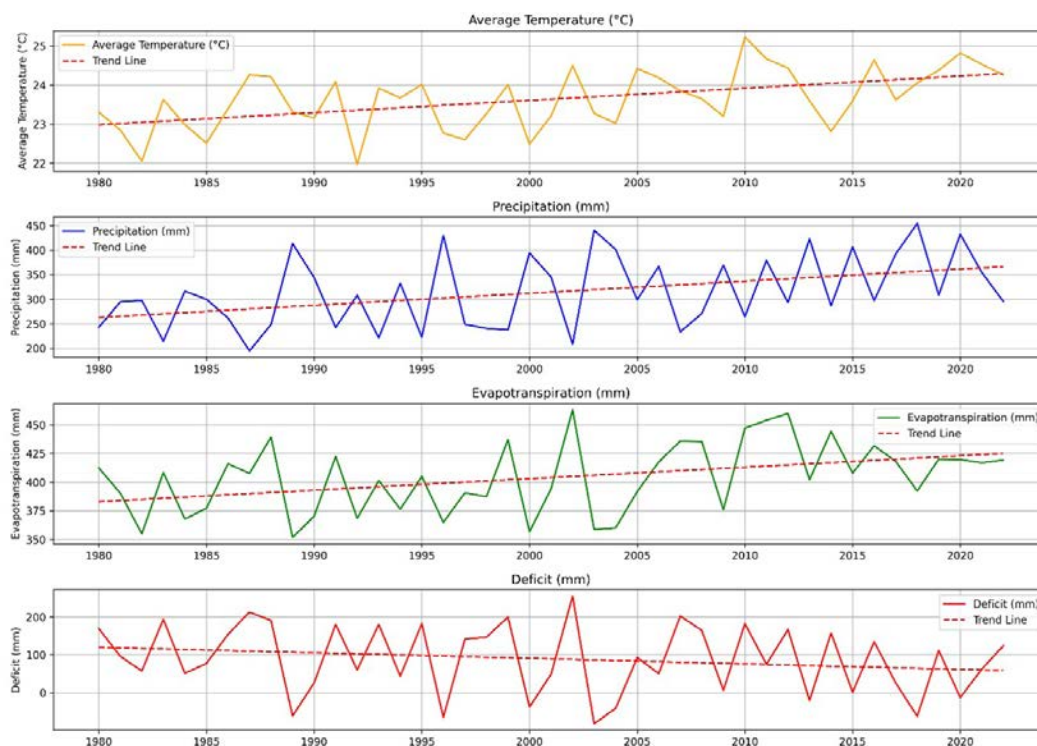


Figure 7: Trends in Average Temperature, Precipitation, Evapotranspiration, and Water Deficit during the Growing Season (June-August) from 1980 to 2022, with trend lines highlighting long-term changes in Maryland

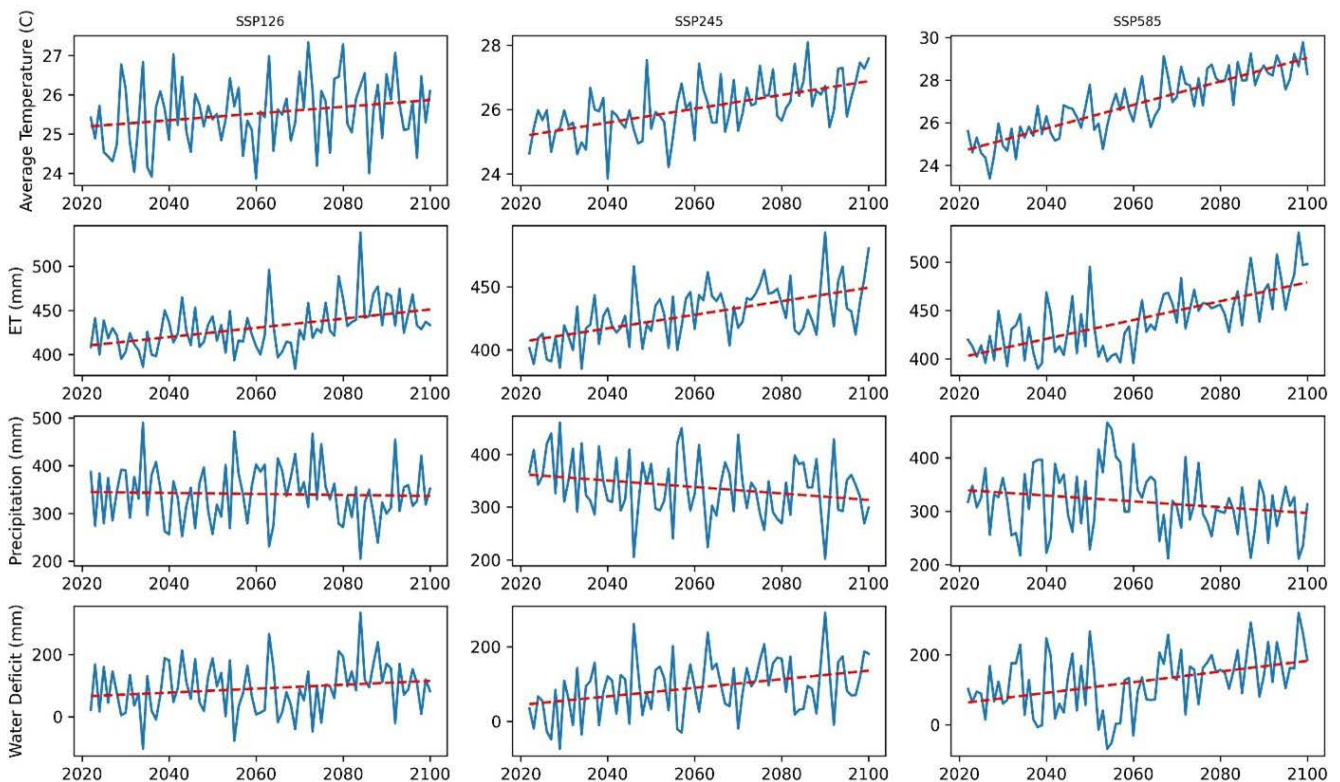
Future Projections of Water Deficit in Maryland Counties

Building upon the analysis of historical data, we extended our study to future projections using the SSP126, SSP245, and SSP585 scenarios. Figure 9 presents the projected trends for average temperature, evapotranspiration (ET), precipitation, and water deficit from 2020 to 2100 during the growing season in Maryland. For the projected data, evapotranspiration (ET), precipitation, and water deficit are derived from daily measurements. These daily values are cumulatively summed throughout the growing season to represent the total values for ET, precipitation, and water deficit for the entire growing season.

- **Average Temperature (°C):** The first row of plots shows a consistent increase in average temperature across all scenarios, with SSP585 displaying the most significant rise, followed by SSP245 and SSP126. This upward trend in temperature is expected to cause increased ET rates, thereby influencing water availability for crops.

- **Precipitation (mm):** The third row reveals slight increases in precipitation across all scenarios, though with considerable variability. SSP126 shows the least change, while SSP585 has more pronounced increases in precipitation, reflecting the higher climate variability expected under severe climate change scenarios.
- **Evapotranspiration (mm):** The second row indicates increasing ET trends across all scenarios, again with SSP585 showing the highest values. This suggests a growing demand for water due to higher temperatures, which exacerbates water deficit concerns.
- **Water Deficit (mm):** The fourth row highlights the projected water deficit, calculated as the difference between ET and precipitation. Despite the increases in precipitation, the significant rise in ET leads to a generally increasing trend in water deficit, particularly under SSP585. This indicates that higher temperatures and increased ET will likely outpace the gains in precipitation, resulting in greater water stress for agriculture. In addition, increases in precipitation may not be occurring during the growing season; thus, such increases do not help to satisfy crop water needs due to increased ET.

These projections underscore the importance of preparing for increased water deficits in the future. The trends suggest that while precipitation may increase slightly, the more substantial rise in temperatures and ET will likely lead to greater water deficits, particularly under more severe climate scenarios. This highlights the critical need for enhanced water management strategies, such as the adoption of efficient irrigation practices, development of drought-resistant crop varieties, and implementation of water conservation measures.



Average Temperature, Evapotranspiration, Precipitation, and Water Deficit across scenarios SSP126, SSP245, SSP585 for Maryland in Growing Season. Red dashed line represents the trend line.

Figure 8: Trends in Average Temperature, Precipitation, ET, and Water Deficit during the Growing Season (June-August) from 2022 to 2100, with trend lines highlighting long-term changes in Maryland.

By understanding these future trends, policymakers and farmers in Maryland can develop adaptive strategies to mitigate the impacts of climate change on water resources, ensuring sustainable agricultural productivity and resilience in the face of evolving climatic conditions.

Using Recycled Water for Irrigations

As climate change progresses, it is crucial to simulate and assess crop water demands under various climatic conditions and explore alternative water sources for supplemental irrigation. This approach aims to enhance farmers' profitability and sustain agricultural practices while preserving limited freshwater resources and supporting ecological health. The team has estimated crop water demand for major row crops in southern Maryland and the mid-Atlantic U.S. under various climatic conditions and assessed the potential of using recycled water from wastewater treatment plants (WWTPs) as an alternative water source for irrigation. The assessment of corn and soybean production under rainfed conditions showed that supplemental irrigation could significantly enhance crop yields. In particular, the comparison between irrigated and rainfed scenarios demonstrated substantial yield improvements for corn and soybean, not only in drought years but also during average and above-average precipitation years. This indicates that the traditionally rainfed region can benefit greatly from supplemental irrigation.

The team has also estimated the irrigation amounts required to supplement growing season precipitation under different climatic conditions, including dry, average, and wet years, to meet crop water demand. Given the considerable reduction in groundwater levels within the confined aquifer system and the increasing frequency of short-term droughts and rising temperatures, alternative water sources are crucial for sustainable irrigation practices in the region.

The discharge capacity of nearby WWTPs was compared to the crop water demand, revealing that treated wastewater from these facilities could serve as a significant irrigation water source. This approach not only provides an alternative to depleting groundwater resources but also promotes the reuse of treated wastewater, contributing to sustainable water management.

RECOMMENDATIONS

To address the challenges of water resource management in Maryland, several key areas of future work should be considered:

- Develop a regional groundwater-flow model to simulate flow through the Coastal Plain aquifer systems, providing a detailed assessment of aquifer recharge and long-term sustainability.
- Sustain and expand the groundwater monitoring networks in the state to fill existing data gaps and ensure continuous monitoring of groundwater levels across various aquifers (especially confined aquifers).
- Develop a user-friendly interface to access water use, water quality, and groundwater-level data, and integrate federal, state, and local databases to improve data accessibility and integration, which will enable comprehensive analysis for sustainable water management.
- Establish methods to track and quantify water withdrawals of less than 10,000 gallons per day, including domestic and self-supplied withdrawals to provide a more accurate picture of water use. Additionally, enhance water quality data management by creating a spatially accessible system for groundwater quality data with accurate aquifer assignments to help identify and address areas of degraded water quality effectively.

- Expand the web-based aquifer information system. Transitioning the current GIS-based system to a web-based platform will allow broader access for local governments, state agencies, consultants, well drillers, and the public, thereby enhancing collaborative resource management.
- Integrate climate models into water resource management strategies to better anticipate and address future water deficits caused by increased temperatures and ET rates.
- Establish adaptive strategies to mitigate water stress during the growing season, focusing on efficient supplemental irrigation practices and crop selection suited to future climate conditions.

CHALLENGES

Further investigation of water data availability in Maryland revealed the need for comprehensive monitoring and improved data management systems. Upon investigation of these issues the following challenges are identified:

- **Data Gaps:** There is a significant need to fill data gaps and enhance the understanding of complex aquifer systems, particularly in the Coastal Plain and Eastern Shore of Maryland, where groundwater is the main source for both urban and agricultural water use. In addition, adding layers of data on water use, water quality, and groundwater levels would improve the utility of the aquifer information system in the State of Maryland.
- **Monitoring:** A thorough set of groundwater-level data is required to evaluate the impact of well withdrawals and manage future withdrawals and permits. Although the Maryland Geological Survey and USGS maintain monitoring wells across the state, there are data gaps (both temporal and spatial) in certain areas and aquifers (especially confined aquifers), necessitating sustained monitoring efforts to understand long-term impacts.
- **Water Use Monitoring:** Accurately quantifying water withdrawals from various aquifers is fundamental for sustainable water resources management. The Maryland Department of the Environment keeps records of withdrawals over 10,000 gallons per day; however, the dataset needs to be more accessible, and smaller withdrawals (<1,000 gallons per day) and domestic supplies also require quantification.
- **Groundwater Quality Data:** Despite the availability of groundwater-quality data, accessibility issues exist, highlighting the need for a user-friendly interface to access and analyze the data spatially with accurate aquifer assignments.

To effectively address the challenges of water resource management in Maryland, it is essential to bridge the identified gaps with targeted solutions. The recommendations outlined provide a roadmap to tackle the pressing issues of groundwater sustainability, monitoring, data integration, and accessibility. These proposed actions directly respond to the challenges uncovered during the investigation, including data gaps, insufficient monitoring, limitations in water use tracking, and the need for improved groundwater quality data systems. By aligning the recommendations with the specific challenges, a comprehensive approach can be developed to ensure the sustainable management of Maryland's critical water resources.

REFERENCES

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. *FAO Irrigation and Drainage Paper No. 56*. Rome: Food and Agriculture Organization of the United Nations.

Cai, J., Y. Liu, T. Lei, and L. S. Pereira. 2007. "Estimating Reference Evapotranspiration with the FAO Penman-Monteith Equation Using Daily Weather Forecast Messages." *Agricultural and Forest Meteorology* 145 (1-2): 22-35.

National Oceanic and Atmospheric Administration (NOAA). 2023. "National Centers for Environmental Information (NCEI)-NOAA, nClimGrid-Daily." <https://www.ncei.noaa.gov/products/land-based-station/nclimgrid-daily>.

Rahman, A., M. Negahban-Azar, A. Shirmohammadi, and Ritesh Karki. 2024. "Evaluating the Potential of Recycled Water Use for Irrigation in Southern Maryland: Impact on Groundwater Conservation and Crop Yield." *Water Supply* 00 (0): 1. <https://doi.org/10.2166/ws.2024.137>.

Shirmohammadi, A., M. Negahban-Azar, H. Montas, P. Leisnham, and M. A. Pavao-Zuckerman. 2020. "Stressed Aquifers in the Coastal Plain of Maryland Due to Population Dynamics and Climate Change." Paper presented at the ASABE Annual International Meeting, Poster ID: 2001261, Virtual Conference, July 13-15, 2020.

Vogel, E., M. G. Donat, L. V. Alexander, M. Meinshausen, D. K. Ray, D. Karoly, and K. Frieler. 2019. "The Effects of Climate Extremes on Global Agricultural Yields." *Environmental Research Letters* 14 (5): 054010.

Zakaria, Z. A., A. Shabri, and U. N. Ahmad. 2012. "Estimation of the Generalized Logistic Distribution of Extreme Events Using Partial L-Moments." *Hydrological Sciences Journal* 57 (3): 424-432.

Zhang, X., and X. Cai. 2013. "Climate Change Impacts on Global Agricultural Water Deficit." *Geophysical Research Letters* 40 (6): 1111-1117.

Zotarelli, L., M. D. Dukes, C. C. Romero, K. W. Migliaccio, and K. T. Morgan. 2010. "Step by Step Calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method)." Institute of Food and Agricultural Sciences, University of Florida.

SEA LEVEL RISE, SOIL SALINIZATION, SALTWATER INTRUSION, AND SOIL MOISTURE

Rebecca Epanchin-Niell & Lars J. Olson

SUMMARY

Maryland faces high and increasing rates of sea level rise, with intermediate sea level rise estimates of 0.28 m above 2020 levels by 2050 and 0.53 m above 2020 levels by 2070. Chesapeake Bay waters near Cambridge, Maryland, for example, have experienced an average sea level rise of 3.97 mm per year since 1943. These changes are leading to increased flooding, inundation, and salinization of coastal agricultural lands, creating management challenges and reducing crop yields

and profitability. We estimate that about 18,996 acres (7,687 ha) of agricultural land are currently at risk (i.e., potentially affected) by saltwater intrusion and periodic inundation. Our analysis suggests that this will increase to 31,462 acres (12,732 ha) and 43,283 acres (17,516 ha) by 2050 and 2070, respectively. This represents an increase in the affected area of about 66% over the next three decades and 128% by 2070, relative to 2020 levels. This risk is not evenly distributed across Maryland's coastal counties. Instead, the estimated extent of saltwater intrusion and inundation risk is greatest on Maryland's Eastern Shore, particularly in Dorchester and Somerset counties. 10% and 8% of agricultural land in Dorchester and Somerset counties, respectively, are already at high risk (i.e., located below the tidal height elevation expected to be reached at least every other year). Furthermore, 19% and 20% of the current agricultural land in these counties is projected to be at high risk for saltwater intrusion by 2070.

Maryland's dominant crops—corn and soy—do not fare well in the saline and wet soils pervading very low-lying coastal lands. Our analyses suggest that accounting for annual variability in yields, costs, and prices, median corn profitability drops below zero at salinity levels of 3 decisiemens per meter (dS/m), which is commonly observed in low-lying salt affected fields. Median profits for soy are estimated to drop below zero when salinity levels exceed about 6 dS/m. However, these estimates do not account for the additional effects of soil saturation or the offsetting effects of potential crop insurance payments. Reflecting these profit sensitivities, farmers have been observed to plant corn less frequently in very low-lying agricultural areas. Also, while not widely planted, sorghum, which generally is more salt and moisture tolerant, is more common in low-lying areas.

OBJECTIVE

Sea level is rising at more than twice the global rate in the mid-Atlantic region, leading to increased coastal inundation and salinization of soils and groundwater. These changes pose risks to agriculture in Maryland's coastal regions. This section assesses historical trends and future projections of sea level and saltwater intrusion in Maryland; describes observed and anticipated impacts to agriculture; estimates the extent of agricultural land at risk; and describes observed and potential strategies for adaptation.

METHODS

We synthesized literature and data relevant to Maryland coastal regions to describe sea level rise and saltwater intrusion trends, historic and projected consequences for agriculture, and observed and available adaptation options. We reference existing studies, published papers, technical reports, recent research findings, and planning documents, summarizing Maryland-specific information from these sources. In this study, we report new analyses to 1) quantify the relationship between soil salinity, crop yields, and profits for Maryland's main grain crops, and 2) estimate the current and projected extent of Maryland's agricultural land at risk from sea level rise and saltwater intrusion.

Various methods and units are available to measure salinity, including dissolved solids (ppt) or based on electroconductivity (dS/m). Here we use electroconductivity (dS/m), which is particularly relevant for measuring salinity in soils where crops are grown (Gibson et al. 2021).

Salinity Effects on Small Grain Yields and Corn and Soy Profitability

Several sources previously compiled crop salt tolerance information (e.g., Gibson et al. 2021; Maas & Grattan 1999; NCRS 1996; Conway 2001; Tanji & Kielen 2002). We use salinity tolerance functions from Gibson et al. (2021) and Tanji & Kielen (2002) to plot estimated yield for four of Maryland's major grain crops—corn, soybean, sorghum, and wheat—across a range of salinity levels. Reported salinity tolerance functions are based on lab and field studies and not specific to the mid-Atlantic region, but serve as a reference for yield sensitivity.

To assess salinity effects on expected profits for Maryland corn and soy, we combine salinity-yield relationships with historic data on costs, prices, and yield. Specifically, we use annual, state-level historic crop input prices and expected output prices from 2008 to 2023. These data were gathered from Maryland enterprise crop budgets (Shannon Dill, personal communication; <https://extension.umd.edu/programs/agriculture-food-systems/program-areas/farm-and-agribusiness-management/grain-marketing/crop-budgets/>), with all costs and prices converted to 2023 U.S. dollars (USD) using the consumer price index. We also compile county-level yield data for 2008 to 2023 from the National Agricultural Statistics Survey (USDA 2023). We combine these data with salinity tolerance functions from Tanji & Kielen (2002) to estimate expected profitability per acre across years and counties for corn and soy across salinity levels. Profitability is calculated as revenues minus costs, where revenues are the baseline yield per acre (bushels per acre) adjusted by estimated salinity tolerance, multiplied by crop price per bushel (\$/bushel). Costs are the total input costs per acre. We plot county-year-salinity profit estimates with a box plot, excluding outlier values. The plot illustrates profit variability and effects of salinity for lower and upper Eastern Shore Maryland counties, which are the regions most at risk to salinization. Profit variability includes effects from yield variation (e.g., due to pests, weather) and price and cost variability. Estimates are not adjusted for productivity changes over time and are based on state-level input costs and projected (rather than harvest-time) prices; they also do not adjust for potential crop insurance payouts.

Predicting Agricultural Area at Risk from Sea Level Rise and Saltwater Intrusion

Based on ongoing soil salinity analysis indicating a strong relationship between soil salinity and elevation of land relative to tidal water (Epanchin-Niell, unpublished data), we estimate the extent of agricultural land area within current and projected tidal reach using a variety of data sources. We use 2022 data from USDA's crop sequence boundary data (USDA 2024) to identify agricultural land across Maryland coastal counties. These data essentially delineate agricultural field boundaries and identify annual land cover within them. We classify land covers as agricultural (e.g., crop or pasture) or not, and as small grain crop (e.g., corn, soy, sorghum, etc.) or not. We intersect these crop data with fine-scale elevation data that measures land height relative to sea level. Specifically, we calculate land elevation as the difference between land height (lidar data) and NOAA's interpolated, historic (1983 to 2001) mean higher high water (MHHW) elevation datum (NOAA 2022). Land elevation is then used to quantify the extent of agricultural land with elevation below the specified tidal elevation thresholds (e.g., MHHW and two measures of tidal level extremes) under current and projected sea level conditions.

The three tidal heights that we consider are:

- 1)** MHHW, which is the average height of the highest tide each day,
- 2)** the 99% "annual exceedance probability level" of tidal fluctuations, which is the height that tides have a 99% probability of reaching at least once a year, and
- 3)** the 50% probability extreme tidal height, which is expected to be reached on average once every 2 years (NOAA 2024).

We focus on these tidal elevation thresholds because high tide events contribute to saturation and salinization of coastal lands, which are drivers of reduced agricultural productivity. These 99% and 50% exceedance probability levels account for storm tides (“a combination of the astronomical tide, the storm surge, and limited wave setup caused by breaking waves”), but do not specifically measure water movement upslope (NOAA 2024). Our analysis also does not account for landscape features that may constrain or promote inland water movement.

To quantify the extent of agricultural land at risk of inundation, we define thresholds using tidal height levels averaged across six Maryland tidal gauge stations (8570283 Ocean City, 8571892 Cambridge, 8573364 Tolchester Beach, 8574680 Baltimore, 8575512 Annapolis, and 8577330 Solomons Island). For each station, we calculated the difference between NOAA extreme water levels (99% and 50% exceedance probability) and MHHW levels for that station, and averaged these differences across stations. We add these averaged tidal heights to current and future MHHW projections (Sweet et al. 2022) to define the projected height of extreme tidal levels for 2020, 2050, and 2070. For future MHHW projections, we use Sweet et al. (2022)’s intermediate sea level rise scenario with a 1 m sea level rise by 2100 and average estimates across the six tidal gauge stations (Table 1).

To estimate the extent of agricultural land at risk we quantify the area of agricultural land with elevation below each tidal elevational threshold (Table 1).

Year	MHHW Level	99% Tidal Exceedance Level (0.37 Above MHHW)	50% Tidal Exceedance Level (0.57 Above MHHW)
2020	0.17	0.56	0.74
2050	0.45	0.82	1.02
2070	0.70	1.07	1.27

Table 1: Estimated Elevation (m) of Tidal Heights Above Historic (1983 to 2001) MHHW.

RESULTS

Historic and Projected Sea Level Rise and Saltwater Intrusion

Sea levels are rising globally due to warming (and hence expanding) waters, melting glaciers, and changing currents, as well as due to vertical land movement from land subsidence and isostatic rebound. While sea levels are rising globally, rates in the mid-Atlantic are more than twice the global average (Sallenger et al. 2012). Figure 1 shows sea level measurements and projections for the Cambridge tidal gauge station in the Chesapeake Bay, which are similar to other Maryland tidal gauges. We use mean higher high water (MHHW) as our measure of sea level (rather than mean sea level), because MHHW better captures the elevational extent of regular tidal inundation and is therefore more relevant for understanding coastal inundation and saltwater intrusion risk. Historic data shows high annual variability in the observed MHHW levels (Figure 1). The average rate of mean sea level rise since 1943 at the Cambridge Station is 3.97 mm per year as compared to 1.7 mm per year globally (NOAA 2023). These rates are predicted to increase. Under an intermediate scenario with 1 m of global sea level rise by 2100, Sweet et al. (2022) predicts an increase in MHHW levels of 0.28 meters by 2050, 0.53 m by 2070, and relative to 2020 levels.

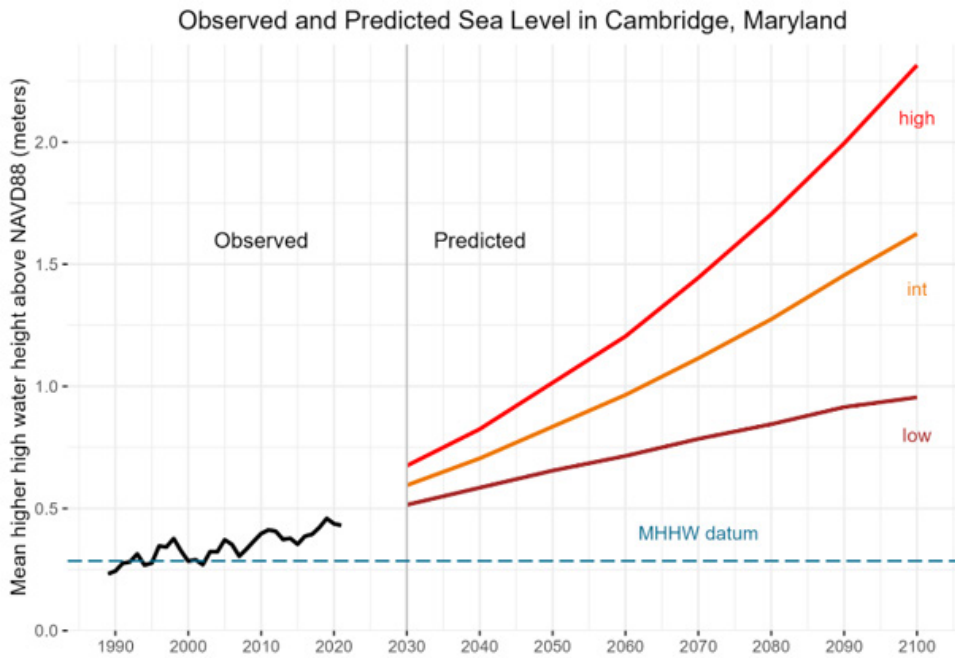


Figure 1: Historic and predicted mean higher high water (MHHW) levels near Maryland (Cambridge, Maryland tide gauge), measured relative to NAVD88 datum. The dashed horizontal line represents the local historic (1983-2001) MHHW level (i.e., the average of the highest daily observed water levels at a location). Sea level rise projections are Sweet et al.'s (2017) regional 50th percentile estimates under the intermediate-low, intermediate, and intermediate-high scenarios, based on global mean sea level rise values of 0.5 m, 1.0 m, and 1.5 m, respectively, by 2100. Figure replicated from Epanchin-Niell et al. 2023.

Figure 2 shows the land elevation above historic (1983-2001) MHHW for Maryland's coastal counties, highlighting that most land is greater than 5 m above historic (1983-2001) MHHW levels. Lower Eastern Shore counties (Dorchester, Wicomico, Somerset, and Worcester) are the counties with the greatest area of land less than 1 m above historic MHHW levels.

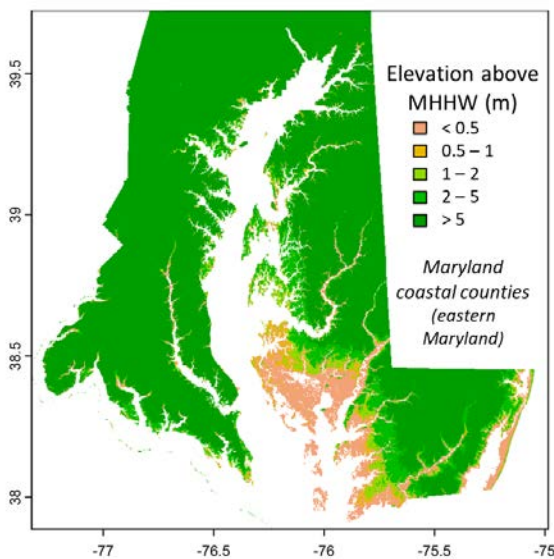


Figure 2: Land elevation above historic mean higher high water (MHHW) levels (1983 to 2001) for Maryland's coastal counties. [For reference, MHHW is expected to rise by 0.45 m and 1.25 m, relative to historic MHHW conditions, by 2050 and 2100, respectively, under intermediate 1 m global sea level rise scenarios (Sweet et al.)(2022).]

Drivers of Saltwater Intrusion

Saltwater intrusion occurs naturally at the land-sea interface, but a number of factors increase the reach of salinization inland, including sea level rise, storms and tides, drought, water extraction, and increased hydrologic connectivity (e.g., due to extensive ditching in rural landscapes) (Tully et al. 2019). Rising sea levels increase subsurface seawater pressure as well as the aboveground reach of seawater. Storms and extreme tides can also push seawater inland. Droughts reduce freshwater flows that otherwise inhibit seawater encroachment and can make soils more susceptible to absorption of saline water from tidal or storm overwash events. Water extraction activities can reduce surface and groundwater flow, enabling seawater to move upstream or into surficial aquifers, and can exacerbate land subsidence and relative rates of sea level rise. Topography, including low-lying lands, shallow slopes, and ditching, also influences susceptibility to saltwater intrusion. Drainage ditches, for example, can serve as conduits for saltwater to reach further inland, particularly during high tidal water events.

Box 1. Factors Increasing Susceptibility to Saltwater Intrusion:

- Sea level rise
- Storms and extreme tide events
- Droughts
- Water management (e.g., water withdrawals and groundwater pumping)
- Hydrologic connectivity (e.g., from ditches and canals)

Consequences of Sea Level Rise and Saltwater Intrusion for Agriculture

Rising sea levels increase coastal inundation frequency and extent and can raise below-ground water tables with significant consequences for agriculture (Tully et al. 2019; O'Donnell et al. 2024; MDP 2019; Sudol et al. 2023). These changes—more extensive inundation and higher water tables—negatively impact infrastructure (e.g., flooding buildings; rendering septic tanks nonfunctional), reduce access to agricultural sites (e.g., due to flooded roads; fields becoming too saturated for farm equipment), and reduce crop yields (e.g., reduced growth from oversaturated soils). Inundation can also impact runoff of nutrients and other pollution.

Simultaneously, rising sea levels contribute to salinization of soils and groundwater via overwash during flood events, subsurface seawater movement, and other pathways. Such salinization directly harms agricultural productivity, as traditional crops are typically harmed by saline conditions, resulting in yield losses (Tully et al. 2019; O'Donnell et al. 2024; MDP 2019; Sudol et al. 2023), as further quantified below. Salinization also can promote salt-tolerant invasive weeds such as *Phragmites australis* (Phragmites), degrade water quality for drinking and irrigation, and harm infrastructure (e.g., via corrosivity). Salinization can also mobilize nutrients such as nitrogen and phosphorus that have built up in soils over decades of agricultural application; this can contribute to nutrient pollution in downstream waterways (Ardón et al. 2013).

Box 2. Consequences of Sea Level Rise and Saltwater Intrusion

- Increased coastal flooding and water tables (affecting farm access due to flooded roads or saturated fields)
- Higher water tables (saturating the root zone and hindering crop health)
- Crop yield declines and associated profit losses
- Expansion of salt-tolerant weeds
- Increased mobility of nutrients (e.g., phosphorus and nitrogen), with potential consequences for downstream water quality (e.g., eutrophication; harmful algal blooms)
- Corrosion of infrastructure
- Reduced drinking water quality
- Loss of fresh irrigation water

Of particular note is saltwater intrusion's consequences for agricultural yields. Most traditional crops, including those grown in Maryland, are sensitive to salinization, with yields declining above crop-specific salinity tolerance thresholds. We summarize the salt susceptibility of Maryland's main grain crops (soy, corn, wheat, and sorghum) below (Figure 3).

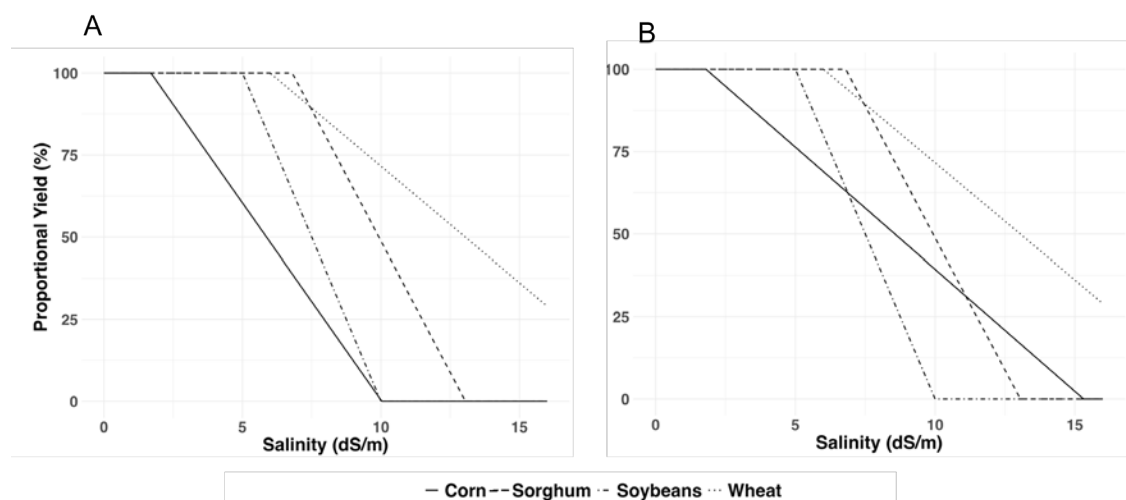


Figure 3: Achievable proportion of maximum crop yield (in bu/acre) at different salinity levels for corn, sorghum, soybeans, and wheat. Salinity is in units of electrical conductivity (EC) in dS/m (decisiemens per meter), based in saturated paste extraction. Salinity tolerance parameters were obtained from A) Tanji & Kielen (2002) and B) Gibson et al. (2021).

Figure 3 shows that corn is anticipated to begin incurring yield declines at lower salinity levels (2 dS/m) than soy, sorghum, or wheat. However, corn yields decline less steeply than sorghum or soy yields—measured as proportional yield. Estimates of corn sensitivity differ across sources, with corn yields dropping to zero at 10 dS/m (Tanji & Kielen 2002) versus >15 dS/m (Gibson et al. 2021). Sorghum salt sensitivity is intermediate to soy and wheat, with wheat estimated to be the least salt sensitive. Importantly, these yield loss estimates account only for the effects of salinity, are not Maryland specific, and do not reflect additional stressors such as increasing water tables and inundation frequency associated with sea level rise.

For the two primary Maryland grain crops—corn and soy—we also estimate how expected profitability depends on soil salinity levels (Figure 4). The upper and lower Eastern Shore counties exhibit similar profit patterns. Corn and soy have overlapping profitability ranges at low salinity levels, but median corn profits drop below zero at salinity levels of about 3 dS/m, while median soy profits remain positive through 6 dS/m. In the absence of crop insurance payouts or reductions in crop input costs, potential financial losses are estimated to be high (>\$400 per acre) under high salinity conditions, with greater losses for corn due to higher salt sensitivity and higher average input costs. While not accounted for in our estimates, losses could be exacerbated at moderate and low salinity levels due to surface and root zone inundation.

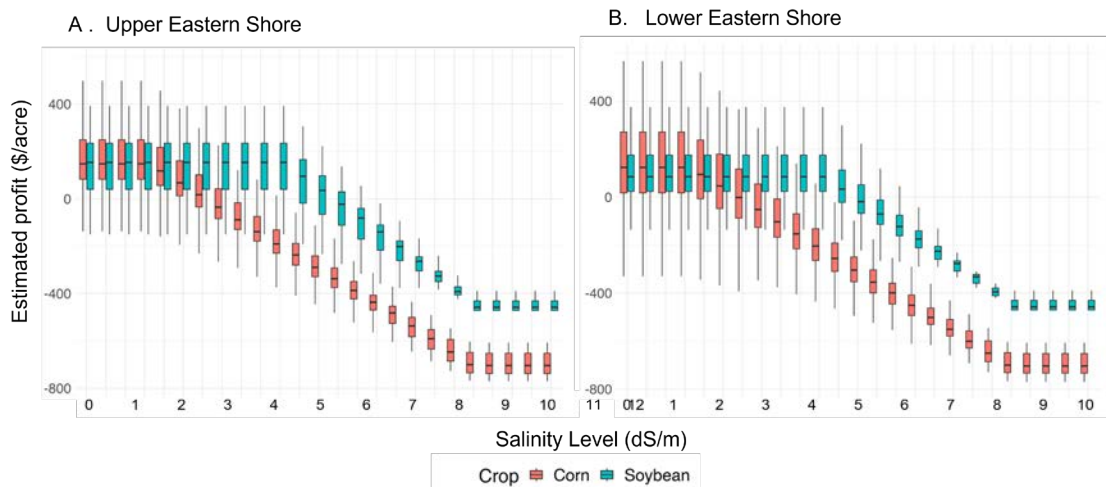


Figure 4: Corn and soybean profit distribution estimates across salinity levels in the A) Upper Eastern Shore and B) Lower Eastern Shore based on 2008 to 2023 yields, costs, and prices. Salinity is in units of electrical conductivity (EC) in dS/m (decisiemens per meter). Salinity tolerance parameters were obtained from Tanji & Kielen (2002). The line inside each box represents the median profit level (year by county observations). The box represents the interquartile range (IQR), and whiskers extend from the box to the smallest and largest values within 1.5 times the IQR. Note, for clarity these figures exclude extreme outliers, and therefore underrepresent profit variability.

Estimated Extent of Maryland Agricultural Lands at Risk from Saltwater Intrusion

Due to the variety of drivers of saltwater intrusion and variability in context across the landscape, the extent of saltwater intrusion is not well known (O’Donnell et al. 2024), but efforts are ongoing to better understand the distribution of risk.

Previously developed global salinity maps (e.g., Hassani, et al. 2021) are too coarse to assess specific risk to Maryland agriculture, but a recent study (Mondal et al. 2023) used remote sensing to develop the first dataset of the distribution and extent of visible salt patches across the Delmarva Peninsula. Table 2 summarizes estimates of salt patch extent and growth across Maryland’s Eastern Shore counties from 2011 to 2017 (Mondal et al. 2023).

	Salt Patch Area	Farmland Within 50 m of Salt Patch	Farmland Within 100 m of Salt Patch	Farmland Within 200 m of Salt Patch
2011-2013	249 ha	7,684 ha (1.9%)	19,414 ha (4.7%)	49,914 ha (12.2%)
2016-2017	445 ha	16,236 ha (4.1%)	39,775 ha (10.1%)	96,521 ha (24.5%)
Percent Change	79% increase	111% increase	105% increase	93% increase

Table 2: Extent of At-Risk Farmland for Maryland’s Nine Eastern Shore Counties, Based on Mondal et al. (2023). Total estimated area (and as a percentage of total agricultural land) is listed for each time period. The percentage change between time periods also is reported.

The nine Maryland Eastern Shore counties experienced a 79% increase in salt patch area, with a total estimated area of about 445 ha in 2017. Mondal et al. (2023) also calculated the extent of agricultural land within different distances of observed salt patches to estimate the extent of land at risk of salinization, recognizing that high salinity levels can extend well beyond visible salt patches. Accounting for this proximity-based risk, the amount of farmland at risk (i.e., near salt patches) was estimated to have approximately doubled from 2011 to 2017 (Table 2). Notably, the study estimated potential annual profit losses of US\$39.4 million to US\$107.5 million across the Delmarva, assuming potential profit loss within 200 meters of salt patches.

Considering spatial variation in risk among Maryland counties, Mondal et al. found that Somerset County had the largest extent of salt patches and at-risk farmland (as a percentage of the county's farmland). In 2017, visible salt patches comprised approximately ~0.4% of Somerset County farmland and ~0.2% of Dorchester County farmland. In 2011-2013, 4.7% of Somerset County's farmland was within 50 m of a remotely sensed salt patch, increasing to 8% in 2016-2017. Similarly, the percentage of farmland within 100 m of a salt patch increased from 11.7% to 16.9% over these time periods.

For comparison, and to enable future risk prediction, salinization extent can also be estimated through linking soil salinity sampling and predictive models. Data collected in Somerset County in 2019 and in Somerset and Dorchester counties in 2022 provide additional insights on the current and future extent of saltwater intrusion in these low-lying, Maryland counties. For example, preliminary data analysis (Epanchin-Niell, personal communication) indicates that elevated soil salinity typically occurred at sampling locations with elevations less than 0.6 m above current MHHW levels, which corresponds to the approximate height that tidal waters are expected to reach with at least a 50% probability in any given year (Table 1). This supports that the 50% tidal exceedance level may be a reasonable approximate elevation threshold for indicating risk of saltwater intrusion in the region. Thus, using NOAA's "annual exceedance probability levels" and projected sea level rise estimates, we calculated the extent of agricultural land at risk from saltwater intrusion and sea level rise, as outlined in the methods section (Figures 5 and 6).

Examining the total area at risk across Maryland's coastal counties, we find substantial agricultural land (i.e., crop or pastureland) and cropland (planted in small grains; e.g., corn, soy, sorghum, and wheat) at risk.

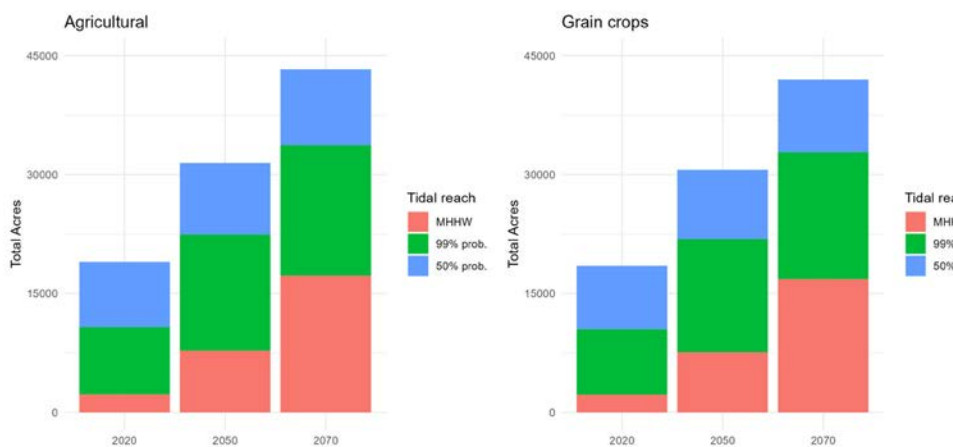


Figure 5: The area (acres) of land in agriculture (left) and planted in grain crops (e.g., corn, soy, wheat, sorghum) (right) with elevations below MHHW level (pink) and below extreme tidal levels (99% prob-green; 50% prob-blue), in 2020, 2050, and 2070, based on sea level rise and tidal projections. These land areas have a high likelihood of saltwater intrusion and periodic inundation.

	MHHW Level	99% Tidal Exceed- ance Level (0.37 Above MHHW)	50% Tidal Exceed- ance Level (0.57 Above MHHW)
2020			
Acres	2,287	10,787	18,996
Hectares	925	4,365	7,687
% of Total Ag	0.2%	0.9%	1.5%
2050			
Acres	7,790	22,453	31,462
Hectares	3,153	9,087	12,732
% of Total Ag	0.6%	1.8%	2.6%
2070			
Acres	17,273	33,741	43,283
Hectares	6,990	13,655	17,516
% of Total Ag	1.4%	2.7%	3.5%

Table 3: Extent of agricultural land in Maryland at high risk of saltwater intrusion and sea level rise based on land elevation below tidal levels, projected for 2020, 2050, and 2070. [% of total ag is the percentage of agricultural land within Maryland’s coastal counties.]

We estimate that about 18,996 acres (7,687 ha) of agricultural land are currently at risk (i.e., potentially affected) by saltwater intrusion and periodic inundation, accounting for 1.5% of agricultural land in Maryland’s coastal counties. We estimate this area will increase to 31,462 acres (12,732 ha) and 43,283 acres (17,516 ha) by 2050 and 2070, respectively. This represents an increase in the affected area of about 66% over the coming 30 years and 128% over the coming 50 years (i.e., from 2020 to 2050 and 2070, respectively).

Risk, however, is not distributed evenly across Maryland’s coastal counties, as their topography and distribution of agricultural land vary. Figure 6 illustrates variation across counties in the area estimated to be affected by saltwater intrusion.

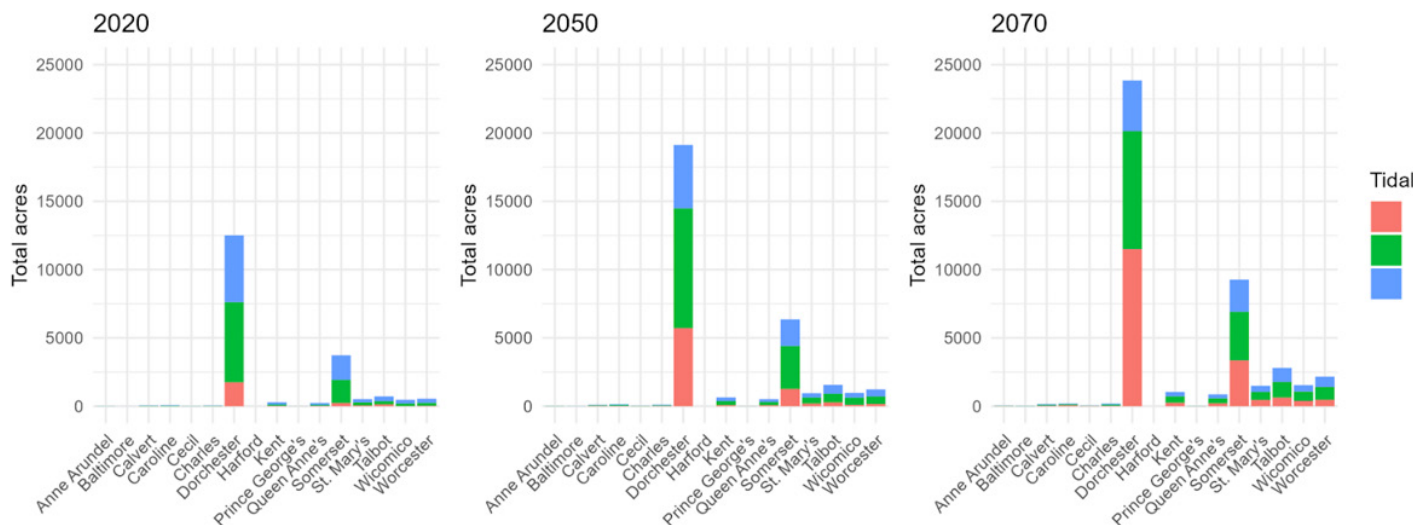


Figure 6: The extent of agricultural land (acres) across Maryland coastal counties within various tidal inundation likelihoods. Specifically, we show the extent of agricultural land in each county below MHHW levels (pink bar), below the elevation with a 99% probability of being reached by extreme tides in each year (green bar), and below the elevation that has a 50% chance of being reached by an extreme tide in a given year (blue). We show the extent of agricultural land at risk in 2020, 2050, and 2070 based on Maryland’s intermediate sea level rise projections (1 m by 2100; Sweet et al. 2022). [2.47 acres/ha]

Analysis shows that Dorchester County has the highest acreage at risk, followed by Somerset County, and then other lower Eastern Shore counties. We find that 10% and 8% of agricultural land in Dorchester and Somerset counties are already within reach of tidal inundation (i.e., located below the tidal height elevation expected to be reached in 50% of years). We estimate that the area at risk will increase to 19% and 20% of their agricultural areas by 2070 under Sweet et al.’s (2022) intermediate sea level rise projections (Figure 6).

	2020	2050	2070
Dorchester	12,394 (10.2%) [5,015 ha]	18,966 (15.6%) [7,675 ha]	23,661 (19.5%) [9,575 ha]
Somerset	3,637 (7.8%) [1,472 ha]	6,248 (13.3%) [2,528 ha]	9,148 (19.5%) [3,702 ha]

Table 4: Extent (acres) of agricultural land at risk (i.e., potentially affected by saltwater intrusion and periodic inundation) in Maryland’s two most affected counties, based on land elevation with a 50% or greater likelihood of being exceeded by tidal levels per year. (% of total agricultural area in county) [area reported in hectares].

Potential Strategies for Adaptation

Farms in low-lying coastal areas already face substantial threat from sea level rise and saltwater intrusion, and analysis shows that more areas will be affected over the coming decades. In most cases, low-lying lands eventually will have to transition out of agriculture, as farming will cease to be profitable as flood frequency and salinization increase and land is eventually submerged. While it may be feasible to delay salinization and inundation using protective measures, these low-lying coastal agricultural lands may be best viewed and managed as lands in transition. Even within a single farm field, strategies will likely need to shift over time as conditions change. Furthermore, the preferred adaptation options will necessarily depend on farmer and landowner preferences, as well as the (changing) site context.

Agricultural adaptation options can be coarsely categorized based on their method for reducing impacts from sea level rise and saltwater intrusion (e.g., Tully et al. 2019; Sudol et al. 2020; Kirwan et al. 2024): protective measures to delay salinization and inundation, alteration of farm practices to reduce profit losses, and transitions that shift land out of agriculture. We discuss each of these types of strategies.

Protective strategies aim to protect land from sea level rise and saltwater intrusion. For example, efforts may include installation of berms or levees, raising field elevation with imported soils or dredged material from agricultural ditches (Tully et al. 2019), installing or maintaining protective vegetative buffers that can slow upland flow of tidal water (e.g., converting some low-lying land to wetland vegetation to protect upland crops; Guimond and Michael 2020), adding soil amendments (e.g., gypsum, which binds with soil, so that excessive sodium remains in the pore water and can leach out; Weissman et al. 2021; J. Miller, personal communication), installing tide gates, and relying on freshwater or precipitation to flush salts from soils. These approaches differ in costs and efficacy across contexts. Some also can alter future risks or limit future transition options. For example, earth movement (e.g., berm/levee installation) could hinder future transition to salt marsh or exacerbate salinization and flood impacts if the structures are overtopped during extreme events. Similarly, tide gates can protect against inland seawater flow, but also could exacerbate risks if poorly maintained such that salt water is inadvertently trapped inland. Strategies such as ditching to drain fields can ultimately exacerbate salinity impacts by serving as conduits for seawater to reach further inland. The efficacy of gypsum depends on drainage which is needed for sodium to leach out. In summary, evaluation of protective measures must consider a diverse array of context-specific costs, benefits, and efficacy, as well as consequences for longer-term adaptation options.

Other options include adaptation to salinization and inundation by changing agricultural practices to reduce profitability losses. For example, to reduce yield or profit losses, farmers may switch crops, reduce costly crop inputs, change planting times, or enroll in crop insurance, among other strategies. Shifts in cropping choices have already been observed in Maryland's low-lying coastal counties, including reduced corn acreage in very low-lying agricultural land and increased sorghum acreage. Additional crops that are under evaluation as alternative transition crops include giant miscanthus and switchgrass. In contrast, salt-tolerant soybeans have not been evidenced to substantially improve yields in response to saltwater intrusion in our region, perhaps due to intolerance of saturated soils (J. Miller et al. unpublished data). Similarly, barley has been shown to be relatively salt-tolerant, but does poorly in wet soils. Asparagus and quinoa also have been suggested as salt-tolerant crop options (Sudol et al. 2020), but would require very different farming practices than traditional regional crops. Availability of markets, yield potential, and compatibility of farming techniques are important aspects to consider regarding a shift to new crops. In addi-

tion, for new crop considerations (e.g., giant miscanthus, quinoa), potential invasiveness should be preemptively evaluated to ensure that they do not pose a risk of spreading into and degrading natural coastal habitats.

Other potential margins for adjustment include reduced use of high-cost inputs (e.g., fertilizer) in low-yielding fields. While this likely would further reduce yields, those losses might be at least partially offset by the reduced costs. In addition, this could provide an additional benefit of reducing the amount of nutrients available to leach into downstream water bodies, which may be especially important in these areas because saltwater intrusion can increase nutrient mobilization. Crop insurance may also be useful to temporarily offset profit losses, depending on a farmer's specific context, but indemnity payments often depend on historic yields and thus longer-term benefits may be reduced.

The third major category of adaptation options is eventual transition out of agriculture, which also has been observed in salt-affected fields in Maryland. This approach can follow a variety of potential paths, both in terms of the subsequent land use and the financial support leveraged for the transition. For example, farmland can be abandoned (i.e., planting ceased), actively planted in a conservation land cover (e.g., salt-tolerant pollinator mix), converted to a freshwater impoundment, or transitioned to saltwater marsh, among other options. Each of these transitions provides different potential benefits for the farmer, landowner, and environment. For example, benefits may include wildlife habitat, hunting or recreational opportunities, flood mitigation for upslope farmland, or alternative revenue streams (e.g., hunting leases).

In many cases, farmers or landowners may be able to obtain financial and technical support for these land transitions through enrollment in government or NGO easement programs or agricultural or wetland payment programs. Financial benefits can include subsidies and technical assistance for restoration activities, reductions in tax liabilities, and financial payments for maintaining land in conservation. Support can be available through federal and state programs (e.g., Conservation Reserve Enhancement Program (CREP), Conservation Reserve Program (CRP), Environmental Quality Incentives Program (EQIP), and Wetlands Reserve Easements (WRE)), land conservancies such as Eastern Shore Land Conservancy, Lower Shore Land Trust, and The Nature Conservancy, and via entities such as Ducks Unlimited. Other opportunities include potential enrollment in a wetland mitigation bank or water quality trading program. Transitioning to alternative land uses can also be done without participation in any formal program or agreement.

Each adaptation option and potential agricultural transition in response to sea level rise and saltwater intrusion poses different costs and benefits—for the farmer, landowner, and environment, across contexts, and as sea level rises. They also vary in their long- and short-term implications. For example, conversion to saltwater marsh versus freshwater impoundments may provide different recreational values, habitat values, and carbon sequestration benefits. Protective measures, such as installing berms or levees, can hinder longer-term environmental benefits such as from natural inland migration of wetlands. Similarly, active management to prevent invasive species encroachment (e.g., by *Phragmites*) can provide important environmental benefits by allowing better natural marsh migration.

Of final note with respect to easement and conservation programs to facilitate farmland transition out of agriculture: most easement and conservation programs have been developed to maintain land in a fixed state into the foreseeable future. However, this context does not hold for land near the coastal margin, as sea level rise will necessarily induce changes in the land. Thus, ongoing

work is aimed at developing innovative easement and conservation strategies that can better fit this transitional context, such as learning how to legally accommodate and encourage management practices that will be effective and beneficial in these transitioning landscapes; determining how to address easement lands that eventually may transition to open water; and designing effective monitoring. Coastal resilience easements, administered by the Maryland Department of Natural Resources, provide one example of a program that is piloting easement options specific to transitional coastal contexts (MDDNR 2024). These private land easements allow for transition of marsh habitat, require a management plan to reduce vulnerabilities to coastal hazards such as invasive species, and include development setbacks in areas subject to sea-level rise inundation by 2050 (to allow for unobstructed inland migration of wetlands).

CONCLUSION

Maryland faces high and increasing rates of sea level rise, with intermediate sea level rise estimates of 0.28 m by 2050 and 0.53 m by 2070, relative to 2020 levels. These changes are causing increased flooding, inundation, and salinization of coastal agricultural lands, complicating management and reducing crop yields. We estimate that about 18,996 acres (7,687 ha) of agricultural land in Maryland are currently at risk (i.e., potentially affected) by saltwater intrusion and periodic inundation, and this amount will increase by 66% and 128% by 2050 and 2070, respectively.

However, saltwater intrusion risk is unevenly distributed across Maryland's coastal counties, with Dorchester and Somerset counties bearing the largest impact. We estimate that 10% and 8% of agricultural land in Dorchester and Somerset counties, respectively, are currently at risk (i.e., have elevation below tidal heights predicted to be reached at least every two years). We estimate that this amount will rise to 19% and 20% of the current agricultural land in these counties by 2070. Maryland's dominant crops—corn and soy—fare poorly in the saline and wet soils pervading very low-lying coastal lands. Our analyses indicate that median corn profitability drops below zero at salinity levels of around 3 dS/m, which is commonly observed in low-lying, salt-affected fields. Profits for soy are estimated to drop below zero around 6 dS/m, which also is commonly observed. These estimates do not account for the additional yield reductions from high soil saturation or the offsetting effects of potential crop insurance payments. Observations of farmers' crop choice decisions support that farmers are responding to these profit differentials—they are planting corn less frequently in low-lying coastal fields and planting soy and sorghum relatively more frequently. As land becomes increasingly affected by sea level rise and saltwater intrusion, a range of adaptation options are available, which vary in their costs, benefits, and outcomes, depending on context. Broadly, options include protective measures, changing agricultural practices, and transitioning out of agriculture. Because lands are on a trajectory of continually increasing sea level and associated consequences, management will also need to continue to adjust over time. Some actions, such as protective measures (e.g., elevating land or building levees), may in some cases be able to prolong the time before fields become salinized, but also could have unanticipated consequences such as increasing future salinization and inundation risk or limiting future options (e.g., levees may hinder future land transition to marsh). For salt-affected lands that continue to be farmed, farmers may opt to switch to new crops (e.g., sorghum), reduce crop inputs, or invest in crop insurance, for example. Eventually, however, very low-lying land will likely have to transition out of agriculture. These transitions will provide different benefits and costs to the farmer and landowner, which will depend on their preferences, choice of land use transitions, and whether and which programs they engage with to support the transition (e.g., with or without financial or technical assistance). Notably, these agricultural and land use transitions also can impact environmental outcomes of state and regional interest, such as wetland habitat goals, conservation outcomes,

downstream water quality, and even upland flood and saltwater intrusion risk. Ultimately, the best choices for farmers and landowners will depend on their specific context and goals, and substantial research is still needed to provide improved understanding of the trade-offs and efficacy of these different adaptation measures.

RECOMMENDATIONS

We outline a range of adaptation options for farmers and landowners but note the importance of considering both short-term and longer-term trade-offs when deciding how to respond. The science on these options is rapidly expanding, which hopefully will continue to enable more informed decisions as more areas face impacts and need to adapt.

In terms of policy and research recommendations, we highlight the following needs:

- Continued improvement in understanding the spatial distribution and timing of risks from sea level rise and saltwater intrusion.
- Refined understanding of drivers and mediators of impacts, including consideration of how adaptation to different climate stressors (e.g., irrigation decisions) could exacerbate or mediate other climate impacts.
- Improved understanding of the trade-offs and efficacy of different adaptation measures, including short- and longer-term consequences, including the effects on future marsh migration of protective measures (e.g., levees) and wetland impoundments; invasion potential of new crop suggestions; and greenhouse gas implications of different land use transitions.
- Development and maintenance of a conservation program catalog that highlights programs that could be relevant in saltwater intruded landscapes, including program attributes, trade-offs, and context-specific considerations.
- Assurance that requirements for existing programs (e.g., CREP, EQIP) include suitable options for transitional, wet, and salty contexts. For example, programs that specify allowable species for restoration plantings should ensure that options include those that are suitable for transitional, coastal landscapes.
- Continuation of ongoing efforts to adapt conservation easement programs for application in changing coastal landscapes and to meet farmer and landowner needs.
- Better understanding of how different transition pathways will contribute differentially to farmer, landowner, and environmental objectives.
- Recognition and coordinated planning for the significant landscape changes expected to occur over the coming decades across the Eastern Shore, and particularly in Dorchester and Somerset counties.

- Greater attention to equity and distributional issues associated with the inevitable changes and loss of agricultural lands and implications of management and policy responses.
- Continued and expanded integration across planning efforts in coastal areas, including among agricultural and environmental planning efforts (e.g., how programs can simultaneously reduce stressors on farmers and agricultural landowners and contribute to environmental goals such as wetland restoration).

CHALLENGES

- Lack of data on the efficacy and trade-offs of implementing different adaptation options.
- Many agricultural data are not available at a finer resolution than county-level, limiting analysis in relation to saltwater intrusion impacts, which in most cases affect only a small fraction of a county.
- Limited availability of data on the spatial and temporal distribution of saltwater intrusion.
- Limited information on how responses to different climate stressors in Maryland might interact (e.g., changing irrigation needs could affect saltwater intrusion impacts).

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REFERENCES

Ardón, M., J. L. Morse, B. P. Colman, and E. S. Bernhardt. 2013. "Drought-Induced Saltwater Incursion Leads to Increased Wetland Nitrogen Export." *Global Change Biology* 19: 2976-2985.

Conway, T. 2001. "Plant Materials and Techniques for Brine Site Reclamation." Plant Materials Technical Note No. 26. 7 p. https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/kspmstn260201.pdf. [Date last accessed: November 2020].

Epanchin-Niell, R., C. Kousky, A. Thompson, and M. Walls. 2017. "Threatened Protection: Sea Level Rise and Coastal Protected Lands of the Eastern United States." *Ocean & Coastal Management* 137: 118-130.

Epanchin-Niell, R. S., A. Thompson, X. Han, J. Post, J. Miller, D. Newburn, K. Gedan, and K. Tully. 2023. "Coastal Agricultural Land Use Response to Sea Level Rise and Saltwater Intrusion." Paper presented at the 2023 Annual Meeting, July 23-25, Washington, D.C. 335970, Agricultural and Applied Economics Association. <https://ideas.repec.org/p/ags/aaea22/335970.html>.

Gedan, K. B., R. Epanchin-Niell, and M. Qi. 2020. "Rapid Land Cover Change in a Submerging Coastal County." *Wetlands* 40: 1717-1728.

- Gedan, K. B., and E. Fernández-Pascual. 2019. "Salt Marsh Migration into Salinized Agricultural Fields: A Novel Assembly of Plant Communities." *Journal of Vegetation Science* (2019). <https://doi.org/10.1111/jvs.12774>.
- Gibson, N., S. McNulty, C. Miller, M. Gavazzi, E. Worley, D. Keese, and D. Hollinger. 2021. "Identification, Mitigation, and Adaptation to Salinization on Working Lands in the U.S. Southeast." United States Department of Agriculture, Forest Service, Research and Development, Southern Research Station. https://www.srs.fs.usda.gov/pubs/gtr/gtr_srs259.pdf.
- Guimond, J. A., and H. A. Michael. 2021. "Effects of Marsh Migration on Flooding, Saltwater Intrusion, and Crop Yield in Coastal Agricultural Land Subject to Storm Surge Inundation." *Water Resources Research* 57 (2): e2020WRO28326.
- Hassani, A., A. Azapagic, and N. Shokri. 2021. "Global Predictions of Primary Soil Salinization Under Changing Climate in the 21st Century." *Nature Communications*. <https://doi.org/10.1038/s41467-021-26907-3>.
- Kirwan, M. L., H. A. Michael, K. B. Gedan, K. L. Tully, S. Fagherazzi, N. G. McDowell, G. D. Molino, D. Pratt, W. G. Reay, and S. Stotts. 2024. "Feedbacks Regulating the Salinization of Coastal Landscapes." *Annual Reviews in Marine Science* 17.
- Maas, E. V., and S. R. Grattan. 1999. "Crop Yields as Affected by Salinity." *Agricultural Drainage* 38: 55-108. Agronomy Monographs, Chapter 3. <https://access.onlinelibrary.wiley.com/doi/abs/10.2134/agronmonogr38.c3>.
- Maryland Department of Planning. 2019. "State of Maryland Plan to Adapt to Saltwater Intrusion and Salinization." J. Dubow and D. H. Cornwell, primary authors; D. Andreasen, A. Staley, K. Tully, K. Gedan, and R. Epanchin-Niell, contributing authors. <https://planning.maryland.gov/Documents/OurWork/envr-planning/2019-1212-Marylands-plan-to-adapt-to-saltwater-intrusion-and-salinization.pdf>.
- Maryland Department of Natural Resources. 2024. "Climate Change and Coastal Conservation." https://dnr.maryland.gov/ccs/Pages/habitats_slr.aspx.
- Mondal, P., M. Walter, J. Miller, R. Epanchin-Niell, K. Gedan, V. Yawatkar, E. Nguyen, and K. L. Tully. 2023. "The Spread and Cost of Saltwater Intrusion in the U.S. Mid-Atlantic." *Nature Sustainability* 6 (11): 1352-1362.
- NRCS. 1996. "Plant Materials for Saline-Alkaline Soils." Technical Notes—Plant Materials No. 26-96-MT-26 (Revised). Bridger, MT: U.S. Department of Agriculture Natural Resources Conservation Service. 5 p. (ID#13126). https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/mtpmstn13126.pdf. [Date last accessed: November 2020].
- NOAA. 2022. "National Oceanic and Atmospheric Administration. Digital Coast: Sea Level Rise Viewer." [slr-new-mapping-tool.pdf](https://www.noaa.gov). <https://www.noaa.gov>. Accessed May 2023.
- NOAA. 2023. "National Oceanic and Atmospheric Administration. Tides and Currents. Relative Sea Level Trends for Northern Atlantic." <https://tidesandcurrents.noaa.gov/sltrends/sltrends.html>. Accessed May 2023.

- NOAA. 2024. "Exceedance Probability Levels and Tidal Datums." NOAA Tides & Current. <https://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=8573927>.
- O'Donnell, K. L., E. S. Bernhardt, X. Yang, R. E. Emanuel, M. Ardón, M. T. Lerdau, A. K. Manda, A. E. Braswell, T. K. BenDor, E. C. Edwards, and E. Frankenberg. 2024. "Saltwater Intrusion and Sea Level Rise Threatens U.S. Rural Coastal Landscapes and Communities." *Anthropocene*, 100427.
- Sallenger, A. H., K. S. Doran, and P. A. Howd. 2012. "Hotspot of Accelerated Sea-Level Rise on the Atlantic Coast of North America." *Nature Climate Change* 2: 884-888.
- Sudol, T. A., C. D. M. Hesed, J. M. Clark, and F. C. Moser. 2023. "Resisting, Accepting, and Directing Sea Level Rise on the Chesapeake Bay: Agricultural Producers' Motivations and Actions." *Journal of Environmental Management* 332: 117355.
- Tanji, K. K., and N. C. Kielen. 2002. *Agricultural Drainage Water Management in Arid and Semi-Arid Areas*. ISBN 92-5-104839-8. Pages 1-105. Annex 1. Crop Salt Tolerance Data. Food and Agriculture Organization of the United Nations. <https://www.fao.org/4/Y4263E/y4263e0e.htm>.
- Tully, K., K. Gedam, R. Epanchin-Niell, A. Strong, E. S. Bernhardt, T. BenDor, M. Mitchell, J. Kominoski, T. E. Jordan, S. C. Neubauer, and N. B. Weston. 2019a. "The Invisible Flood: The Chemistry, Ecology, and Social Implications of Coastal Saltwater Intrusion." *BioScience* 69 (5): 368-378.
- Tully, K. L., D. Weissman, W. J. Wyner, J. Miller, and T. Jordan. 2019b. "Soils in Transition: Saltwater Intrusion Alters Soil Chemistry in Agricultural Fields." *Biogeochemistry* 142: 339-356.
- U.S. Department of Agriculture (USDA). 2024. "Crop Sequence Boundaries 2016-2023 Dataset." https://www.nass.usda.gov/Research_and_Science/Crop-Sequence-Boundaries/datasets/NationalCSB_2016-2023_rev23.zip. [Accessed March 2024].
- U.S. Department of Agriculture (USDA). 2023. "National Agricultural Statistics Service. Quick Stats." <https://quickstats.nass.usda.gov/>. Accessed July 2023.

ECONOMETRIC ANALYSIS

Lars J. Olson, Rebecca Epanchin-Niell and Zeyang Dong

SUMMARY

All Maryland counties are projected to experience declining corn productivity growth by 2050. Impacts will be strongest in eastern Maryland, where climate is projected to lead to reductions in average yields (negative productivity growth) by the end of the century. Some counties may face declining yields by the middle of the century (Dorchester, Queen Anne's, Somerset, and Worcester). These impacts are driven by projected increases in corn killing degree days. Development of corn varieties with greater tolerance to extreme heat would help alleviate these projected impacts.

OBJECTIVES

The objective of this portion of the study was to apply state-of-the-art econometric modeling to examine how Maryland agriculture has been affected by climate since 1950 and to use the models to estimate future impacts based on climate projections from the Coupled Model Intercomparison Project (CMIP), an international climate modeling project, designed to better understand past, present, and future changes in the climate. Our projections use the most recent data from this model (CMIP6) under the 4.5°C radiative forcing (RCP4.5), which represents the moderate pathway for future greenhouse gas emissions and climate projections.

METHODOLOGY

Our methodology builds on a rich literature in econometrics that examines how climate is impacting agriculture (Mendelsohn et al. 1994; Deschenes and Greenstone 2007; Schlenker and Roberts 2009; Fisher et al. 2012; Hsiang 2016; Carter et al. 2018; Keane and Neal 2020; Ortiz-Bobea et al. 2021). These models typically estimate a crop yield production function where yield is a function of inputs, technological progress, location-specific fixed factors (soil type, elevation, etc.), and weather shocks. Technological progress is modeled as total factor productivity growth, while inputs are controlled for using location and/or time fixed effects. After controlling for inputs, technological change, and location-specific factors, the literature finds that variations in yield are generally well explained by changes in climate and weather. The coefficients on climate variables indicate the direction and magnitude of climate impacts. Once coefficients have been estimated, a model can be combined with outputs from future climate projections to forecast how changes in future climate are anticipated to impact agricultural productivity growth.

Previous studies often use county-level climate data, which lacks precision. Urban areas tend to experience higher temperatures due to heat island effects, potentially overstating the warmth necessary for crop growth and amplifying the impact of climate change on early crop maturation. Conversely, in mountainous regions like western Maryland, temperatures decrease with altitude, which could lead to an underestimation of early crop maturation rates if not accounted for. Variations in urbanization rates and forest coverage across counties can exacerbate differences in calculated temperatures if non-agricultural areas are not excluded.

Our analysis uses gridded climate data for Maryland from the National Centers for Environmental Information (Durre et al. 2022) with daily observations of maximum and minimum temperatures, and precipitation from 1951 to 2022, with a resolution of approximately 1/24 of a degree (nominally 5 km). We map the gridded data onto counties, using the agricultural land distribution in each county to weight grid locations by the density of agricultural land. Agricultural lands are identified using two datasets: agricultural density data and the USDA Cropland Data Layer (CDL) (USDA 2023). The former, developed by Yu and Lu (2017-2018), provides annual cropland percentage maps at a 1 km resolution for the U.S. from 1850 to 2016. The CDL, released by the USDA National Agricultural Statistics Service (NASS), offers detailed crop type classifications at a 30-meter resolution from 2008 to 2022. We identify agricultural areas from 1951 to 2016 primarily using agricultural density data, and we use CDL data from 2017 onward. We overlay agricultural data onto climate data and calculate temperature and precipitation weighted by agricultural land coverage within each county. Degree days are calculated from daily maximum and minimum temperatures by approximating the duration each day that a crop is exposed to one-degree Celsius temperature intervals through a sinusoidal function following the methodology developed by Snyder (1984).

The analysis focuses on corn, the primary crop in Maryland, and the only crop with complete county-level yield data from 1951 to 2022. The primary climate variables we consider are growing degree days, killing degree days, and precipitation. Thresholds for growing degree days (GDD) and killing degree days (KDD) are 8°C and 30°C, respectively, based on the thresholds in AquaCrop version 7.0 from the Food and Agriculture Organization of the United Nations (FAO 2023). Corn yield data, spanning from 1951 to 2022, is sourced from the USDA NASS. Growing degree days are generally beneficial for crops as they reflect the accumulation of temperatures favorable to crop growth, while killing degree days capture the accumulation of heat that is detrimental to crop yields. This should be reflected by positive and negative coefficients, respectively, in the econometric models.

We use a suite of related modeling approaches to econometrically examine the impact of climate on Maryland corn production. The first uses the one-way county fixed-effect within panel data estimator to regress the change in corn productivity growth on GDD, KDD, and precipitation. The second follows the mean observation OLS (MO-OLS) methodology developed by Keane and Neal (2020). In addition to capturing spatial variation in estimated impacts, one advantage of this approach is that trends in the estimated climate coefficients can provide insight into the extent that farmers are adapting to a changing climate.

Climate change impacts vary spatially due to differences in geographical features, environmental conditions, and adaptation strategies. Additionally, changes in climate can influence ecosystem dynamics, affect pest prevalence, soil fertility, and water availability. Counties located close to each other are more likely to share similar climate patterns and environmental conditions in ways that vary systematically across space. Moreover, farmers in adjacent regions may adopt similar production practices and adaptation strategies. Together, these contribute to systematic spatial variation in crop yield responses, or spatial autocorrelation. Most econometric models of the impact of climate on agriculture assume there is no spatial autocorrelation, despite the fact that the data often provides evidence to the contrary. The third model we use is a spatial error within model (SEM) (Mínguez Salido et al. 2019) that corrects for omitted variable bias and uses weights based on the inverse distance between the centroid of agricultural lands in neighboring counties to account for spatial dependence in the model residuals.

RESULTS

Corn - Trends in Yield, Growing Degree Days, Killing Degree Days and Precipitation

The primary climate variables impacting corn yields in Maryland are two temperature related variables, growing degree days (GDD) and killing degree days (KDD), along with precipitation. Figure 1 depicts the evolution of these primary climate variables and corn yield over time for counties in Maryland. The black line represents the mean values of each variable. The dark gray area and light gray area represent the range between the 25th to 75th percentile and the 10th to 90th, respectively. There is substantial variation in both climate and yield over time.

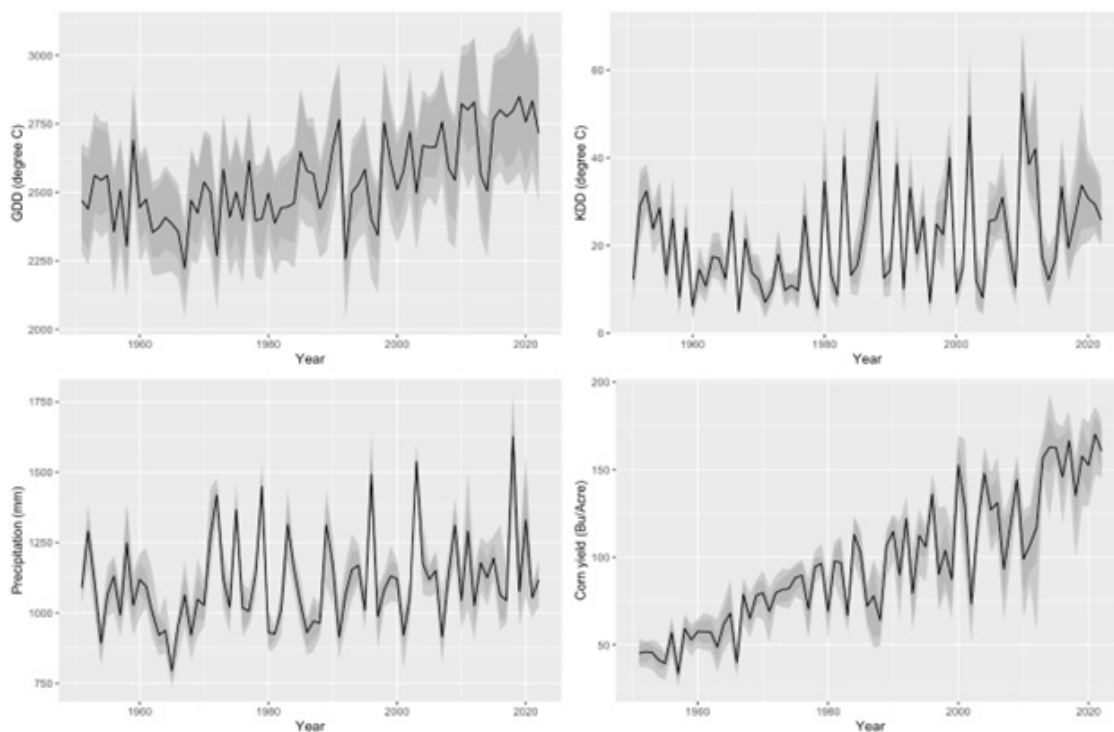


Figure 1: Evolution of Primary Climate Variables and Corn Yield for Maryland, 1951 to 2022.

The climate during the 1950s and 1960s is somewhat different from subsequent periods. Both corn GDD and KDD declined during that period. From the 1970s to the present, corn GDD has increased by 15% while KDD has increased by 80%. There has been a slight upward trend in precipitation. Average corn yields have more than tripled, reflecting substantial technological progress in agriculture and the adoption of more efficient production practices. There is substantial variation across counties in corn yield growth.

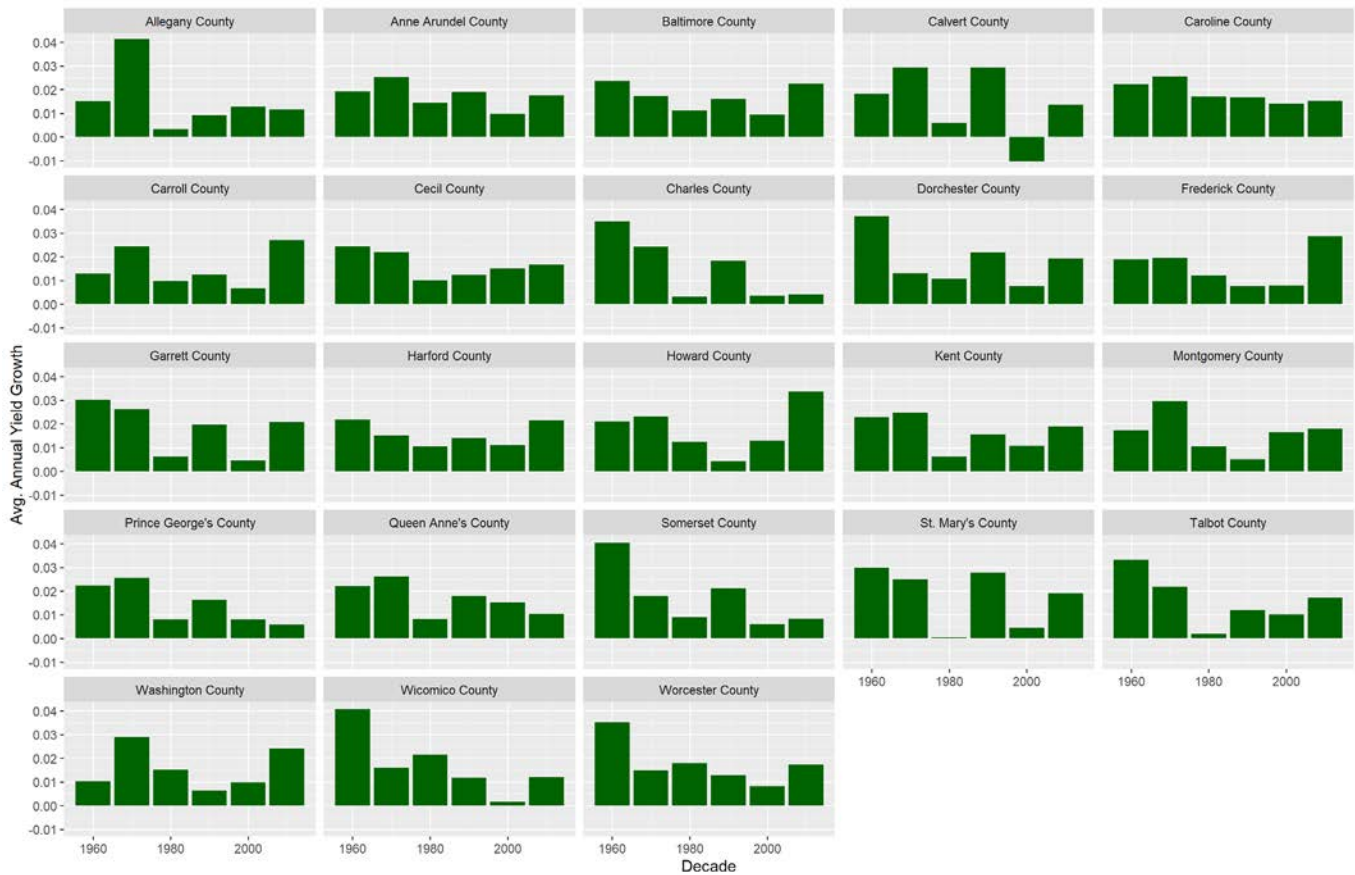


Figure 2: Average Annual Growth in Corn Yield by County and Decade.

The highest corn productivity growth occurred in the 1960s and 1970s. Then productivity growth declined. In the most recent decade, average corn productivity growth increased in some counties, particularly those in central and northern Maryland.

Figure 3 shows county variation in average corn KDD by decade. Eastern Shore counties, in particular, have experienced significant increases in corn KDD. Since 1970, Maryland counties have experienced one additional KDD every 3.5 years, on average. This detrimental impact is partially offset by the increase in corn growing degree days and a modest trend in increased precipitation during the corn growing season.



Figure 3: Average corn killing degree days (KDD) by county and decade.

In Figure 1, it is apparent that peaks in KDD correspond to drops in corn yield, with increased volatility in yields observed after the mid-1990s. This suggests one mechanism through which variations in climate impact corn productivity in Maryland. Econometric analysis allows us to estimate and characterize the extent of these impacts.

In all models, increases in KDD have a significant negative effect on corn yield growth. GDD is only significant in the county fixed effects model, while precipitation is significant in the county fixed effects and SEM models. The estimated impacts are relative to overall productivity growth in corn yields of about 1.9% per year. The top section of Table 1 gives the average of the climate indicators in the 1970s and 2010s. The bottom section of the table shows the estimated impact of a one-unit change in each climate indicator on corn productivity growth. The results indicate that a one-degree increase in killing degree days reduces productivity growth by one-half to three-fourths. Over the past two decades, some Eastern Shore Maryland counties have experienced a one-degree increase in killing degree days every two to three years, on average. The offsetting beneficial effects of a longer growing season and slightly increased precipitation have been modest by comparison, and those changes in climate are not enough to overcome the negative impacts of more killing degree days. While Maryland has experienced corn productivity growth, the impacts of a warming climate can be likened to reducing the rate of return on investment by one-half to three-fourths.

	Growing Degree Days (100 days)	Killing Degree Days (days)	Precipitation (cm)
Mean of Climate Indicator, 1971-1980	24.8	14.4	117
Mean of Climate Indicator, 2011-2020	27.4	27.0	119
Estimated Change in Corn Productivity Growth Induced by Changes in Climate			
Model	GDD (100 degree increase)	KDD (1 degree increase)	Precipitation (1 cm increase)
County Fixed Effects	+0.9%*	-1.45%***	+1.8%***
MO-OLS	-0.8%	-1.31%***	+1.9%
SEM	-0.8%	-0.08%***	+1.7%***
Significance Codes: *** = 0.0001, * = 0.05			

Table 1: Estimated Climate Impacts on Corn Productivity Growth in Maryland.

Corn - Projected Impacts on Future Productivity

Projected future climate impacts on corn productivity are obtained by combining the model projections of future climate in Maryland from the Coupled Model Intercomparison Project (CMIP), an international climate modeling project designed to better understand past, present, and future changes in the climate. Our projections use the most recent data from this model (CMIP6) under the 4.5°C radiative forcing (RCP4.5), which represents the moderate pathway for future greenhouse gas emissions and climate projections (Thrasher et al. 2022). Figure 4 depicts historical observations (dark green) and future projections (lighter green) of corn productivity growth across all counties in Maryland, with historical observations depicted from 1951 to 2020, and future projections depicted from 2021-2100. Outliers exceeding +/- 25 percent (0.25) are omitted. All Maryland counties are projected to experience declining corn productivity growth by 2050. Impacts will be strongest in eastern Maryland, where projected increases in corn killing degree days are predicted to lead to reductions in average yields (negative productivity growth) by the end of the century. Some counties may face declining yields by the middle of the century (Dorchester, Queen Anne’s, Somerset, and Worcester).

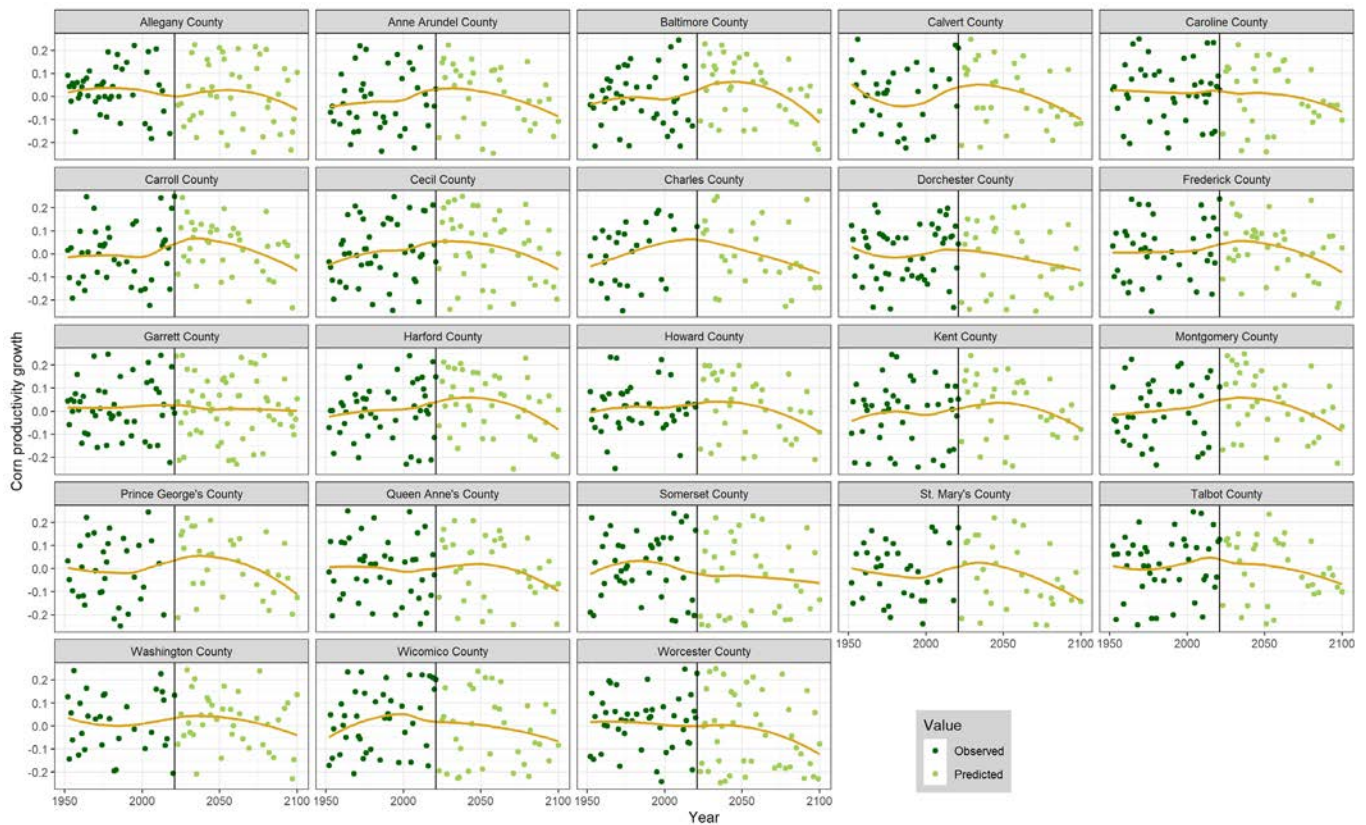


Figure 4: Historical and projected corn productivity growth in Maryland, CMIP6 RCP4.5 scenario.

RECOMMENDATIONS

- Development of corn varieties with greater tolerance to a range of climatic conditions, including extreme heat, would help alleviate the impacts associated with the projected increase in corn stress/killing degree days.
- Careful management of irrigation to reduce vapor pressure deficits may mitigate damage from heat stress, particularly during critical crop growth stages like the window surrounding silking when the kernel set occurs. Advances in other crops may create additional alternatives, although at this time, soybeans also suffer from reduced yields under extreme heat.
- Robust data collection, management and sharing for important agro-economic crops throughout the state.

CHALLENGES

Data limitations prevented the analysis of most commercial agricultural crops in Maryland. Most crops are not adequately reported even at the county/year level. The analysis could be extended to climate impacts on soybeans from 1971 to present, but a more comprehensive analysis of climatic factors is needed to identify the best-performing model.

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REFERENCES

- Carter, C., X. Cui, D. Ghanem, and P. Merel. 2018. "Identifying the Economic Impacts of Climate Change on Agriculture." *Annual Review of Resource Economics* 10 (1).
- Deschênes, O., and M. Greenstone. 2007. "The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather." *American Economic Review* 97: 354-385.
- Duque, Yara. 2020. *LeSage & Pace (2009) Introduction to Spatial Econometrics Statistics: A Series of Textbooks and Monographs*.
- Durre, I., A. Arguez, C. J. Schreck III, M. F. Squires, and R. S. Vose. 2022. "Daily High-Resolution Temperature and Precipitation Fields for the Contiguous United States from 1951 to Present." *Journal of Atmospheric and Oceanic Technology*. <https://doi.org/10.1175/JTECH-D-22-0024.1>.
- Fisher, A. C., W. M. Hanemann, M. J. Roberts, and W. Schlenker. 2012. "The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather." *American Economic Review* 102: 3749-3760.
- Hsiang, S. 2016. "Climate Econometrics." *Annual Review of Resource Economics* 8: 43-75.
- Keane, M., and T. Neal. 2020. "Comparing Deep Neural Network and Econometric Approaches to Predicting the Impact of Climate Change on Agricultural Yield." *The Econometrics Journal* 23 (3): S59-S80. <https://doi.org/10.1093/ectj/utaa012>.
- Keane, M., and T. Neal. 2020. "Climate Change and U.S. Agriculture: Accounting for Multidimensional Slope Heterogeneity in Panel Data." *Quantitative Economics* 11: 1391-1429.
- Lobell, D. B., and G. P. Asner. 2003. "Climate and Management Contributions to Recent Trends in U.S. Agricultural Yields." *Science* 299: 1032.
- Lobell, D. B., et al. 2014. "Greater Sensitivity to Drought Accompanies Maize Yield Increase in the U.S. Midwest." *Science* 344: 516-519.
- Food and Agricultural Organization of the United Nations. 2023. "Release Note AquaCrop." <https://www.fao.org/aquacrop>.
- Mendelsohn, M., W. D. Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *American Economic Review* 84: 753-771.

- Mínguez Salido, Román, Roberto Basile, and María Durbán. 2019. "An Alternative Semiparametric Model for Spatial Panel Data." *Statistical Methods & Applications* 29 (October): 1-17. <https://doi.org/10.1007/s10260-019-00492-8>.
- Ortiz-Bobea, A., et al. 2021. "Anthropogenic Climate Change Has Slowed Global Agricultural Productivity Growth." *Nature Climate Change* 11: 306-312.
- Schlenker, W., and M. J. Roberts. 2009. "Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change." *Proceedings of the National Academy of Sciences USA* 106: 15594-15598.
- Snyder, R. L. 1985. "Hand Calculating Degree Days." *Agricultural and Forest Meteorology* 35 (1): 353-358. [https://doi.org/10.1016/0168-1923\(85\)90095-4](https://doi.org/10.1016/0168-1923(85)90095-4).
- Thrasher, B., W. Wang, A. Michaelis, et al. 2022. "NASA Global Daily Downscaled Projections, CMIP6." *Scientific Data* 9: 262. <https://doi.org/10.1038/s41597-022-01393-4>.
- USDA National Agricultural Statistics Service. 2023. "Cropland Data Layer." Published crop-specific data layer [Online]. <https://croplandcros.scinet.usda.gov/>.
- USDA National Agricultural Statistics Service. 2023. "Quick Stats." <https://quickstats.nass.usda.gov/>.
- Yu, Z., and C. Lu. 2017. "Historical Cropland of the Continental U.S. from 1850 to 2016, Links to GeoTIFFs." *PANGAEA*. <https://doi.org/10.1594/PANGAEA.881801>.
- Yu, Z., and C. Lu. 2018. "Historical Cropland Expansion and Abandonment in the Continental U.S. during 1850 to 2016." *Global Ecology and Biogeography* 27 (3): 322-333. <https://doi.org/10.1111/geb.12697>.

LEGAL CONSEQUENCES OF CLIMATE CHANGE ON MARYLAND AGRICULTURE

Paul Goeringer

SUMMARY

In legal contexts, existing statutes and common law principles typically provide relief to agricultural operations harmed by violations of law. However, the consequences of climate change that can affect farmers—such as extreme weather events, groundwater salinization, growing zone shifts, and others—pose unique challenges, as existing legal frameworks often offer inadequate or no relief. To bring an action in court, to either prevent the continued issue or pay for the losses to the ongoing wrong, an agricultural operation must establish "standing." The impacts of climate change affect all parties, which makes it difficult to demonstrate standing.

Our objective is to explore potential improvements to legal standing for agriculture, enabling litigation related to the impacts of climate change. Looking to individual states or international precedents may reveal pathways to provide relief.

BACKGROUND AND RESEARCH RESULTS

For individuals or entities to bring a case before a court, they must possess legal standing. Standing ensures that only litigants with a direct and substantial interest in the lawsuit can access the judicial system, preventing courts from becoming “roving commissions assigned to pass judgment on the validity of the Nation’s laws” (Broadrick v. Oklahoma 1973).

Three requirements establish standing:

- 1.) A concrete, particularized harm,
- 2.) Proof that the harm is linked to the defendant’s actions, and
- 3.) The alleged harm must be remediable by a favorable court decision.

While this principle aims to uphold the integrity of the legal system, its applicability is under scrutiny, especially in climate change lawsuits. Traditional standing criteria often require revision to address the widespread and complex nature of climate-related harm (Martin and Landman, 2020). Plaintiffs in climate change lawsuits—commonly environmental activists, state governments, individual citizens, or environmental interest groups—struggle to demonstrate they have suffered the necessary concrete, particularized harm. Climate change effects typically manifest gradually, complicating the proof of individualized harm in cases of global environmental impact. Critical aspects of agriculture are increasingly affected by climate change in ways that are difficult to redress. Issues such as changes in heat index, groundwater salinization, weather variability, physical damage from storms, and shifts in growing zones represent harms not easily addressed by traditional legal standards.

Unfortunately, courts frequently dismiss climate change litigation due to the perceived inadequacy of the requested relief in tackling global climate issues. This pattern underscores an urgent need to reevaluate the legal system’s approach to climate change.

The traditional standing doctrine emphasizes individualized harm and direct causation. However, applying it to climate change reveals significant gaps that require attention. The widespread impacts of climate change make establishing direct causation challenging, as attributing specific environmental harms to individual actors or entities is often impossible. The stringent requirements of traditional standing inadvertently neglect crucial climate change cases, leaving affected parties without a legal avenue for recourse. Additionally, the emphasis on concrete and immediate injuries overlooks the long-term, cumulative effects of climate change, complicating the establishment of standing in related litigation. Therefore, while traditional standing doctrine serves as a fundamental principle in many legal contexts, its application to climate change cases highlights the pressing need for reform to better accommodate the unique challenges presented by this global phenomenon.

The complex relationship between climate change and agriculture warrants a focused examination of how an environmental standing doctrine can serve the interests of the agriculture industry. Agriculture is both a contributor to and a victim of climate change, making its integration into the standing framework particularly relevant (U.S. Environmental Protection Agency 2023). A clear legal pathway can empower farmers, agricultural enterprises, and stakeholders to advocate for sustainable practices and safeguard their interests against climate change impacts.

Consider the challenges posed by changing weather patterns on crop yields or the implications of water scarcity on livestock and irrigation-dependent agriculture. These concerns highlight the need for legal mechanisms that acknowledge the agriculture sector's unique vulnerabilities. Issues of standing in environmental doctrine have long been complex, particularly regarding agricultural operators. In our work, we explored what a legal standing doctrine should entail for climate change litigation. To combat this, the General Assembly could modify the existing state constitution to provide protection similar to Montana's constitutional protection to ensure a clean and healthy environment for present and future generations in the state (Mont. Const. art. IX, § 1). At the same time, dedicated courts could be established with backgrounds in climate change impacts to handle potential litigation. This would be similar to what we see already in the federal Tax Court system and in other states that have established specialized courts to handle criminal issues. Both could effectively address the standing issues that often hamper this type of litigation.

First, "environmental injury" would necessitate a reevaluation of what constitutes harm concerning climate change. This broadened definition would encompass widespread ecological harms rather than focusing solely on immediate damage to individuals or property. This concept would broaden to encompass the widespread ecological and environmental harms of climate change. Significant injuries, such as loss of biodiversity, disruptions in ecosystems, and degradation of natural resources, would merit legal consideration.

Second, "climate change causation" would establish connections between human activities—particularly greenhouse gas emissions—and resultant climatic shifts and environmental impacts. This component would necessitate a robust evidentiary framework to establish a direct connection between specific human actions and broader environmental impacts, providing a concrete basis for attributing responsibility and accountability.

Lastly, the focus on "injunctive emission reduction remedies" emphasizes proactive measures. Rather than solely seeking compensation for past harms, the doctrine would prioritize implementing strategies to mitigate future emissions and ongoing environmental degradation. This forward-looking approach aligns with the overarching goals of sustainable environmental stewardship. For examples of potential ways to address the standing issue in climate change cases, we might consider looking to other states or internationally.

In *Held v. State*, the Montana court found that the state's constitution requires: "[t]he state and each person shall maintain and improve a clean and healthful environment in Montana for present and future generations." A district court found that a group of sixteen youths could challenge Montana's role in "exacerbating climate change violated the State's constitutional provision." (137 Harv. L. Rev. 1491).

At the same time, other countries with a tradition of utilizing common law, such as India, have developed specialized courts to handle environmental claims related to climate change and other environmental issues. India has established a *Green Bench* or specialized court to address issues concerning environmental protection, sustainability, and conservation of natural resources. Concerned citizens, environmental activists, nonprofits, and other entities can use public interest litigation to file cases for the environment and the public interest.

However, broadening standing for agriculture in Maryland regarding climate change could have unintended consequences, necessitating thorough investigation prior to implementation. Agriculture, like many industries, contributes to climate change, and changes in standing doctrine could be utilized against agricultural interests as well.

In this project, we found data collection relatively straightforward. The Sabin Center for Climate Change Law at Columbia University was a valuable resource for climate change litigation in the U.S. and internationally. It provided us with a starting point to explore the issues and learn more about the search strategy we should implement. We utilized legal databases such as Westlaw to review existing literature, enhancing our understanding of the subject and informing our contemplation of potential legal reforms.

REFERENCES

Broadrick v. Oklahoma, 413 U.S. 601 (1973).

U.S. Environmental Protection Agency. "Climate Change Impacts on Agriculture and Food Supply." Last updated November 16, 2023. <https://www.epa.gov/climateimpacts/climate-change-impacts-agriculture-and-food-supply#:~:text=The%20Link%20Between%20Agriculture%20and,that%20contribute%20to%20climate%20change.>

Environmental Law-Climate Change-Montana Court Holds That Montana Youth Can Access Equitable Relief for Climate Impacts.-Held v. State, No. Cdv-2020-307 (Mont. Dist. Ct. Aug. 14, 2023), 137 Harv. L. Rev. 1491 (2024). <https://harvardlawreview.org/print/vol-137/held-v-state.>

Martin, Marisa, and James Landman. "Standing: Who Can Sue to Protect the Environment." *American Bar Association*, October 9, 2020. https://www.americanbar.org/groups/public_education/publications/insights-on-law-and-society/volume-19/insights-vol-19---issue-1/standing--who-can-sue-to-protect-the-environment/.

Montana Constitution article IX, § 1.

Praveen Bhargav, *Everything you need to know about the National Green Tribunal (NGT)*, *Conservation India*, May 2, 2011, <https://www.conservationindia.org/resources/ngt.>

"Standing." *Legal Information Institute, Cornell University*. <https://www.law.cornell.edu/wex/standing> (last visited November 6, 2023).

Objective III: Modeling Vulnerabilities and Opportunities

BUILDING MODELS TO LINK HISTORICAL CLIMATE-AGRICULTURAL SYSTEMS

Majid Mirzaei and Adel Shirmohammadi

SUMMARY

This report presents the findings from a comprehensive study conducted to establish predictive models linking historical climate data with agricultural outcomes in Maryland. The research focuses on synthesizing long-term climate data and developing machine learning models to predict crop yields and water withdrawals. The primary objective was to build machine learning models that effectively predict agricultural parameters such as crop yield and water withdrawals based on historical climate data. The study utilized various data sources including NOAA, and employed machine learning techniques such as Random Forest, Lasso, and Ridge regression. These models were trained on data spanning from 1980 to 2022, aiming to forecast future agricultural outcomes under different climate scenarios.

KEY FINDINGS IN THIS STUDY CAN BE CLASSIFIED AS FOLLOWS:

- 1. Crop Yield Predictions:** The study identified significant climatic variables impacting crop yields, such as temperature and precipitation. The machine learning models indicated that precipitation has a strong correlation with corn and soybean yields, while temperature influences wheat yields more significantly.
- 2. Water Withdrawal Predictions:** A Random Forest model was developed to predict agricultural water withdrawals during growing seasons. Key predictors include evapotranspiration and temperature variables.
- 3. Future Projections:** Machine learning models project varying impacts on crop yields and water withdrawals under different future climate scenarios (SSP126, SSP245, and SSP585). These projections are vital for planning and adapting agricultural practices to future climate conditions. The study faced significant constraints due to limited availability of detailed long-term agricultural data in Maryland. This limitation affected the depth and accuracy of the predictive models and highlighted the need for more robust data collection and sharing mechanisms.

Yield Predictions through Multimodal Machine Learning Analysis of Climatic Variables

In agricultural research, the precise quantification of the relationship between crop yields and climatic variables is essential for optimizing agricultural productivity. Given the constraints associated with the availability of training and testing datasets, our investigation adopts a comprehen-

sive approach by utilizing a variety of machine learning techniques to ascertain the most effective predictive model for each crop type. This analysis methodically assesses numerous climatic parameters, such as temperature, precipitation, and humidity, to identify the principal determinants of crop yield. This approach not only elucidates the influence of varying climatic factors on agricultural outputs but also provides strategic insights for mitigating the deleterious effects of adverse meteorological conditions and climate change on agricultural practices. The findings of this study are anticipated to offer substantial benefits to farmers, agricultural strategists, and policymakers, facilitating informed decision-making to sustain and enhance agricultural productivity in the face of evolving climatic scenarios.

Identifying Key Parameters for Machine Learning Models in Agricultural Predictions

In this study, we focus on refining the process of building machine learning models to improve the prediction of crop yields. Initially, we identify the most influential parameters essential for accurate predictions while discarding less impactful ones. This simplifies the model, enhancing its efficiency and interpretability. Using feature importance ranking and sensitivity analysis, we distinguish crucial climatic parameters that significantly affect crop yields. This enables us to concentrate on a concise set of vital parameters, ensuring the model remains streamlined yet effective. After identifying these key parameters, we employ pair plots to visually demonstrate their relationships with crop yields, illustrating both the interactions between variables and the distribution of crop yield data. This graphical analysis helps clarify how various climatic factors correlate with crop yields. Focusing on three primary crops in Maryland—corn, soybean, and wheat. Figure 1 reveals no strong linear relationships between corn yield and individual weather variables (PRCP, minimum temperature [Tmin], maximum temperature [Tmax]). The lack of clear trends suggests that crop yields are likely influenced by complex interactions of multiple factors, necessitating further investigation and more complex models for accurate prediction; therefore, we further analyze these relationships using heat maps. These heat maps display the correlation coefficients between crop yields and climatic parameters, revealing the predictive power of each variable for different crops (Figure 2).

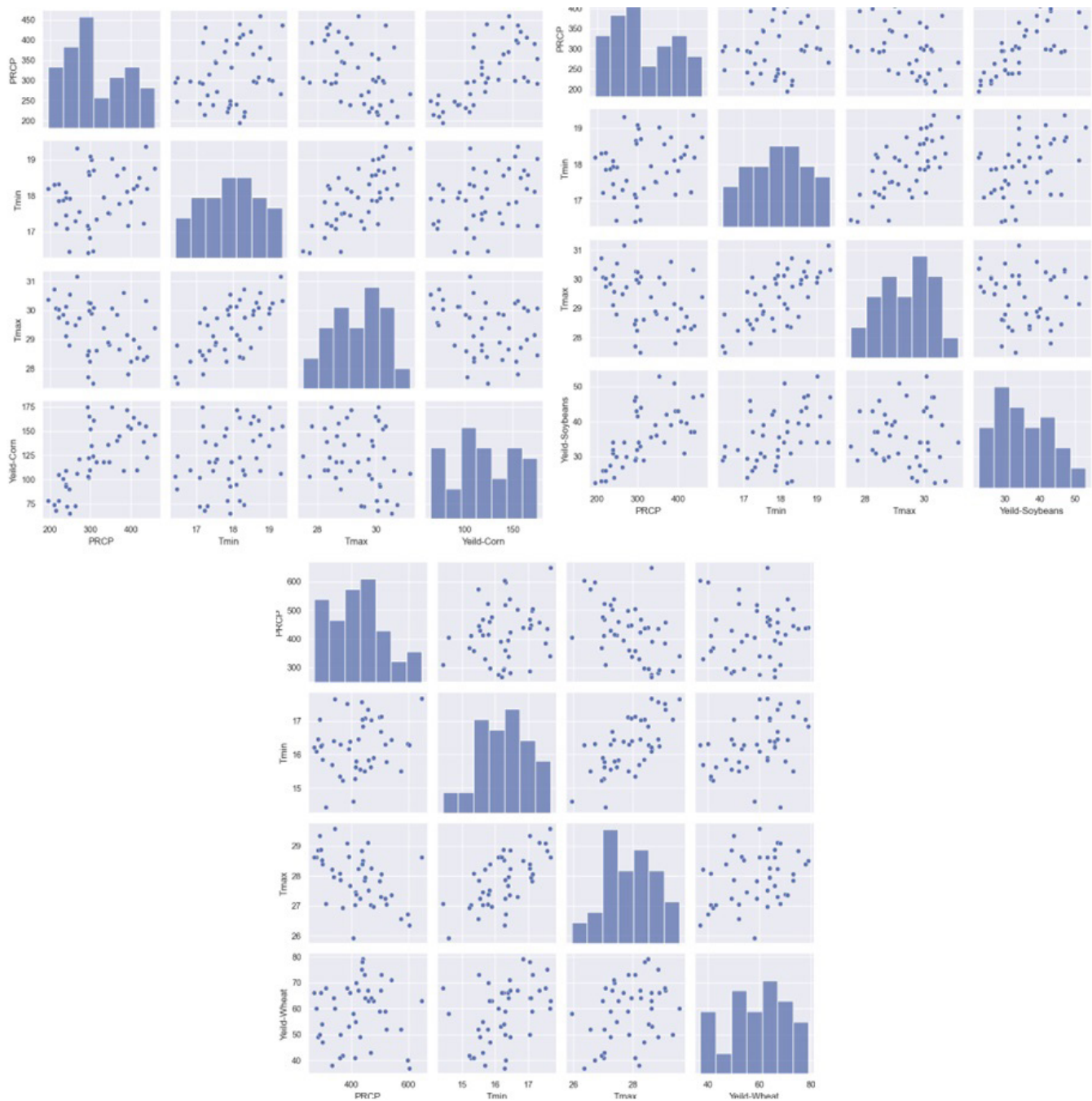


Figure 1: Pair plot showing the relationships between crop yields and maximum temperature (Tmax), minimum temperature (Tmin), and precipitation (PRCP).

Figure 2 displays heat maps illustrating the correlations between PRCP, Tmin, Tmax, and crop yields. The heat maps quantify these correlations, revealing that PRCP has the highest correlation with corn and soybean yields, indicating that variations in precipitation significantly affect their yields. For wheat, temperature (both Tmin and Tmax) is the dominant factor influencing yield.

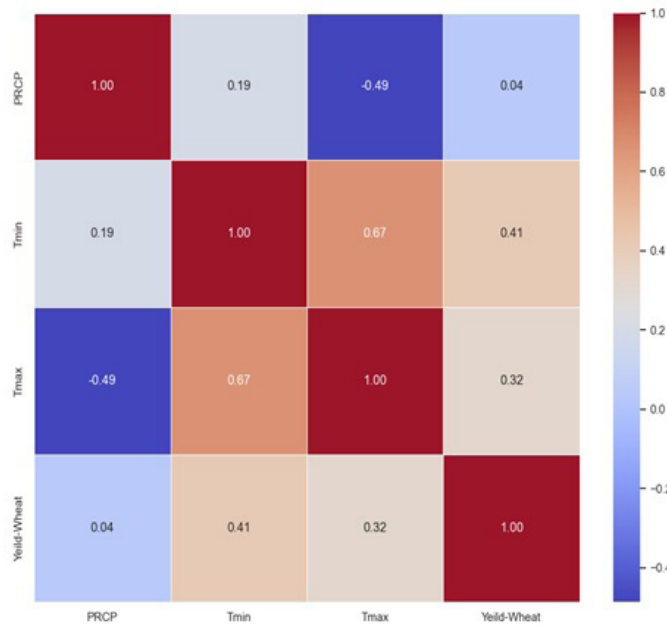
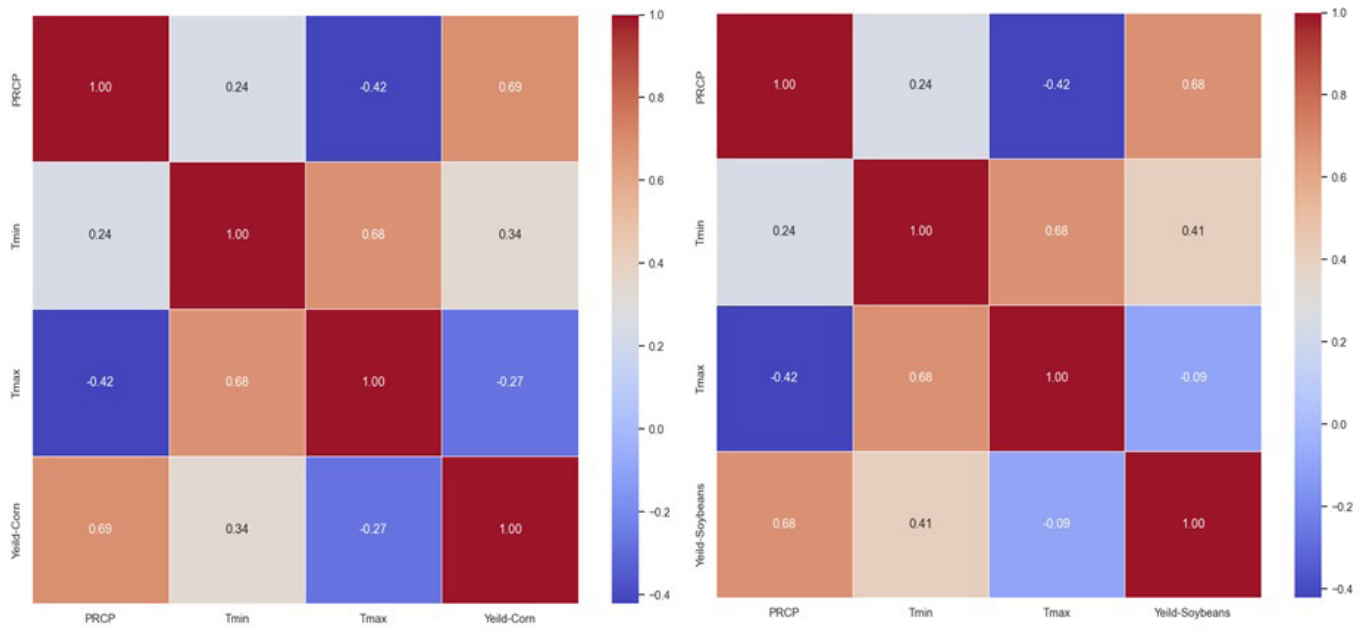


Figure 2: Heat maps of correlations between PRCP, Tmin, Tmax, and crop yields.

This approach not only improves the predictive accuracy of our models but also provides valuable insights to farmers and agricultural planners in Maryland, enabling more precise and informed decision-making in response to climatic changes.

Selecting the Optimal Machine Learning Model for Crop Yield Prediction

Selecting the optimal machine learning model for predicting crop yields in Maryland necessitates assessing model performance on both training and test datasets. Given our limited dataset of 43 years (1980-2022) (USDA NASS), it is essential to carefully select models that balance performance and avoid overfitting. This limitation is a critical consideration for future efforts to build better models. We have identified five machine learning techniques that are particularly effective for analyzing small datasets. These methods include Lasso (Kumar et al. 2019), Ridge (Ahmed et al. 2022), Linear Regression (Liu et al. 2021), Random Forest (Jeong et al. 2016), and Gradient Boosting (Ravi and Baranidharan 2020).

Figure 3 compares the Root Mean Square Error (RMSE) for various models and provides insights into their effectiveness. Machine learning model evaluation necessitates a thorough examination to ensure robustness and avoid overfitting (Hackeling 2017). Overfitting occurs when a model performs well on training data but poorly on test data, indicating it has captured noise rather than the underlying patterns (Ying 2019). Thus, while training performance is important, the test set results are paramount. A significant discrepancy between training and test performance suggests overfitting. In this analysis, we considered multiple models. The evaluation criterion was the comparison of model performance in both training and test datasets, with a particular emphasis on test set results to identify the best model. Finally, the Ridge regression model was selected for corn and soybean yields due to its consistent performance across datasets, indicating minimal overfitting. For wheat, Linear Regression demonstrated the best results (Figure 3). These selections ensure that the models generalize well to new data, providing reliable yield predictions.

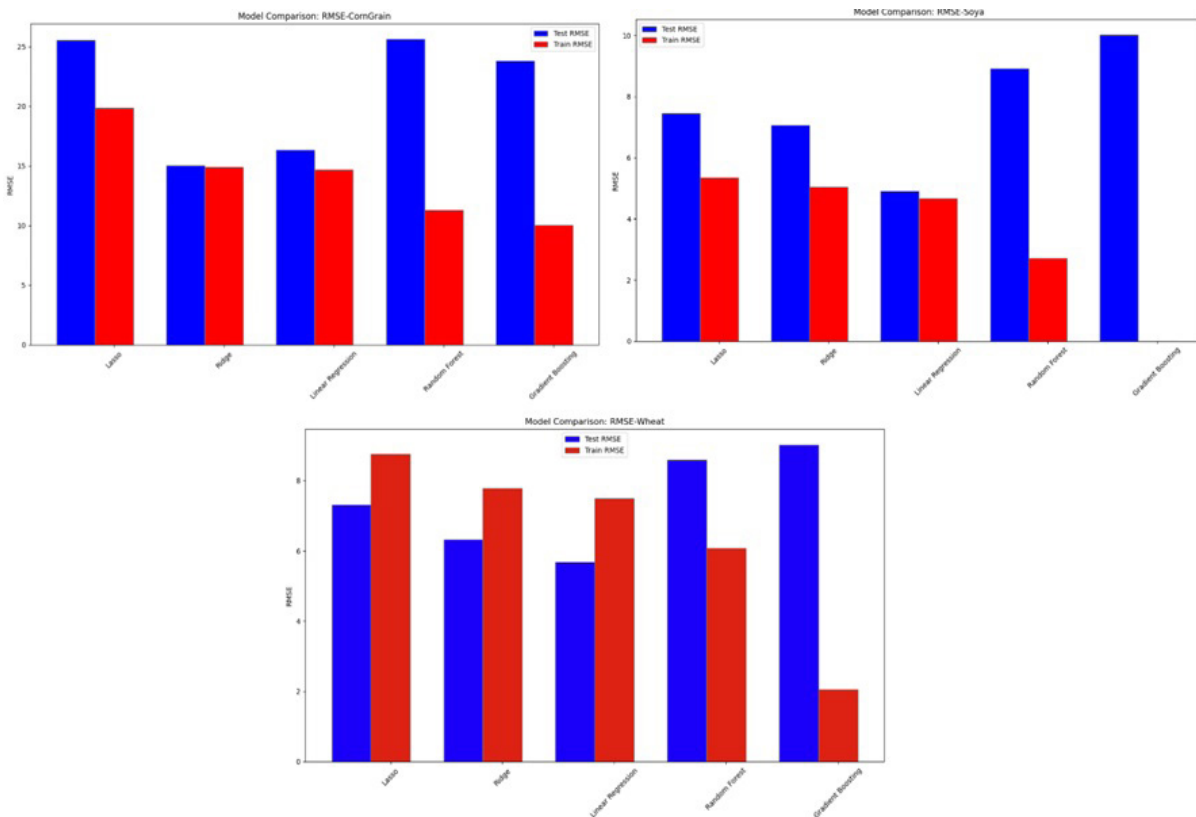


Figure 3: RMSE Comparison of Machine Learning Models on Training and Test Data for Crop Yield Prediction.

Figure 4 displays the predicted versus actual yield plots for the training and test sets of all crops using their respective selected machine learning models. The plots illustrate how well each model fits the data. For each crop, the left plot represents the training set, and the right plot represents the test set. The red dashed line indicates perfect predictions. These plots help visualize the models' accuracy, showing that the selected models perform reasonably well on both training and test sets, indicating their potential for reliable yield prediction across different crops.

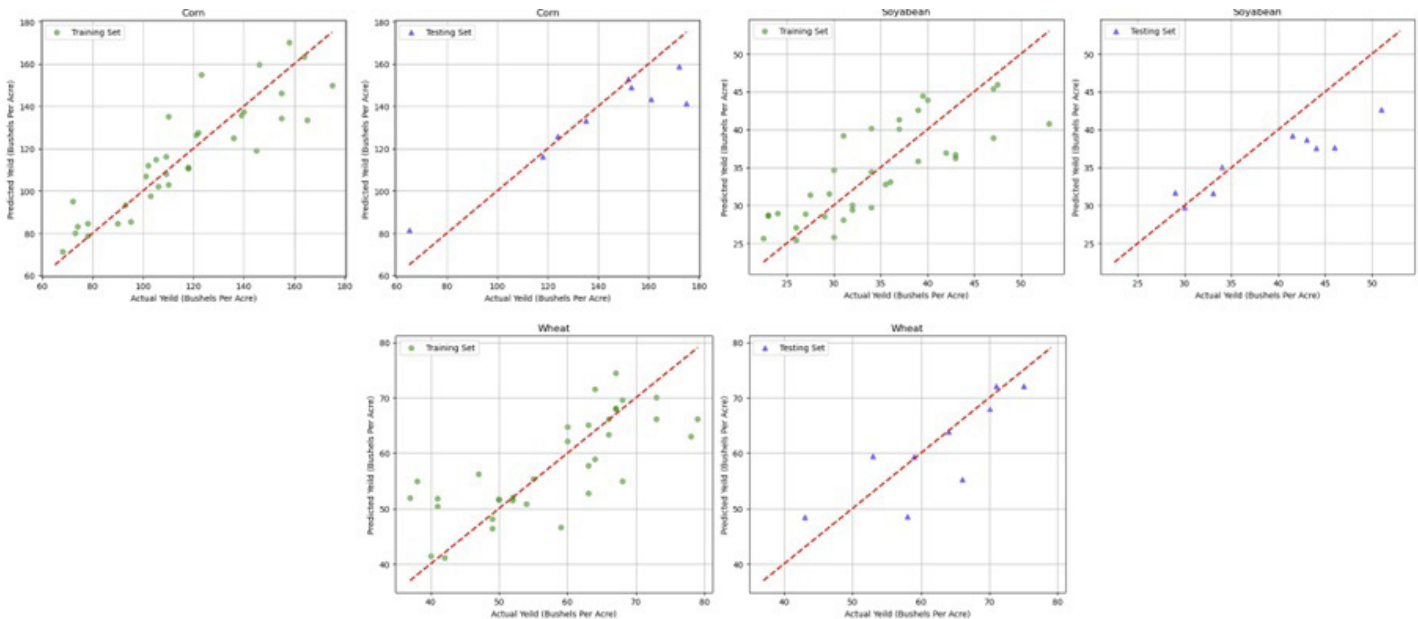


Figure 4: Predicted vs. Actual Yield for Training and Test Sets Across All Crops Using Selected Machine Learning Models

Projecting Future Crop Yields Under Different Climate Scenarios

The application of trained machine learning models to predict future crop yields under different climate scenarios (SSP126, SSP245, and SSP585) is depicted in Figure 6. These models, trained on historical data, project yields for corn, soybean, and wheat from 2020 to 2100. Each row represents a different crop, and each column corresponds to one of the three climate scenarios. SSP126 represents a lower greenhouse gas concentration pathway, SSP245 an intermediate pathway, and SSP585 a higher concentration pathway. The blue, green, and red lines represent yield projections under SSP126, SSP245, and SSP585, respectively, with dashed red lines indicating the trends over time. These projections highlight the potential impact of various climate futures on crop yields. For instance, corn and soybean yields show significant variability across the scenarios, with distinct trends emerging. Wheat exhibits an increasing trend under SSP126 and SSP585 but more variability under SSP245. This analysis underscores the importance of considering multiple climate scenarios in agricultural planning and the potential need for adaptation strategies to mitigate adverse impacts on crop yields.

Based on Figure 5, which shows the trends of Tmin, Tmax, and precipitation from 2022 to 2100 under scenarios SSP126, SSP245, and SSP585, we observe notable differences in climate projections. These results come from trained machine learning models that project future crop yields. Minimum and maximum temperatures increase significantly from SSP126 to SSP585, while precipitation remains relatively constant under SSP126 but decreases under SSP245 and SSP585. Given that corn and soybean have a strong correlation with precipitation and a weaker correlation with Tmin and Tmax, the stable precipitation under SSP126 means that corn and soybean yields are projected to remain relatively unchanged from 2022 to 2100. Conversely, wheat, which has a strong relationship with temperature, is expected to see an increase in yield under SSP126 due to the rising temperatures.

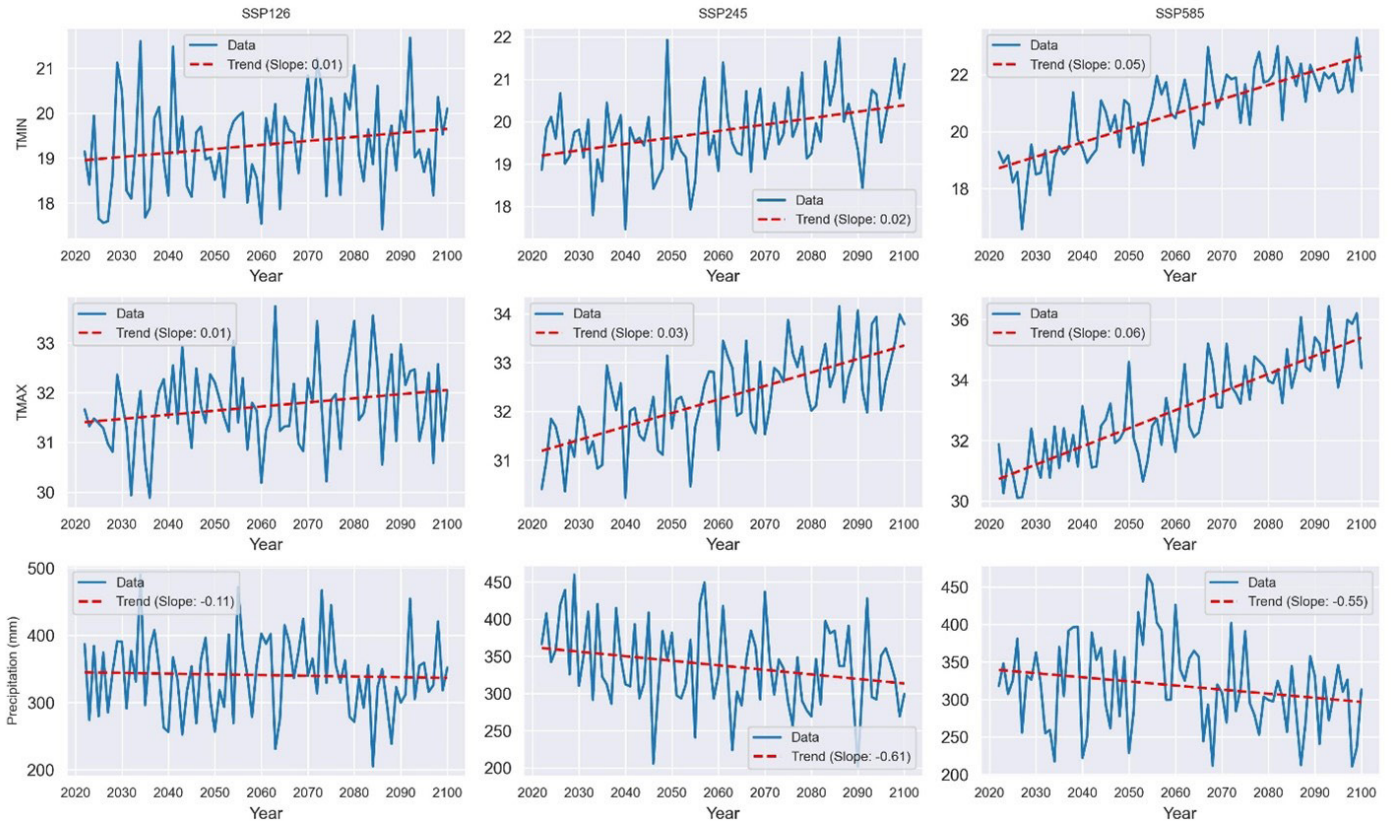


Figure 5: Minimum Temperature, Maximum Temperature, and Precipitation across scenarios SSP126, SSP245, SSP585 for Maryland in Growing Season. The red dashed line represents the trend line.

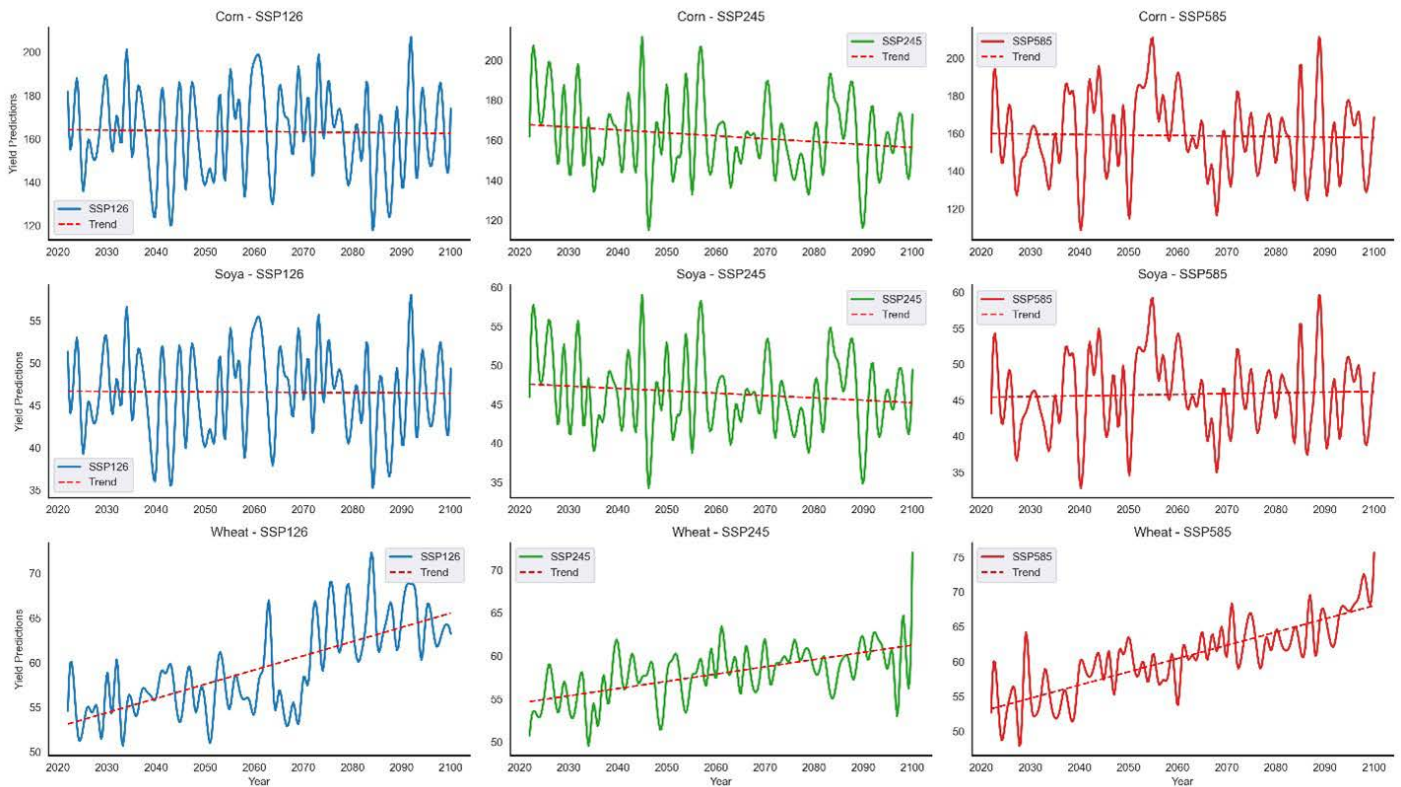


Figure 6: Projected Crop Yields Under Different Climate Scenarios (SSP126, SSP245, SSP585) from 2020 to 2100

For SSP245 and SSP585, precipitation decreases at almost the same rate, but the trend of increasing temperature is higher in SSP585 compared to SSP245. This affects crop yield predictions differently. In SSP245, the effect of decreasing precipitation is significant for corn and soybean yields, resulting in a decline. However, for wheat, the moderate temperature increase under SSP245 still leads to yield gains due to its strong relationship with temperature. In SSP585, despite the decline in precipitation being similar to SSP245, the much higher trend of temperature increase has a different impact. The substantial rise in temperatures under SSP585 mitigates the negative effect of reduced precipitation on corn and soybean yields, resulting in little change in their yields. For wheat, the yield continues to increase significantly under SSP585 due to the pronounced temperature rise.

These projections, derived from machine learning models, highlight the complex interactions between temperature and precipitation under different climate scenarios and their combined impact on crop yields. This emphasizes the importance of machine learning in predicting crop yields and how it can inform future management strategies in Maryland, ensuring resilience and effective planning in agricultural practices.

Random Forest Model for Agricultural Water Withdrawal Prediction During Growing Seasons

In this analysis, we built a Random Forest (RF) model to predict agricultural water withdrawal during growing seasons. The accompanying figures provide insights into the model's performance and feature importance. The feature correlation matrix (Figure 7-a) reveals the relationships between various features used in the model. Key variables include precipitation (PRCP), evapotranspiration (ET), minimum temperature (Tmin), maximum temperature (Tmax), average temperature (Tavg), and water withdrawal (WWD). High correlations are observed among temperature-related variables (Tmin, Tmax, Tavg), indicating their strong interdependence.

The feature importance plot (Figure 7-b) from the RF model shows that evapotranspiration (ET) is the most important predictor, followed by minimum temperature (Tmin), maximum temperature (Tmax), average temperature (Tavg), and precipitation (PRCP). This highlights the significance of temperature and evapotranspiration in predicting water withdrawal during the growing season. Figures 7-c and 7-d display the actual versus predicted water withdrawals for the training and test sets, respectively. In the training set (Figure 7-c), the model shows a strong alignment with the actual values, indicating good fit. However, the test set results (Figure 7-d) reveal some discrepancies, particularly at higher values, suggesting areas for model improvement and potential overfitting on the training data.

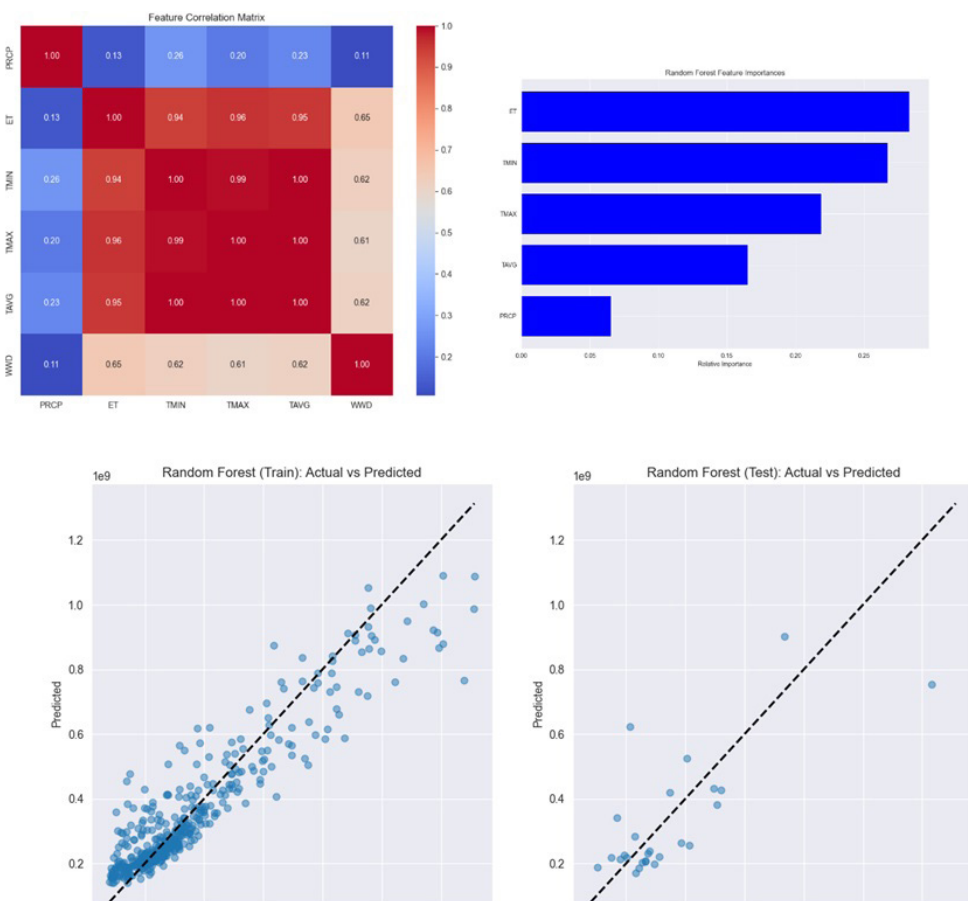


Figure 7: Analysis of Random Forest Model for Predicting Agricultural Water Withdrawal During Growing Seasons (a) Heatmap of Feature Correlation Matrix, (b) Random Forest Feature Importances, (c) Model Performance on Training Set (Actual vs. Predicted), (d) Model Performance on Test Set (Actual vs. Predicted).

Trends in Climate Variables and Water Withdrawal over Time

Figure 8 illustrates the trends in key climate variables and agricultural water withdrawal from 1980 to 2022. The average temperature shows a clear increasing trend, indicating changing climate conditions that can significantly impact agricultural practices and water needs. Precipitation levels display variability but suggest a modest overall increase. Evapotranspiration, reflecting the water transferred from land to the atmosphere, also shows an increasing trend, pointing to higher water demand from crops as temperatures rise. Water withdrawal for agricultural purposes exhibits a substantial upward trend, correlating with increases in temperature and evapotranspiration. These trends highlight the necessity of incorporating climate data into water resource management strategies to develop sustainable practices and ensure agricultural productivity in Maryland.

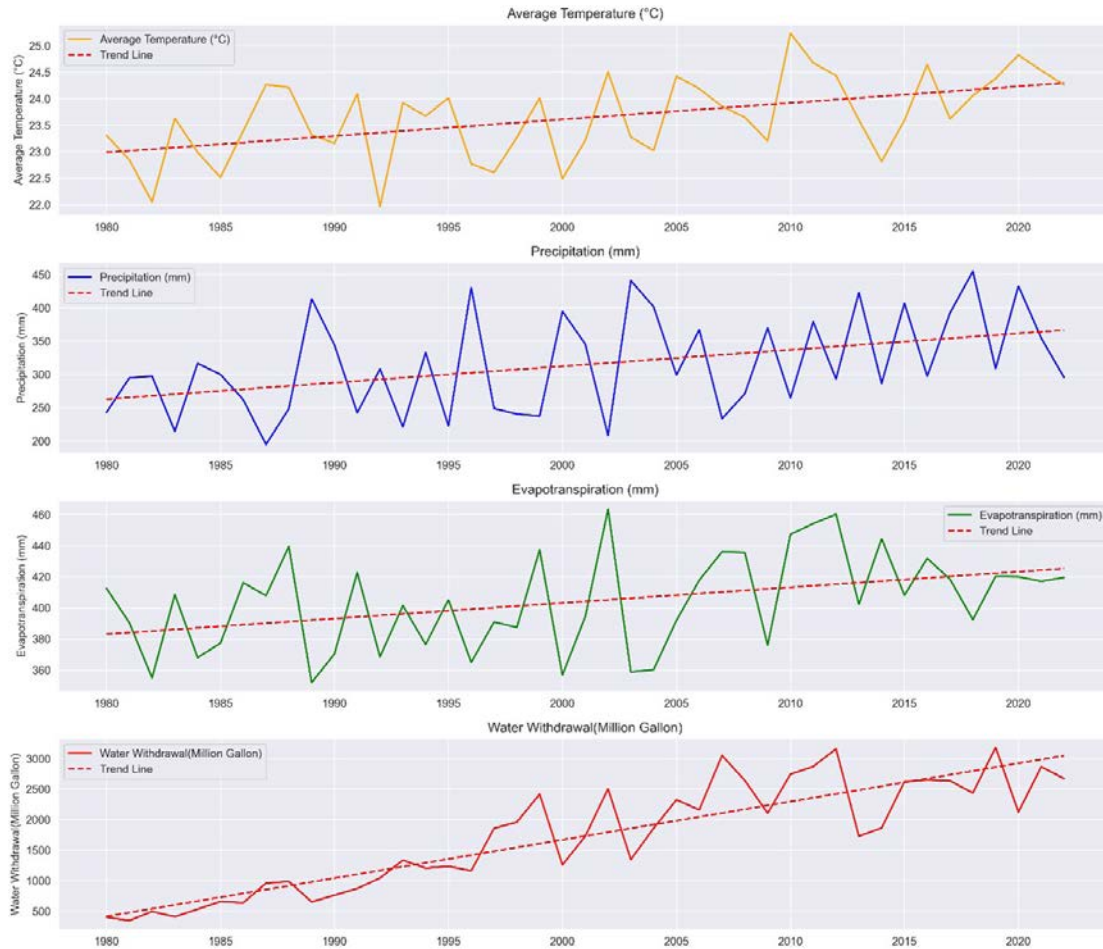


Figure 8: Trends in Average Temperature, Precipitation, Evapotranspiration, and Water Withdrawal during the Growing Season (June-August) from 1980 to 2022, with trend lines highlighting long-term changes in Maryland.

Projected Agricultural Water Withdrawal Under Different Climate Scenarios Using Machine Learning (ML) - Random Forest Analysis

Figure 9 illustrates the projected agricultural water withdrawal in Maryland under three climate scenarios: SSP126, SSP245, and SSP585, using a calibrated Random Forest (RF) model. Each scenario represents a different pathway of greenhouse gas concentrations and their impact on climate variables.

The first row of plots shows the projected average temperature (°C) for each scenario. There is a noticeable increasing trend, with SSP585 showing the highest temperature rise over time, followed by SSP245 and SSP126. The second row depicts the projected evapotranspiration (ET, mm). Similar to the temperature trends, ET increases across all scenarios, with SSP585 showing the highest increase, indicating greater water loss through evaporation and plant transpiration. The third row presents the projected precipitation (mm). While there is variability in precipitation, SSP126 shows a relatively stable trend, whereas SSP245 and SSP585 exhibit more pronounced fluctuations and slight decreasing trends. The fourth row shows the projected agricultural water withdrawal (Million Gallons). Water withdrawal increases across all scenarios, with SSP585 showing the most significant rise, reflecting the combined effects of higher temperatures and evapotranspiration. SSP245 also indicates a substantial increase, while SSP126 shows a more moderate rise. The red dashed lines in all plots represent trend lines, highlighting the overall direction of change over time. These projections underscore the increasing demand for water in agriculture due to climate change, emphasizing the importance of adaptive water management strategies to cope with future climatic conditions. By integrating climate data into predictive models, stakeholders can make informed decisions to ensure sustainable water use in Maryland's agricultural sector.

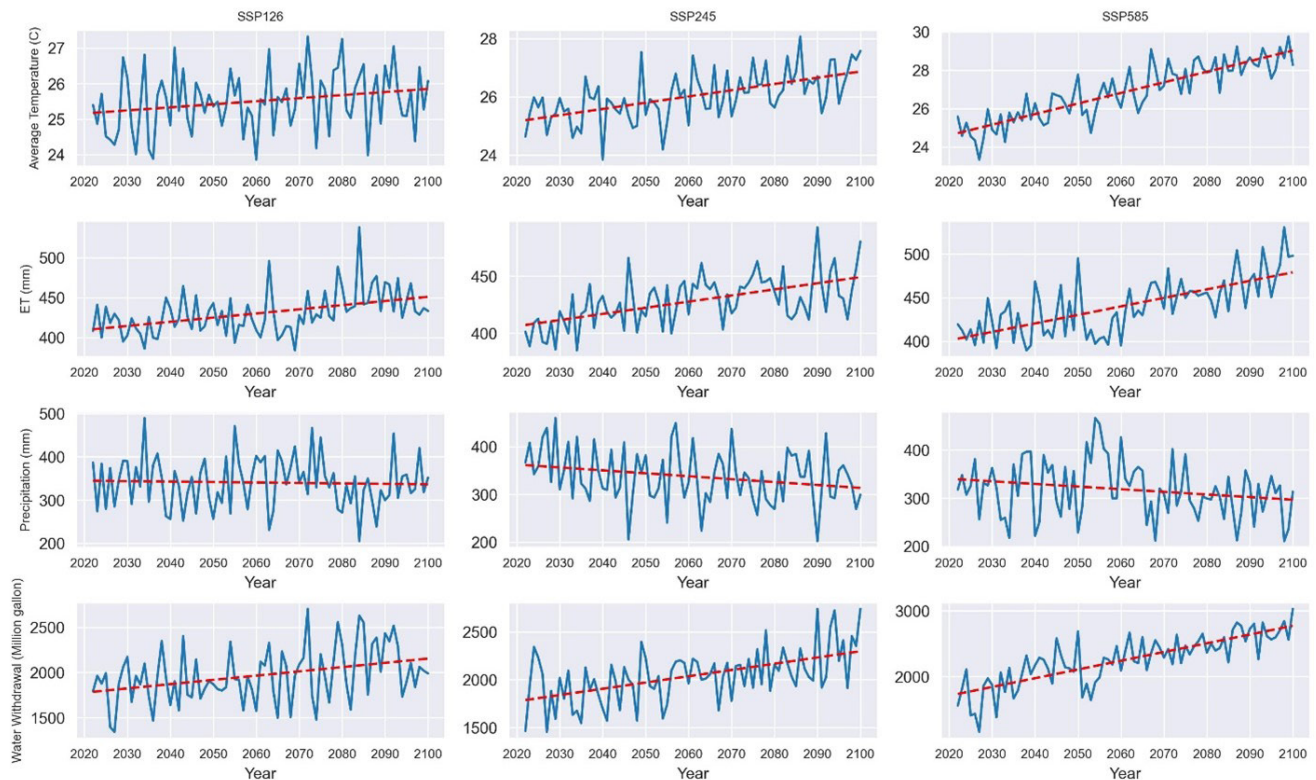


Figure 9: Average Temperature, ET, Precipitation, and Water Withdrawal across scenarios SSP126, SSP245, SSP585 for Maryland in the Growing Season. The red dashed line represents the trend line.

Given these projections, it is crucial for the state to consider implementing policies that support farmers in adapting to these changes. Potential measures include investing in efficient irrigation systems, promoting water conservation practices, and providing subsidies or incentives for adopting sustainable farming technologies. Additionally, developing comprehensive water management plans that account for future climate variability can help mitigate the risk of water shortages. By proactively addressing these issues, Maryland can help its agricultural community remain resilient and productive in the face of climate change.

CONCLUSION

Machine learning techniques have proven crucial in linking historical climate data with agricultural outcomes, providing actionable insights for future planning. However, the effectiveness of these models is heavily dependent on the availability and quality of input data. Addressing the data limitations and implementing the recommended policies will be essential for enhancing the resilience and productivity of Maryland's agricultural sector in the face of changing climate conditions.

RECOMMENDATIONS

- There is a need for more robust data collection, management, and sharing.
- We recommend that state agencies, in collaboration with state-level academic institutions and with financial support from state legislatures, make a concerted effort to collect, store, and manage data on a long-term basis for different aspects of the agroecosystem.

CHALLENGES

Lack of long-term historical data on different aspects of the agroecosystem (e.g., observed crop disease data, soil carbon, comprehensive water withdrawals data for agriculture, etc.) posed a significant limitation on artificial neural network (ANN) modeling and thus forecasting the status of climate change impacts under future scenarios for some components of the agroecosystem.

REFERENCES

- Ahmed, A. M., E. Sharma, S. J. J. Jui, R. C. Deo, T. Nguyen-Huy, and M. Ali. 2022. "Kernel Ridge Regression Hybrid Method for Wheat Yield Prediction with Satellite-Derived Predictors." *Remote Sensing* 14 (5): 1136.
- Hackeling, G. 2017. *Mastering Machine Learning with scikit-learn*. Packt Publishing Ltd.
- Jeong, J. H., J. P. Resop, N. D. Mueller, D. H. Fleisher, K. Yun, E. E. Butler, ... and S. H. Kim. 2016. "Random Forests for Global and Regional Crop Yield Predictions." *PLoS One* 11 (6): e0156571.
- Kumar, S., S. D. Attri, and K. K. Singh. 2019. "Comparison of Lasso and Stepwise Regression Technique for Wheat Yield Prediction." *Journal of Agrometeorology* 21 (2): 188-192.

Liu, Y., G. B. Heuvelink, Z. Bai, P. He, X. Xu, W. Ding, and S. Huang. 2021. "Analysis of Spatio-Temporal Variation of Crop Yield in China Using Stepwise Multiple Linear Regression." *Field Crops Research* 264: 108098.

Ravi, R., and B. Baranidharan. 2020. "Crop Yield Prediction Using XG Boost Algorithm." *International Journal of Recent Technology and Engineering* 8 (5): 3516-3520.

USDA NASS. 1979-2023. Quick Stats. <https://quickstats.nass.usda.gov/#3FF2AE19-7FE8-35D3-BA17-6>.

Ying, X. 2019. "An Overview of Overfitting and Its Solutions." In *Journal of Physics: Conference Series*, Vol. 1168, p. 022022. IOP Publishing.

Objective IV: Stakeholder Engagement

QUALTRICS SURVEY

Hughes Center, Terry Newer, Lars Olson, and Adel Shirmohammadi

SUMMARY

An internal review board (IRB)-approved survey was disseminated to stakeholders at multiple extension and commodity group meetings, and administered to 229 volunteer stakeholders. The Qualtrics survey consisted of multiple questions in five categories: demographics, plants, animals, general questions, and optional questions. Administration of the survey was not designed to capture the attitudes of a random sample of stakeholders nor for research purposes. Responses reflect the views of those who volunteered.

All Maryland counties are represented across a diverse group of stakeholders. Respondents were generally proactive in managing climate-related risks by altering production practices, with cost and risk being the primary barriers to adaptation. Pests, diseases, and inconsistent growth were the most cited issues, but a wide range of issues impacted at least some stakeholders. A longer production season, more cost-share programs, and new markets were the most frequently cited potential new opportunities.

OBJECTIVES

The objective of this section was to obtain feedback from stakeholders, assess their understanding of the impact of climate change in their agricultural production systems, and determine if they are using adaptive measures in their operations.

RESULTS

Two hundred twenty-nine respondents answered the surveys; however, many of these surveys were incomplete or contained partial responses. The minimum time respondents spent on the survey was 14 seconds. The maximum was over 21 hours. The average response time was 2 hours, 56 minutes, and the median response time was 8 minutes, 22 seconds. Below are the main conclusions gleaned from the survey.

1. All Maryland counties are represented, with Montgomery, Caroline, Cecil, and Queen Anne's County having the most out of 103 responses that listed their county. Most counties have fewer than five responses.

Montgomery	11.65%	12
Caroline	8.74%	9
Cecil	8.74%	9
Queen Anne's	7.77%	8

2. Distribution of Occupations (87 responses)

Occupation	Primary Occupation		Secondary Occupation		Total
Farmer/Producer	72.00%	54	28.00%	21	75
Other (please specify:)	62.50%	10	37.50%	6	16
Agribusiness	58.33%	7	41.67%	5	12
Farm Consultant	44.44%	4	55.56%	5	9
Animal Processor	40.00%	2	60.00%	3	5
Extension	100.00%	5	0.00%	0	5
Integrator	25.00%	1	75.00%	3	4
Shellfish/Aquaculture	25.00%	1	75.00%	3	4
Commodity Group	33.33%	1	66.67%	2	3
Commodity Specialist	66.67%	2	33.33%	1	3
Waterman	0.00%	0	100.00%	3	3

3. Top Ag/Farm Organization Memberships

Total	100%	115
Maryland Farm Bureau	32.17%	37
Delmarva Chicken Association	10.43%	12
Future Harvest	10.43%	12
Specify unlisted organization (environmental, crop, etc.)	9.57%	11
Does not apply	8.70%	10
Maryland Grain Producers Association	6.09%	7
Maryland State Horticultural Society	5.22%	6
Specific Animal Breed Association (specify)	4.35%	5

4. Several sectors have few responses.

Seafood/Shellfish	2
Dairy Cattle	5
Goats	6
Swine	9
Sheep	10
Forestry	10
Commercial Broiler Operations	14

5. For all animals (combined), the main weather-related perceptions are that the grazing season has lengthened, and muddy conditions have somewhat increased.

6. Strategies to manage flooding/drainage

Answer	%	Count
Cover Cropping	19.86%	28
I do not have any flooding or drainage issues	19.15%	27
Drainage Ditches	17.02%	24
Title Drains	9.93%	14
Installation of grass swales	8.51%	12
Runoff and Sediment Ponds	7.09%	10
Berms	5.67%	8
Spinner Ditches	4.96%	7
Please specify other drainage systems:	4.26%	6
Box Drains	2.84%	4
Flood Control Gates	0.71%	1
Levees	0.00%	0

7. Saltwater intrusion/tidal flooding

Is saltwater intrusion (SWI) a problem on your property?

Answer	%	Count
1. No, SWI is not a problem for me.	87.72%	50
2. SWI only impacts a small portion of my land.	7.02%	4
3. SWI has a moderate impact on my land.	3.51%	2
4. SWI has a major impact on my land.	1.75%	1
Total	100%	57

Is tidal flooding a problem on your land?

Answer	%	Count
1. Definitely not	81.36%	48
2. Every once in a while, maybe with a heavy storm.	11.86%	7
3. I get tidal flooding at least once a month.	3.39%	2
4. Tidal flooding occurs most or all of the time on some of my land.	3.39%	2
Total	100%	59

8. Barriers to adopting new practices

Barrier	Somewhat Agree		Strongly Agree		Total
Capital to purchase	37.31%	25	49.25%	33	67
Upfront costs (equipment, fuel, seed, etc.)	38.81%	26	49.25%	33	67
Time constraints	49.23%	32	29.23%	19	65
Access to credit and financial/grant programs	27.27%	18	27.27%	18	66
Increased regulation	47.76%	32	26.87%	18	67
Amount of risk involved	58.21%	39	25.37%	17	67
Knowledge level	41.45%	27	23.08%	15	65
Lack of technical assistance	33.85%	22	20.00%	13	65
Access to insurance programs	25.76%	17	16.67%	11	66
Access to markets	27.69%	18	10.77%	7	65
Other (please specify)	20.00%	2	50.00%	5	10

9. Opportunities for farming as a result of predicted changes in climate

- **Not likely:** Increased yield and agritourism (23 and 21 responses)
- **Somewhat Likely or Likely:** All possible responses ranging from 21 to 41 responses, with 41 responses for a longer production season.

10. Irrigation systems used

Answer	%	Count
I do not use irrigation.	47.73%	42
Drip	22.73%	20
Center Pivot	12.50%	11
Movable Pipes and/or Sprinklers	10.23%	9
Center Pivot with high-pressure spray, MESA, LESA, or LEPA	2.27%	2
Flood or Ditch Irrigation	2.27%	2
Other (please specify)	2.27%	2

11. Weather-related plant damage

- The most frequent response for all damage categories is “No change observed.”
- Decreased pollinator levels is the only response where decrease outnumbers increase.
- Increases were most reported for disease pressure and changes in the timing and level of insects, but still lower than no change observed.

12. Weather impacts over the past five years

Question	Does not apply		Strongly disagree		Disagree		No change		Agree		Strongly agree		Total
	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	
Due to extreme or abnormal weather events, I've been more likely to alter crop management practices (including planting dates, harvesting, tillage, etc.).	7.55%	4	0.00%	0	1.89%	1	20.75%	11	56.60%	30	13.21%	7	53
Frosts in my area are occurring later into the fall.	5.88%	3	0.00%	0	7.84%	4	23.53%	12	50.98%	26	11.76%	6	51
Spring (March to May) temperature swings are causing production issues for my crops.	5.88%	3	0.00%	0	0.00%	0	35.29%	18	50.98%	26	7.84%	4	51
Spring rain events have shortened my time window for spring planting and fertilization.	5.88%	3	0.00%	0	11.76%	6	25.49%	13	43.14%	22	13.73%	7	51
Spring seems to come earlier each year.	3.85%	2	3.85%	2	19.23%	10	25.00%	13	36.54%	19	11.54%	6	52
My crop yields have increased due to changing weather conditions.	3.85%	2	0.00%	0	15.38%	8	48.08%	25	25.00%	13	7.69%	4	52
The hardiness of some of the plant varieties I grow is not suitable for the changing weather.	15.38%	8	3.85%	2	15.38%	8	36.54%	19	25.00%	13	3.85%	2	52

Question	Does not apply		Strongly disagree		Disagree		No change		Agree		Strongly agree		Total
	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	
Erosion has increased on my farm.	3.85%	2	1.92%	1	21.15%	11	44.23%	23	17.31%	9	11.54%	6	52
Water in irrigation ponds or ditches is in short supply due to a lack of precipitation.	40.38%	21	9.62%	5	7.69%	4	23.08%	12	15.38%	8	3.85%	2	52
I have experienced difficulty accessing groundwater with my irrigation due to a lack of precipitation.	38.46%	20	11.54%	6	5.77%	3	30.77%	16	11.54%	6	1.92%	1	52
Salinity levels in my soil affect the type of crops (if any) I can plant.	40.38%	21	3.85%	2	5.77%	3	36.54%	19	11.54%	6	1.92%	1	52
Coastal flooding has increased.	50.98%	26	1.96%	1	1.96%	1	19.61%	10	9.80%	5	15.69%	8	51
The threat of wildfire has increased for my farm.	23.08%	12	9.62%	5	11.54%	6	40.38%	21	5.77%	3	9.62%	5	52

13. Changes in pest condition over the past five years

Question	Does not apply		Don't Know What This Is		Strongly Disagree		Somewhat Disagree		No Opinion		Somewhat Agree		Strongly agree		Total
	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	
Nematodes have increased and/or caused more issues for my crops.	7.84%	4	11.76%	6	5.88%	3	7.84%	4	29.41%	15	29.41%	15	7.84%	4	51
I have seen new insect pests in my crops.	8.00%	4	4.00%	2	4.00%	2	14.00%	7	14.00%	7	44.00%	22	12.00%	6	50
The pressure from insect pests has increased.	2.00%	1	4.00%	2	2.00%	1	24.00%	12	8.00%	4	46.00%	23	14.00%	7	50
The timing of insect pests' appearance has changed.	5.88%	3	1.96%	1	1.96%	1	13.73%	7	25.49%	13	29.41%	15	21.57%	11	51
I have had new weed species appear.	4.00%	2	0.0%	0	6.00%	3	8.00%	4	24.00%	12	32.00%	16	26.00%	13	50
I have seen new plant diseases occur.	7.84%	4	1.96%	1	1.96%	1	19.61%	10	25.49%	13	33.33%	17	9.80%	5	51
I have had increased pressure from plant diseases.	7.84%	4	0.0%	0	5.88%	3	21.57%	11	15.69%	8	37.25%	19	11.76%	6	51
The growing environment favors plant diseases appearing earlier or more frequently.	5.88%	3	1.96%	1	5.88%	3	7.84%	4	27.45%	14	39.2%	20	11.76%	6	51
Other (specify)	40.00%	2	0.0%	0	20.00%	1	0.0%	0	0.0%	0	0.0%	0	40.00%	2	5

14. Challenge for animal raising over the past five years

Question	Does not apply		Don't Know What This Is		Strongly Disagree		Somewhat Disagree		No Change		Somewhat Agree		Strongly agree		Total
	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	
The length of the overall grazing season has gotten longer.	25.00%	7	0.0%	0	0.0%	0	7.14%	2	17.86%	5	28.57%	8	21.43%	6	28
I have observed an increase in the amount of erosion.	10.71%	3	3.57%	1	14.29%	4	14.29%	4	32.14%	9	14.29%	4	10.71%	3	28
Flooding and/or muddy conditions have become more frequent.	7.14%	2	0.0%	0	7.14%	2	10.71%	3	28.57%	8	32.14%	9	14.29%	4	28
Heat stress in my animals has increased.	3.57%	1	3.57%	1	14.29%	4	7.14%	2	42.89%	12	14.29%	4	14.29%	4	28
I have had more weather-related disease and/or parasite issues.	3.57%	1	3.57%	1	17.86%	5	7.14%	2	53.57%	15	3.57%	1	10.71%	3	28
The reproductive capacity (number of live births, successful breeding, etc.) of my animals has decreased.	37.04%	10	3.70%	1	7.41%	2	0.0%	0	29.63%	8	14.81%	4	7.41%	2	27
I may switch to more heat tolerant breeds.	22.22%	6	3.70%	1	7.41%	2	0.0%	0	51.85%	14	7.41%	2	7.41%	2	27

15. Impacts of changing weather patterns on woodlands

Answer	%	Count
Increased pressure from invasive species	23.81%	5
Increased tree-fall from storms	14.29%	3
Changes in disease pressure	19.05%	4
Salt water intrusion	0.00%	0
Die-off, species decline	19.05%	4
Drainage/flooding issues	14.29%	3
Other (specify)	4.76%	1
I haven't observed any changes due to weather.	4.76%	1
Total	100%	21

16. Cecil and Queen Anne's County have the highest response rates among the counties where responders actively make recommendations, out of a total of 59 responses.

Cecil	10.17%	6
Queen Anne's	10.17%	6

17. Service provided by consultants, extension, and service providers

Answer	%	Count
Fertilizer sales	19.51%	8
Seed sales	14.63%	6
Crop protection sales	12.20%	5
Agronomic consulting	21.95%	9
Economic/marketing consulting	4.88%	2
Data management	7.32%	3
Custom application	4.88%	2
Equipment sales	4.88%	2
Please specify if other	9.76%	4
Total	100%	41

18. Weather-related impacts on farmer observed by service providers

The most climate-related issues include change in weather patterns, increased insect and pathogen pressure, lack of freezing, and soil erosion.

19. Weather-related risk practices used in the past two years

Question	No		Yes		Total
	%	Count	%	Count	
Cover crops	9.43%	5	90.57%	48	53
Crop rotation	15.38%	8	84.62%	44	52
Double cropping	38.46%	20	61.54%	32	52
Wide row or skip-row spacing	64.71%	33	35.29%	18	51
Reduced tillage or no-till	9.43%	5	90.57%	48	53
Soil and foliar testing	18.52%	10	81.48%	44	54
High tunnels	68.63%	35	31.37%	16	51
Crop protection (row covers, shade cloth, or low tunnels)	63.46%	33	36.54%	19	52

Question	No		Yes		Total
Use of alternative water sources (e.g., treated water from the Waste Water Treatment Plants - WWTP) for irrigation of non-food crops	90.38%	47	9.62%	5	52
Frost prevention systems	75.00%	39	25.00%	13	52
Increased use of grafting for plant hardiness	88.46%	46	11.54%	6	52
Use of different soil additives and/or mulching (wood or plastic)	53.85%	28	46.15%	24	52
Changes in planting density	51.92%	27	48.08%	25	52
Other (specify)	50.00%	5	50.00%	5	10

20. Best management practices (BMPs) used in the last two years

Question	I do not know	No		Yes		Total	
Rainwater collection systems, drains, or ponds for irrigation	0.00%	0	50.88%	29	49.12%	28	57
Flood gates and/or berms	3.85%	2	75.00%	39	21.15%	11	52
Stormwater and erosion management systems such as sediment ponds and grass strips	1.64%	1	37.70%	23	60.66%	37	61
Marginal land removed from production	1.82%	1	52.73%	29	45.45%	25	55
Non-renewal of lease for land that is no longer productive	5.88%	3	86.27%	44	7.84%	4	51
Forest stand improvement	5.66%	3	58.49%	31	35.85%	19	53
Silviculture/agroforestry	9.62%	5	71.15%	37	19.23%	10	52
Prescribed grazing	3.70%	2	66.67%	36	29.63%	16	54
Other (please specify)	16.67%	2	33.33%	4	50.00%	6	12

21. Service providers' views on barriers hindering farmer adoption of new technologies and practices

Question	Have not heard of this		Strongly disagree		Somewhat disagree		No opinion		Somewhat agree		Strongly agree		Total
	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	
Access to markets	0.00%	0	15.38%	2	7.69%	1	7.69%	1	46.15%	6	23.08%	3	13
Increased regulation	0.00%	0	0.00%	0	15.38%	2	0.00%	0	61.54%	8	23.08%	3	13
Amount of risk involved	0.00%	0	0.00%	0	7.69%	1	23.08%	3	46.15%	6	23.08%	3	13
Capital to purchase	0.00%	0	0.00%	0	0.00%	0	0.00%	0	30.77%	4	69.23%	9	13
Time constraints	0.00%	0	0.00%	0	7.69%	1	15.38%	2	46.15%	6	30.77%	4	13
Lack of technical assistance	0.00%	0	0.00%	0	38.46%	5	7.69%	1	38.46%	5	15.38%	2	13
Access to insurance programs	0.00%	0	0.00%	0	30.77%	4	46.15%	6	7.69%	1	15.38%	2	13
Knowledge level	7.14%	1	0.00%	0	0.00%	0	21.43%	3	57.14%	8	14.29%	2	14
Upfront costs (equipment, fuel, seed, etc.)	0.00%	0	0.00%	0	7.69%	1	0.00%	0	30.77%	4	61.54%	8	13
Access to credit and financial/grant programs	0.00%	0	0.00%	0	38.46%	5	7.69%	1	30.77%	4	23.08%	3	13
Other (please specify)	20.00%	1	0.00%	0	0.00%	0	40.00%	2	20.00%	1	20.00%	1	5

22. Technologies used in the last two years

Answer	%	Count
Variable rate planters	8.33%	8
Variable rate fertilizer applicators	11.46%	11
Yield monitoring equipment	16.67%	16
Drone use	6.25%	6
Precision Irrigation (high pressure spray, MESA, LESA, LEPA)	1.04%	1
Remote sensing via a mobile device (irrigation, weather, etc.)	6.25%	6
Remote irrigation monitoring via cell phone or computer	9.38%	9
Weather monitoring station and/or weather modeling	14.58%	14
Other (specify)	3.13%	43
Does not apply	22.92%	22
Total	100%	96

23. Animal focused BMPs used in the past two years

Answer	%	Count
Generator capacity	12.61%	15
Renewable energy sources	3.36%	4
Ventilation systems to cool and/or warm animals	11.76%	14
Misting system or sprinklers in my barn or gathering areas	6.72%	8
Extra insulation to buildings for temperature management	5.04%	6
Pasture irrigation systems	1.68%	2
Smart monitoring systems for my barns	4.20%	5
Shade structures to manage heat stress in animals (shelters, trees, wallows, etc.)	9.24%	11
Intensive pasture management and rotation	8.40%	10
Soil and nutrient management for pastures	12.61%	15
New pasture seed mixes	6.72%	8
Erosion control practices (such as stream crossings and fencing along streams)	7.56%	9
Enhanced footing or matting in high animal traffic areas to prevent slippage/falls	3.36%	4
Expanded manure management (storage, tarping, etc.)	5.88%	7
Other (please specify)	0.84%	1
Total	100%	119

24. Currently used BMPs for Saltwater Intrusion

Answer	%	Count
Relocating wells to area less prone to SWI	3.51%	2
Use of subsurface dam	1.75%	1
Use of subsurface drainage	5.26%	3
Taken affected land out of production	7.02%	4
Planting salt resistant crops	3.51%	2
Other (please specify)	1.75%	1
Use of dikes or breakwaters	0.00%	0
Installation of living shoreline	3.51%	2
Installation of rip-rap	1.75%	1
SWI is not a problem for me.	71.93%	41
Total	100%	57

25. Water persistence

Answer	%	Count
Flooding is present for a short time after a heavy rain event but quickly drains away in a few hours.	43.06%	31
Flooding is persistent after a heavy rain and takes 1-3 days to drain away.	29.17%	21
Flooding is persistent after a heavy rain and remains for several days.	6.94%	5
Does not apply	20.83%	15
Total	100%	72

26. Strategies for flooding and drainage problem in the next five years

Answer	%	Count
I do not have any flooding or drainage issues.	16.79%	23
Tile Drains	11.68%	16
Box Drains	2.92%	4
Drainage Ditches	9.49%	13
Berms	8.76%	12
Runoff and Sediment Ponds	6.57%	9
Spinner Ditches	3.65%	5
Flood Control Gates	2.19%	3
Levees	0.73%	1
Please specify other drainage systems:	4.38%	6
Installation of grass swales	16.06%	22
Cover Cropping	16.79%	23
Total	100%	137

27. Benefits from BMPs

Question	Does not apply		Don't Know What This Is		Strongly Disagree		Somewhat Disagree		No Change		Somewhat Agree		Strongly agree		Total
	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	
Rainwater collection systems, drains, or ponds for irrigation	21.54%	14	0.00%	0	4.62%	3	1.54%	1	20.00%	13	29.23%	19	23.08%	15	65
Flood gates and/or berms	31.75%	20	0.00%	0	3.17%	2	6.35%	4	33.33%	21	17.46%	11	7.94%	5	63
Stormwater and erosion management systems such as sediment ponds and grass strips	18.46%	12	0.00%	0	3.08%	2	3.08%	2	15.38%	10	38.46%	25	21.54%	14	65
Marginal land removed from production	26.56%	17	0.00%	0	10.94%	7	4.69%	3	26.56%	17	25.00%	16	6.25%	4	64
Non-renewal of lease for land that is no longer productive	43.55%	27	0.00%	0	4.84%	3	4.84%	3	32.26%	20	11.29%	7	3.23%	2	62
Forest stand improvement	30.16%	19	1.59%	1	3.17%	2	1.59%	1	23.81%	15	20.63%	13	19.05%	12	63
Silviculture/agroforestry	38.10%	24	4.76%	3	3.17%	2	3.17%	2	23.81%	15	11.11%	7	15.87%	10	63
Prescribed grazing	39.68%	25	0.00%	0	4.76%	3	1.59%	1	23.81%	15	14.29%	9	15.87%	10	63
Other (please specify)	25.00%	3	0.00%	0	0.00%	0	0.00%	0	25.00%	3	8.33%	1	41.67%	5	12

RECOMMENDATIONS

- Increased technical and financial assistance to reduce risk and up-front costs would help increase implementation of adaptation practices and strategies.
- Improved stakeholder engagement would provide better and more reliable information regarding stakeholder needs and attitudes.

CHALLENGES

Many of the survey responses were incomplete or partial responses. Many sectors are not well represented, which severely limits the usefulness of the data for those sectors. In general, the number of survey responses and their incomplete nature provides only limited data on the perceptions of agricultural stakeholders in Maryland. Interpretation is difficult for questions with many options and few responses. Responses are often spread across options with only a few respondents selecting each option. Such responses identify that at least one respondent had a perception or faced an issue that may not be representative of a more broadly held experience.

Research Team

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1. College of Agriculture and Natural Resources, University of Maryland College Park

2. University of Maryland Center for Environmental Science

3. University of Maryland Eastern Shore

Appendix 2: Summary of Farmer and Stakeholder Outreach

Supplemental budget language passed in the 2021 Maryland General Assembly required the University of Maryland (UMD) Harry R. Hughes Center for Agro-Ecology, the Maryland Department of Agriculture, and the Maryland Department of the Environment to work together and develop a report that details the process and strategy to assess the vulnerability of Maryland agriculture to climate change. This core team expanded to include additional scientists from the UMD College of Agriculture and Natural Resources and the U.S. Department of Agriculture's Northeast Climate Hub on this initiative due to the technical nature of the report. The team also enlisted the voices of a farmer, the Department of Natural Resources, and the Chesapeake Bay Commission. This team is called the Project Leadership Team, and it guided the development and creation of the resulting report, titled "The Study in Preparation for a Maryland Agriculture Climate Vulnerability Assessment," which was released in February 2022 and detailed a two-year process to develop a full assessment. During the 2022 Maryland General Assembly, at the request of the PLT, the governor's budget included \$500,000 to fund the full assessment. Since 2022, the PLT has expanded to include more farmer voices representing the diversity of the Maryland agriculture community, and the project was rebranded as the "Roadmap to Resilience: A Report on Maryland Climate-Smart Agriculture."

Upon receiving funding from the governor's budget, the Hughes Center searched for and hired a coordinator in January 2023 to manage the "Roadmap to Resilience: A Report on Maryland Climate-Smart Agriculture." This coordinator was employed for 18 months and served as the project's primary contact, spending the majority of the time reaching out directly to the agriculture community, getting feedback on how climate impacts their operations and gauging their needs for response strategies. This feedback was received during dozens of conferences, presentations, special meetings, and private conversations. The coordinator also conducted an anecdotal survey that received 229 responses from farmers and agricultural service providers across Maryland. The PLT oversaw the coordinator's effort to inform this report and ensure that science, recommended policies, and programs respond directly to farmers' needs.

Conferences, listening sessions, University of Maryland Extension events and meetings where stakeholder feedback was gathered include:

1. Future Harvest Conference Farmer Listening Session (January 2023)
2. Maryland Association of Soil Conservation Districts Conference (August 2023)
3. University of Maryland College of Agriculture and Natural Resources Cornerstone Event (October 2023)
4. Forever Maryland, Maryland Land Conservation Conference (October 2023)
5. Forests and Forestry in Maryland (November 2023)
6. Chesapeake Watershed Forum (November 2023)

7. Rural Maryland Summit (November 2023)
8. Washington County Agronomy Day (November 2023)
9. Southern Maryland Crops Conference (December 2023)
10. Northern Maryland Field Crops Day (December 2023)
11. Maryland Farm Bureau Convention (December 2023)
12. State Soil Conservation Committee Meeting (December 2023)
13. Meeting with Southern Maryland Agricultural Development Commission (January 2024)
14. Meeting with MARBIDCO (Maryland Agricultural and Resource-Based Industry Development Corporation) (January 2024)
15. Central Maryland Vegetable Growers Meeting (January 2024)
16. Lower Shore Agronomy Day (January 2024)
17. Urban Farmer Winter Meeting (January 2024)
18. Mid-Atlantic Fruit and Vegetable Convention (January 2024)
19. Mar-Del Watermelon Convention (February 2024)
20. Delmarva Soil Summit (February 2024)
21. Cecil County Winter Agronomy Meeting (February 2024)
22. Harford County Mid-Winter Agronomy Meeting (February 2024)
23. Eastern Shore Pest Management Conference (February 2024)
24. Eastern Shore Vegetable Growers Meeting (February 2024)
25. Central Maryland Agronomy Update Meeting (February 2024)
26. Mid-Shore Agronomy Meeting (February 2024)
27. Western Maryland Regional Fruit Meeting (February 2024)
28. Meeting with Grain Producers Utilization Board (February 2024)
29. Queen Anne's County Agronomy Day (March 2024)
30. Meeting with Maryland Soybean Board (March 2024)
31. Meeting with Chesapeake Bay Foundation (March 2024)
32. Meeting with Future Harvest (March 2024)
33. Meeting with Chesapeake Bay Trust (March 2024)
34. Meeting with Maryland Nursery, Landscape and Greenhouse Association (March 2024)
35. Meeting with Delmarva Chicken Association (March 2024)
36. Urban Agriculture Farmer Listening Session (April 2024)
37. Online Farmer Listening Session (May 2024)
38. Lower Eastern Shore Farmer Listening Session (May 2024)
39. Central/Northern Maryland Farmer Listening Session (June 2024)
40. Maryland International Agriculture Conference (October 2024)
41. University of Maryland Eastern Shore Small Farms Conference (November 2024)

During the development of the report, the PLT developed a request for proposals, which was released in February 2023. The proposal offered a science-based review of the impacts of changing climatic conditions on Maryland agriculture, as documented in this report, and was funded in March 2023. The research team comprised a dozen researchers and extension specialists with diverse expertise in crop and animal production systems, soil science, water resources and hydrology, climatology, and agricultural resource economics from three different state institutions (UMD, University of Maryland Eastern Shore and the University of Maryland Center for Environmental Science). The research team completed the Technical Research Report (Appendix One) in June 2024, after which the writing of the "Roadmap to Resilience" began based on scientific research and stakeholder feedback.



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