United States Department of Agriculture

Research, Education, and Economics
Agricultural Research Service

National Program 305
Crop Production
Action Plan
2024-2029

Table of Contents

Vision

The vision for the ARS National Program for Crop Production (NP305) is to enable the full realization of the genetic potential in crop cultivars by using optimal crop production management, and to develop crops and cropping systems that are safe from pests and diseases. This will increase crop yields, product quality, and producer profits, and protect pollinators and the environment (Figure 1).

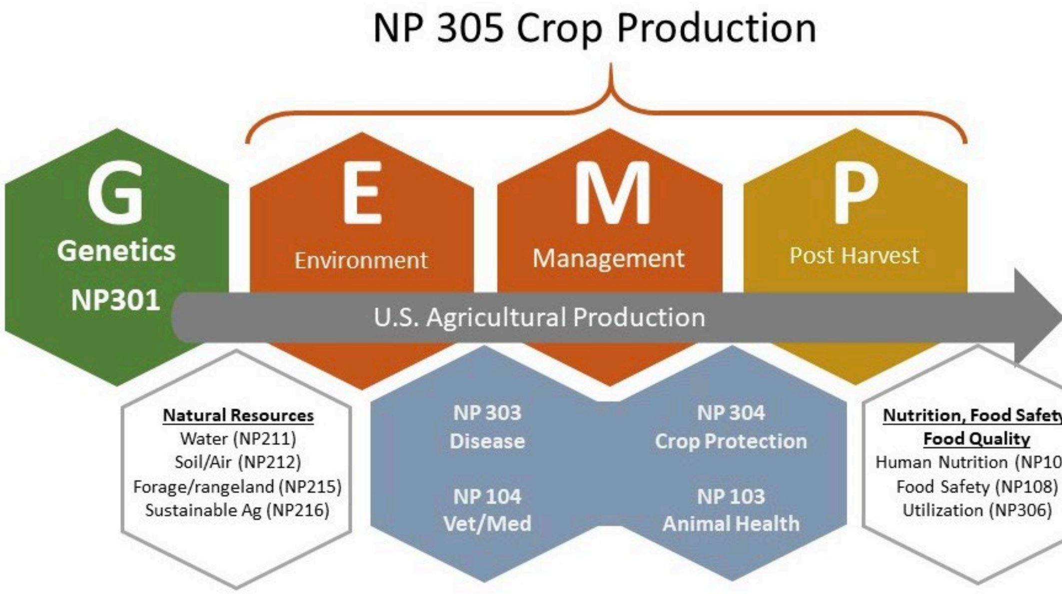

Figure 1: General model for agricultural research components in NP305. Genetics research (G) maximizes genetic potential of crop plants through breeding. Environment (E) includes the conditions under which crops are grown, i.e., climate, weather, soil, air, water, and other agroecosystem components. Management (M) is the role of the farmer to manipulate the environment for producing the highest crop yield and quality based on a plant's genetic potential. Postharvest (P) refers to post-field production and processing research for food safety, security, and product use.

Mission

The mission of NP305 is to enhance U.S. agricultural crop productivity, efficiency, and sustainability, and ensure a high quality and safe supply of food, fiber, feed, and ornamental and industrial crops for the United States. NP305 research also includes solving challenges in agricultural production associated with sustaining the health, diversity, and abundance of critical plant pollinators.

Relationship of this National Program to the USDA Strategic Plan *USDA Science and Research Strategy for FY 2023-2026*

This Action Plan outlines research that supports primarily the following objectives in the *USDA Science and Research Strategy for FY 2023-2026*:

- Priority 1 – Accelerating Innovative Technologies & Practices
  - Objective 1.5 – Create technologies suitable for use across diverse scales, systems, types, and locations of farms.
- Priority 2 – Driving Climate-Smart Solutions
  - Objective 2.2 – Enhance research and technology development and improve the technical GHG mitigation potential of agriculture and forestry sectors to reduce GHG emissions, sequester carbon, and generate low-carbon sources of energy.

  - Objective 2.3 – Position the agricultural sector to be resilient in the face of climate change. Expand equitable, climate-smart technologies, approaches, and field-based practices to help producers, ranchers, and forest landowners adapt to the consequences of climate change.
  - Objective 2.5 – Conduct science that supports sustainable markets for agriculture and forest bioproducts and clean energy to identify potential for new revenue streams and drive sustainable economies and supply chains with reduced waste and GHG emissions.
- Priority 4 – Cultivating Resilient Ecosystems
  - Objective 4.1 – Determine the DNA sequences of plant and animal genomes and use this information to apply molecular biology techniques, such as genome editing and other advanced breeding methods, to improve sustainability through research, including leveraging public-private partnerships and open science approaches.
  - Objective 4.3 – Sustainable Agro- and Aquatic Ecosystems: Restore and improve resiliency of agro- and aquatic ecosystems by accelerating the adoption of sustainable agricultural systems that are transformative, diversified, and integrated (e.g., integrated crop-livestock, crop-aquaculture, perennial, and agroforestry systems), and recognizing the need for sustainable inputs.
  - Objective 4.5 – Biodiversity: Identify and enable the adoption of practices that demonstrably conserve or improve biodiversity, improve air quality, improve water quality and retention, enhance carbon sequestration, and protect pollinator populations.

Relationship of this National Program to the ARS Strategic Plan

Research outlined in this Action Plan supports Program Area 3, Crop Production and Protection, in the 2023-2026 ARS Strategic Plan. NP305 research specifically aligns with ***Strategic Goal 4: Make Safe, Nutritious Food Available to All Americans.***

Introduction

Sustainable U.S. crop production includes both economic and environmental factors and requires new technologies and advanced knowledge and methods. This is because input costs, such as energy, water, nutrients, pesticides, and labor, are increasing. Simultaneously, the availability of arable land is declining due to urbanization; and climate change is posing a myriad of challenges to crop production. A systems approach is necessary because new production strategies must be economically, environmentally, and socially sustainable. Research products that are needed include information and decision support tools such as software and dashboards, improved technology such as more efficient spray systems, and accurate and reliable sensors. Information and tools must be integrated into overall production systems for new, alternative, and conventional crops and crop sequences, and rapidly transferred to growers. As the mechanism for delivering the genetic potential of crops from "seed to table", NP305 research must continually be refocused to support the research and development needs of changing production systems, climate patterns, environmental shifts; economic drivers affecting U.S. farmers; advances in plant breeding, genetics, and pest management (weeds, insects, and pathogens); and product quality and use.

An integral component of NP305 research includes bee pollination research. The honey bee (*Apis mellifera*) is the pollinator most often managed for commercial crop pollination. Bee populations continue to suffer significant losses from pests, pathogens, pesticides, and poor nutrition—factors that are intensified by climate change and other stressors. Beekeepers have needed to adopt new management strategies to maintain honey bee health and to compensate for the increase in colony losses in order to meet pollination service demands. New techniques and tools are needed for managing honey bee diseases and pests and ensuring that sustainable population levels can be maintained to maximize colony readiness and meet pollination needs. There is also an important need to conserve and commercially develop non-*Apis* bees (all bees other than honey bees), which are effective pollinators of crops such as alfalfa, oilseeds, tree fruits, and greenhouse produce. As part of that goal, NP305 seeks to maintain bee pollinator health and encourage the proper management of pollinators and honey production. NP305 supports research to develop knowledge, strategies, systems, and technologies for a diversity of crops in a range of production systems that are climate smart, promote pollinator health, and improve environmental quality and worker safety.

The NP305 Action Plan focuses on the most critical issues and needs of U.S. production agriculture. It comprises two major Research Components: Climate-Smart Sustainable Crop Production Systems; and Healthy, Productive, Diverse, and Sustainable Pollinator Populations. Anticipated research products for one component are often vital to the success of research conducted under the other. Each Research Component includes Problem Statements that were formulated in part from interactions with various stakeholder groups, including 5-year Retrospective Review panel members; Federal partners and stakeholders from USDA, including National Institute for Food and Agriculture (NIFA), Animal and Plant Health Inspection Service (APHIS), Economic Research Service (ERS), Agricultural Marketing Service (AMS); and U.S. Forest Service (FS); commodity and professional organizations; and academia.

Within ARS, NP305 aligns with and often contributes to other National Programs (National Programs: USDA ARS), including:

- Incorporating advances in crop genetics (NP301, Plant Genetic Resources, Genomics and Genetic Improvement)
- Incorporating advances in plant disease management (NP303, Plant Diseases)
- Pest and weed mitigation in agricultural production (NP304, Crop Protection and Quarantine)
- Postharvest research on dietary choices (NP107, Human Nutrition)
- Food waste, transport, and safety (NP108, Food Safety)
- Product uses (NP306, Product Quality and New Uses)
- Technology for managing water quality and quantity needed for agricultural production and ecosystem services (NP211, Water Availability and Watershed Management)
- Soil health, efficient nutrient management, air quality, and adaptation to the effects of changing weather patterns (NP212, Soil and Air)
- Strengthening agroecosystems and enhancing natural resource stewardship (NP216, Sustainable Agricultural Systems Research)

In developing the Action Plan, we considered the following challenges:

- Balancing stakeholder and partner needs with fiscal and personnel resources;
- Recognizing and addressing climate change factors that affect sustainable crop production and pollination;
- Ensuring research provides accomplishments that have an effect and can be translated into practice through technology transfer;
- Collaborating nationally and internationally and focusing on relevant issues to ensure targeted areas are addressed;
- Ensuring NP305 has the capacity to respond when research is needed to address unexpected, emerging, or urgent needs and/or issues; and
- Recognizing the Action Plan remains a living document subject to review and realignment when and where required or appropriate.

Component 1: Climate-Smart Sustainable Crop Production Systems

This component encompasses ARS efforts to improve existing and develop new production systems for current and emerging crops. Production systems are complex and depend on the integration of multiple management components. Innovative technologies, methods, and strategies are vital to maintaining and improving productivity and profitability of cropping systems that adapt to and/or mitigate climate change while conserving energy and natural resources (i.e., climate-smart practices), and promoting agroecosystem services to confer sustainability across the agricultural landscape, including marginal lands and urbanized environments.

The focus of Component 1 research is to better understand key factors that limit crop production of new and economically important agronomic and specialty crops grown in diverse production systems from open fields to protected culture systems or controlled environment agriculture (e.g., greenhouses, shade houses, high and low tunnels, and vertical farming) that provide some protection from environmental extremes, pests, and pathogens (Figure 2).

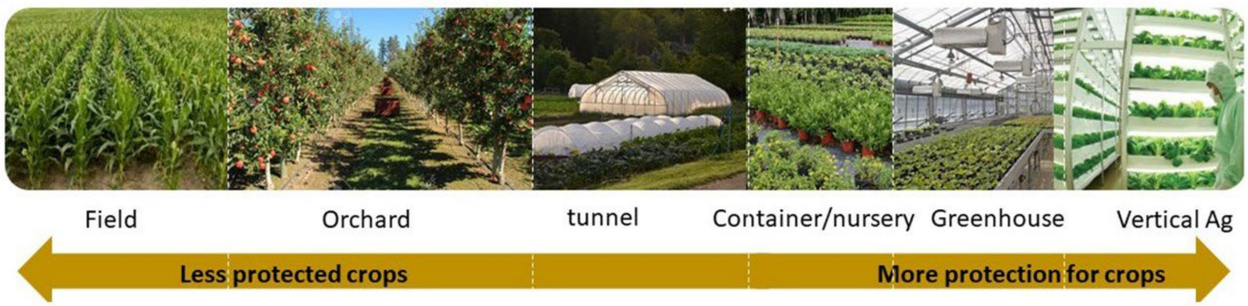

Figure 2: Production systems in U.S. agriculture. Plants in unprotected environments such as field crops are subject to intense environmental exposure.

Research goals are to optimize the integration of biotic factors (e.g., crops, weeds, diseases, pests, and beneficial organisms), abiotic factors (e.g., soil, water, sunlight, and nutrients), and new and/or improved technologies (e.g., models and decision support aids, sensors, and equipment for pest and crop management) at scales from the cellular level to the whole landscape across agricultural systems. Through the integration of these factors, Component 1 goals include developing climate-smart and pollinator friendly sustainable agriculture.

Component 1 is inextricably linked to Component 2, *Healthy, Productive, Diverse, and Sustainable Pollinator Populations,* because many agronomic and horticultural crops depend on insect pollination for optimal production, and pollinators such as bees depend on flowering crops for nutrition and health. Component 1 research considers all types of farming enterprises, including conventional high-, medium-, and low-input production agriculture; protected culture systems; organic systems; orchard and vineyard systems; and systems for new crops.

Research in Component 1 is expected to generate new knowledge; improved management strategies, technologies, models, and decision support aids; and new or improved sensors and equipment for pest and crop management. These discoveries will be transferred to research partners (Federal, State, university, and industry), business partners, growers, and/or extension specialists to apply in the field.

Research in this Component is divided into four main research areas (Problem Statements) listed in Figure 3. Research is based on a systems approach, combining four overlapping aspects of sustainable crop production (Figure 3):

1. Agronomic Crops
2. Fruit and Nut Crops
3. Ornamental, Nursery, and Protected Culture Crops
4. Advanced Automation Systems for Production and Pest Management

Interdisciplinary research is required to understand critical crop management and production issues, and to improve our knowledge of how climate change affects crops and cropping systems. The goal is to develop a coordinated national research program that improves crop management and quality; mitigates the impacts of insects, weeds, and pathogens; and ensures food security in the United States with sustainable, profitable, climate-smart crop production.

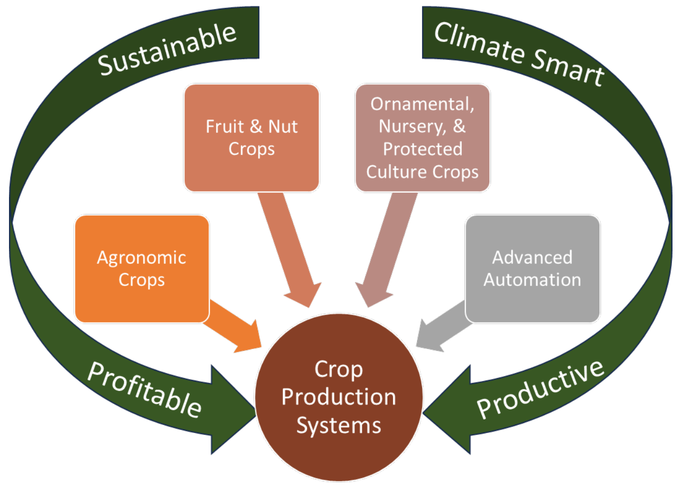

Figure 3: NP305 Component 1 Schematic

Problem Statement 1: Developing Climate-Smart, Productive, and Profitable Agronomic, Horticultural, Ornamental, and Protected Culture Production Systems for U.S. Agriculture.

Problem Statement 1A: Climate-Smart, Productive, and Profitable Agronomic Row Crop Systems

A major challenge faced by agriculture is meeting skyrocketing demands for food, feed, and biofuels driven by the growing human population and renewable energy goals resulting in part from climate change. This challenge is escalated by complex interactions between climate change and changes in crops and cropping systems; these include changes to the abundance and distribution of pests (insects, weeds, and pathogens), loss of pollinators and other beneficial organisms, intensity and frequency of abiotic stressors (moisture and temperature extremes), and nutrient availability and loss. Additionally, the loss of arable land due to urbanization and increased production costs threatens the productivity and profitability of agronomic cropping systems. An improved understanding of how climate change factors will influence cropping system productivity, coupled with new and alternative climate -smart crops and cropping systems and improved pest and crop management practices, are needed to address these challenges. Producers are seeking ways to minimize input costs while maintaining or increasing cropping system productivity and profitability. The overarching goal of NP305 is to provide farmers with economical and environmentally sustainable cropping systems.

Research Focus:

ARS will identify production practices that contribute to profitable climate-smart cropping systems. ARS will use advanced technologies (e.g., remote and proximal sensing, precision agriculture, and models) and traditional methods (e.g., crop selection; planting methods; and disease, insect and weed control) to investigate how climate factors, soil types, crop rotations, crop genotypes, and integrated pest management tactics interact to improve existing cropping systems and develop alternative cropping strategies. These data and information will be used to develop recommendations for cropping systems that are profitable, adapt to and/or mitigate climate change, provide agroecosystems services (e.g., provisioning pollinators and beneficial insects), and mitigate negative effects of pests for improved sustainability.

Anticipated Products:

- Climate-smart alternative crops and cropping systems that minimize inputs and maximize agronomic productivity and floral resources for pollinators and beneficial organisms.
- Improved crop quality, productivity, and profitability.
- New knowledge or improved understanding of interactions among climatic factors, rotations, tillage, soil types, planting dates, plant germplasm/variety, fertility, irrigation, and pests (insects, weeds, and pathogens).
- Remote and proximal sensing tools and precision agricultural tools, software, and models to improve crop production efficiency and predictions and minimize environmental impacts.
- Integrated pest management practices/recommendations for new, alternative, and traditional crop systems that improve agroecosystem services.

Potential Benefits:

- Improved water, air, and soil quality through the adoption of highly efficient, productive, and profitable climate-smart crops, varieties, and cropping systems that reduce GHG emissions and improve agroecosystem services.
- Increased abundance of pollinator friendly mass flowering crops that provide quality food resources to diverse pollinators and other beneficial insects.
- Best management practices that integrate new, alternative, and traditional crops for climate-smart cropping systems.
- Improved knowledge of climate interactions with crop management practices for increased profitability and sustainability of agricultural cropping systems.
- Best management practices that integrate remote sensing and precision agriculture tools into traditional and alternative production systems to maximize production efficiency.
- Improved insect, weed, and disease control for climate-smart cropping systems that protect beneficial organisms and the environment.

Problem Statement 1B: Climate-Smart, Productive, and Profitable Systems for Sustainable Production of Fruit and Nut Crops

Tree fruit, small fruit, and tree nut crops are grown in temperate, tropical, and subtropical climates across the United States. Due to diverse and challenging growing conditions, customized practices must be developed to achieve profitable production. These challenges include the myriad impacts of climate change (e.g., less predictable weather, heat waves, drought, floods, and frost); wildfire smoke; a shrinking pool of skilled workers; less and lower-quality irrigation water; and high costs of energy, farming equipment, and agricultural chemicals. Abiotic stressors such as frost, drought, and heat have direct effects on crop production and can interact with biotic stressors such as existing, invasive, and re-emerging pests, diseases, and weeds. Multi-year field studies in crop production systems are needed to build on previous ARS foundational research in soil health, plant physiology, germplasm development, entomology, plant pathology, horticulture, and end-product quality. Lastly, worker and consumer demands for pesticide safety; diverse, nutritious, and affordable foods; and agricultural water use regulations necessitate novel solutions to produce crops in a safer, more environmentally sustainable, and more cost-efficient manner.

Research focus:

Low-cost phenotyping technology and genetic manipulation with advanced genome editing technologies will be used to evaluate germplasm and identify horticulturally valuable traits for scions and rootstocks. This will help overcome the paucity of information that exists and will provide breeding programs with resources needed to develop improved plant cultivars and rootstocks. Microbiomes are known to influence plant health, but there is limited information on their roles in nutrient cycling and how these roles relate to farming practices, particularly for tree crops. ARS researchers will apply 'omic-era' research tools, such as metagenomics and metatranscriptomics, to help harness the power of soil and plant microbiomes by examining complex interactions among plant physiology, pest and disease resistance, and climate. More effective and efficient approaches will be developed to address yield-limiting biotic factors (pests, diseases, and weeds), with a focus on environmentally sound approaches that do not adversely affect pollinators. New techniques will be developed to measure how abiotic factors such as wildfire smoke affect crop quality. Climate-smart strategies might help to further minimize the environmental impacts and long-term costs of farming tree crops. Computational tools and new technologies will provide better water and nutrient monitoring and management.

Anticipated Products:

- Improved understanding of biotic and abiotic stresses on pest, disease, and weed pressure; crop physiology; and crop disease resistance, yield, and quality.
- Low-cost phenotyping technology and advanced genome-editing technologies for evaluating germplasm under complex biotic and abiotic stresses.
- Management strategies for economically sustainable and climate-resilient production.
- Integrated chemical, biological, cultural, and genetic controls that target invasive and persistent native pests, pathogens, and weeds.
- Improved knowledge of how automated practices affect postharvest fruit quality.
- Improved computational and automated methods and equipment for using ground-based and remotely sensed data to track crop water and nutrient requirements and biotic and abiotic plant stress.
- Development of climate smart technologies that can facilitate crop plant adaptation and/or mitigation for better resilience.
- Improved knowledge of the relationships between soil health, nutrient cycling, biological control, and microbiome interactions.
- Improved knowledge of how wildfire affects grapes and wine.

Potential benefits:

- New technologies (e.g., dashboards, sensors, models, software) and automation that improve crop yields, crop quality, harvest efficiencies, and the sustainable use of water, nutrients, and pesticides.
- Superior germplasm for improved crop quality under a range of suboptimal growing conditions (e.g., marginal soils, less water, low-quality water, high rainfall/low temps during bloom and fruit set, high temperatures during fruit development and ripening, and/or high disease/pest/weed pressure).
- Improved water, nutrient, and energy-use efficiency, and sustainability of soil quality for crop production systems (e.g., irrigation and nutrient management strategies, and/or tools to monitor plant responses).
- Scalable crop management practices, biological control agents, and IPM tools that incorporate less toxic and more efficient alternatives, improve pollination services, and help lower the costs of crop protection.
- New soil health and quality metrics that improve crop productivity and longevity and reduce greenhouse gas emissions.
- More diverse, abundant, nutritious, and affordable fruit and nut crops.

Problem Statement 1C: Climate-Smart, Productive, and Profitable Systems for Sustainable Production of Ornamental, Nursery, and Protected Culture Crops

Controlled environment production systems (sometimes referred to as controlled environment agriculture, or CEA) includes nursery, greenhouse, and other protected culture crops (low/high tunnel, vertical farms, etc.). These systems offer greater control over production inputs and the growing environment to enhance climate resilient crop production that is more environmentally, socially, and economically sustainable when compared to field-grown crops. These highly controlled systems offer greater crop yields, enhanced food quality and safety, reduced usage of resources, and, in many cases, containment of agrichemicals. However, the increased control in these systems comes with higher labor and fuel costs, increased reliance on imported substrates, and an enclosed environment that could facilitate the spread of certain emerging diseases and pests that are difficult to control. Within protected-culture crops there are research opportunities to improve water, nutrient, and substrate utilization; improve energy use efficiency; increase the use of mechanization; further develop integrated disease and pest management concepts; and significantly reduce the potential negative impact of crop production on the environment while simultaneously preserving crop productivity and food quality.

Research focus:

ARS will conduct research to optimize the health, resilience, productivity, and profitability of protected culture crop production through improved understanding and mitigation of abiotic and biotic crop stressors. ARS researchers will create climate-resilient technologies to conserve resources in protected culture production while optimizing crop yield and food quality, through research on crop inputs, including water, substrates, lighting, and nutrients. Research on insect, weed, and pathogen interactions with protected culture crops and crop production environments will lead to improved management strategies to reduce crop losses from these pests. Improved crop modeling will reduce resource usage and can be used to create improved decision support tools for crop production. This research will lead to practical crop management strategies for application in protected culture crop production, including hoophouse, nursery, greenhouse, and vertical farm systems.

Anticipated Products:

- Enhanced crop management strategies for protected culture crops, including hoophouse, nursery, greenhouse, and indoor vertical farm operations, to improve productivity, profitability, and climate resilience.
- Improved understanding of the impacts of biotic and abiotic physiological stressors on crop yield and food quality within the context of protected culture production systems.
- Improved understanding of insect, weed, and pathogen interactions with crops and their production environments to enhance management strategies for ornamental, nursery, and protected culture crops.
- Improved water management strategies to improve irrigation water quality, reduce water usage and reliance, enhance water storage and management techniques, and improve water purification and pathogen treatment technologies for protected culture crops.
- New knowledge and innovative technologies for crop production in protected culture systems, including artificial lighting, sensors, environmental control, automation, machine learning, and artificial intelligence.
- Innovative technologies in soilless substrates, fertility management, biological communities, and water management for container culture, hydroponics, and hybrid production systems.
- Decision support tools for growers to plan production and model crop growth, energy, and resource usage in controlled environments.

Potential benefits:

- Tools for improved efficacy in sanitizing horticultural crop production areas.
- Expanded options for effective and cost-efficient irrigation water disinfection.
- New concepts for engineered irrigation water storage, delivery, and reuse solutions, coupled with agrichemical remediation technologies.
- Soilless crop culture technologies to reduce water, fertilizer, and pesticide inputs.
- Methods for manipulating native microbial communities to strengthen crop resilience to both abiotic and biotic stressors.
- Tools for optimized biopesticide application or spray-induced gene silencing products for pest and disease management.
- Best management practices for sustainable crop protection through optimized cultural practices.
- Improved knowledge and prediction of crop risks to stress from extreme climatic events.
- Increased profitability and sustainability from improved pest management practices that simultaneously reduce pesticide usage and crop losses.
- Tools for promoting pollinator health within protected culture through sustainable production practices.
- Reduced costs of energy and other resources in protected culture through optimization of the growing environment and improved resource use efficiency.
- More consistent crop yield and quality through improved environmental management using lighting and control systems.
- Increased climate resilience through temperature stress research and adaptable environmental controls.
- Improved profitability and reduced operational risk for growers considering facility upgrades by modeling options in decision support tools prior to implementation.

Problem Statement 1D: Climate-Smart Advanced Automation Systems for Sustainable Crop Production and Pest Management

The landscape of crop production continues to evolve with new challenges and opportunities brought about by climate change, emerging pests, and advancing technologies. To adequately address these issues, we need to improve our understanding and control of crop health and pest management. This includes not only identifying and monitoring crops and pests but also creating intelligent systems that enable real-time decision-making for site-specific interventions and targeted precision applications. These solutions must advance sustainable practices, environmental stewardship, and cost-effective production.

Research Focus:

ARS will conduct research to improve precision application technologies and develop new equipment and methods in concert with the advancements, opportunities, and challenges presented by AI and new sensor technologies. Investigations will also focus on researching and developing tools for accurately identifying target locations and predicting and detecting crop health issues and pests under shifting climate conditions, thereby enabling preemptive precision actions that incorporate climate variability and pollinator conservation. ARS will leverage advanced data analysis, remote sensing, and predictive modeling to guide site-specific management decisions in a changing climate. This work will generate high-quality research data and products useful for risk assessment and create efficient, intelligent farming systems adaptable to climate change.

Anticipated Products:

- Guidelines for AI-enabled product application systems that improve product quality and improvement.
- Advanced intelligent application equipment integrated with machine learning capabilities for precision application of both conventional and biological pest control agents and that factor in climate impacts and protect pollinators.
- Data-driven documentation of best practices and computer models of application technologies and methods.
- Adaptive pest control application methods, technologies, and equipment with AI capabilities.
- AI-enhanced application systems for optimizing the precision application of pesticides, fertilizers, and irrigation water.
- Advanced sensing tools and field detection methods capable of identifying changes in crop structure, health, and pest dynamics.
- Machine learning algorithms to enhance detection and prediction of pests and diseases and provide real-time, site-specific management guidance that incorporates climate trends and supports pollinator-friendly practices.
- AI-informed best application practices that integrate real-time data to guide sustainable practices for climate-resilient and pollinator-friendly farming.

Potential Benefits:

- Improved targeted precision application of crop protection products that reduces damage to non-target species and pollinators and minimizes agrochemical environmental waste.
- Automated sensing and application systems and predictive models that enhance climate-smart, site-specific crop and pest management for improved crop yield and quality, including assessments on potential impacts to pollinator health.
- AI-enhanced climate-smart decision support systems that provide guidance to applicators for improving the value of application services, including assessments of potential impacts to pollinator health.
- Advanced automated crop production and protection systems that foster a sustainable and diversified workforce for a more sustainable, resilient, and climate-ready industry.
- Optimized and precision application systems that will reduce operational costs, enable the precise use of pesticide and fertilizer products, and foster climate-smart and sustainable practices that protect pollinator health.
- Remote sensing and field detection methods to enhance crop yield and quality through timely, site-specific health and pest management insights and interventions and that consider factors associated with climate and pollinator health.
- Best application practices will boost efficiency, resilience, and international competitiveness for U.S. growers. These methods will optimize resource use; reduce costs; and enhance yields, sustainability, and biodiversity; they will particularly focus on prioritizing pollinator-friendly practices.

Component 1 Resources

- Davis, California
- Fort Pierce, Florida
- Byron, Georgia
- Houma, Louisiana
- Morris, Minnesota
- Poplarville, Mississippi
- Stoneville, Mississippi
- Wooster, Ohio
- Corvallis, Oregon
- Charleston, South Carolina
- College Station, Texas
- Kearneysville, West Virginia

Component 2: Healthy, Productive, Diverse, and Sustainable Pollinator Populations

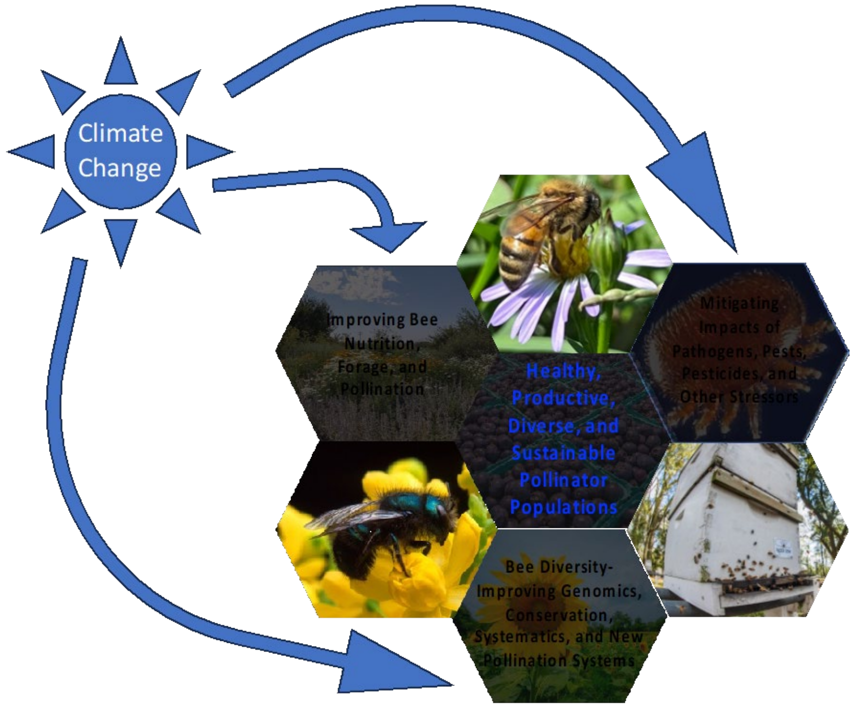

Figure 4: NP305 Component Schematic

Bees are crucial for U.S. agriculture and ecosystem health. The honey bee is one of the most effective pollinators for fruit and nut crops such as cherries, apples, and almonds; row crops such as cucurbits and melons; oilseed crops such as sunflowers and canola; and berries. Honey bees play critical roles in many oilseed and specialty crop commodities due to a number of factors, including the pollinating potential of a honey bee colony due to its wide foraging area (> 1 mile), the large numbers of bees in a typical healthy colony (> 10,000), their generalist nature for many different flowering plants, the ease at which honey bees can adapt to new environments, and the value of hive products. Non-*Apis* bees, including bumble bees, alfalfa leafcutter bees, and blue orchard bees, are also effective pollinators of agricultural crops and many native plant species. These native bees, some of which are solitary or that live in small colonies, perform ecosystem services of monetary value that cannot be easily estimated in economic terms.

Component 2 represents the body of ARS pollinator research for both honey bees and all other (non-*Apis)* bees. The research focuses on developing tools and resources to improve the health and resilience of both honey bees and native bees in the United States despite the challenges of a changing climate. Research is centered on enhancing our understanding of and improving bee nutrition, forage phenology, honey bee queen quality and colony survivorship, and resilience against pests, pathogens, and pesticides. It is coupled with developing genomics and artificial intelligence tools to boost healthy U.S. bee populations and facilitate practical solutions for improving crop pollination and food production (Figure 4).

The research goals of Component 2 are centered upon improving honey bee and non-*Apis* pollinator health, reducing annual losses, and enhancing bee effectiveness for crop pollination. This will be accomplished through a multifaceted approach that is inherently connected to Component 1. Healthy, resilient, and productive bee populations will improve insect-pollinated crop production. Improved bee nutrition, through development of adequate forage and nutritionally sound alternative feeds, is an integral part of improving bee health and diversity. Forage phenology is of particular importance, because climate change is driving a decoupling of forage availability and bee activity and contributing to low overwintering survival. Determining and ensuring a proper diet of balanced nutrients from key pollen sources is critical for maintaining a functioning immune system, longevity, and the overall fitness necessary for improving bee health. Similarly, reducing harmful chemical treatments and identifying less harmful alternatives in crop systems and in honey bee colonies will improve bee survival and productivity. Improving queen productivity and colony reproduction will enhance colony longevity. New treatments to be developed for bee pests and pathogens will span the range from chemical treatments to bioengineered vaccines to improved bee stocks with enhanced resistance and resilience.

ARS researchers will target existing and emerging pests and pathogens that threaten both honey bee and non-*Apis* pollinators. Varroa remains the primary pest and vector of a litany of bee viruses. An emerging pest that is expanding its range, the *Tropilaelaps* mite (tropi), is a particular concern for both honey bees and non-*Apis* pollinators. ARS researchers will mitigate the threat of tropi by developing early detection methods and new control treatments, leveraging genomic and artificial intelligence technologies, and characterizing honey bee and non-*Apis* bee responses to this mite.

The overarching goal of mitigating the threat of pests, pathogens, and other stressors is to minimize their impact on bees by developing effective treatments and resistant stocks of bees. Genetic resource and tool development will expedite breeding programs and pathogen detection systems, inform physiological studies of nutrition and disease response, and will be used to assess non-*Apis* bee diversity. This will contribute to developing new managed pollinator systems involving non-*Apis* bees. Component 2 is focused into three main research areas or Problem Statements, as listed in Figure 5.

Figure 5: ARS pollinator research. Research to improve honey bee and native bee health leverages technological advances and traditional tools to mitigate the effects of poor nutrition, pests, pathogens, and pesticides in a changing climate.

Problem Statement 2A: Improving Bee Nutrition, Forage, and Pollination

The growth and sustainability of bee populations depends on the quality and availability of flowering plants that provide bees with nectar and pollen. The nutrients bees collect in nectar and pollen affect immunity, longevity, colony growth, reproduction, queen quality, resilience to stress, and overwintering survival. However, changes in climate and land use patterns and their effects on flowering plants are generating nutritional challenges to all pollinators. Therefore, determining the nutritional needs of honey bees and non-*Apis* species throughout the year, both when they provide seasonal pollination services and when they not actively pollinating plants, is essential for preventing malnutrition and subsequent queen and colony losses. Factors that affect the nutrient composition of nectar and pollen, such as plant growth conditions and environmental stresses associated with climate change, also need to be identified so that the nutritional value of pollinator plantings and crops requiring or enhanced by bee pollination can be managed and optimized. Microbial communities are the fundamental interface between the environment and bee physiology. Investigations into the gut microbiota of bees are required to obtain a complete picture about how the nutritional landscape affects bee health. The effects of heat and drought stress on flowering, pollen, and nectar production and microbial communities sourced from floral resources also require investigation.

Data for studies measuring the effects of nutrition on colony health and activity usually are collected by intermittent, in-person hive inspections that disrupt normal hive activity. Methods to collect continuous data from colonies are needed to obtain a more complete picture of how the availability of resources and their quality affects colony homeostasis, thermoregulation, and population growth.

In addition to improving the availability and nutritional value of flowering plants, maintaining robust bee populations and a consistent supply of honey bee colonies for pollination requires successful overwintering. More beekeepers are overwintering hives in cold storage to reduce management costs and improve overwintering survival. The greatest colony losses occur during the winter due to inadequate forage and difficulties in minimizing parasitic varroa mite populations. Research is needed to determine nutritional requirements for overwintering colonies and to develop best management practices for preparing colonies for cold storage so that survival and growth are optimized. The role of the queen line on cold storage overwintering also requires further study.

Improving the effectiveness of bee populations (particularly non-*Apis* bees) for crop pollination requires a better understanding of optimal bee distributions in agricultural landscapes and more information that can be used to improve nesting materials and sites. There also is a need for improved short- and long-term storage of non-*Apis* bees to enhance pollinator quality and availability. Crop- and site-specific information on pollinator population sizes would make pollination services from non-*Apis* bees more reliable and economical.

Research Focus:

ARS will investigate and determine the nutritional needs of bees throughout the year, identify key nutrients, and develop scientific tools and strategies (e.g., longitudinal studies) for monitoring bee and colony health and activity. ARS will determine plant growth conditions and practices that affect the nutrient composition of nectar and pollen and characterize microbial communities needed to maintain bee health. The effects of nutrition on queen quality also will be investigated to improve queen health, performance, and longevity. ARS will identify the optimal timing and environmental and nutritional conditions that maximize bee survival in cold storage during winter and define optimal nesting conditions and deployment conditions for bee pollination services.

Anticipated Products:

- Improved knowledge of pollinator forage availability, composition, and quality to increase and maintain robust bee populations.
- Improved knowledge of how environmental factors, especially those related to climate change, affect flowering and nutrients in pollen and nectar needed to support pollinator diversity, growth, survival, and reproduction.
- Improved understanding of environmental effects on floral microbes, bee-microbial interactions, and colony health.
- Establishment of longitudinal studies and application of continuous colony and population-level monitoring to inform management and land use practices.
- Improved understanding of how bee genotypes affect colony behavior, resiliency, and productivity, including responses to native and managed forage landscapes, artificial (supplemental) diets, and overwintering management.
- Improved understanding of the phenology of nutritional resources available in the landscape under changing climatic conditions.
- Improved knowledge of how biological and environmental factors, particularly climate change, affect bee mortality, and strategies such as cold storage to mitigate these effects.

Potential Benefits:

- Reduction in non-*Apis* bee and honey bee colony losses from malnutrition, which affects immunity, longevity, and reproduction.
- Improved honey bee colony survival and non-*Apis* pollinator diversity and abundance to optimize crop pollination and ensure productivity of U.S. crops that require bee pollination.

- Inclusion of bee nutritional needs into crop selection and production programs.
- Optimized pollinator planting compositions for sustained pollinator diversity and growth.
- Development of crop management practices and genotypes that can optimize forage availability and nutritional quality.

Problem Statement 2B: Mitigating Impacts of Pathogens, Pests, Pesticides, and Other Stressors

Pollinator health is profoundly affected by pests, pathogens, pesticides, and other stressors. An increase in annual losses in honey bee colonies and other pollinator populations has led to increased management expenses and a shift in management practices to recover colony numbers for meeting pollination service demands. Sensitivity of honey bees and other pollinators to chemicals, including products needed for crop protection and for the in-hive control of honey bee pests and diseases, imposes additional stress on pollinator health.

The arrival of the ectoparasitic mite *Varroa destructor* in Europe and North America led to devastating honey bee colony losses, in effect driving non-managed colonies close to extinction. The varroa mite, coupled with the viruses it transmits, is partially controlled by chemical treatments and management strategies. Unfortunately, pesticide treatment for varroa can have adverse effects on honey bees and has also led to pesticide resistance in the mite, which has increased the incidence of varroa-transmitted viruses. These viruses also infect the broader pollinator community, amplifying the urgent need for better tools for mite and virus control.

The *Tropilaelaps* mite is a new threat to U.S. honey bees and other pollinators. It is emerging in Indonesia and beginning to expand its range, with a potentially broader host range among bee species. This mite reproduces at three times the rate of varroa, has a more devastating feeding strategy on infested brood, and transmits additional viruses. Current control methods used by Indonesian beekeepers may have reduced the effectiveness of controls in the United States and are not conducive to adoption by the U.S. commercial beekeeping industry. These factors are leaving U.S. pollinators and a significant portion of the nation's food supply at very high risk. There is an urgent need to develop genetic resources for the mite, detection mechanisms to prevent or delay its introduction into the United States, and mitigation strategies to minimize its impact both abroad and if it does begin to infest U.S. bees.

Bacterial diseases, including the highly regulated brood disease American foulbrood, cause both colony losses and an immense regulatory and treatment burden. Chemical stress can involve acute exposures that impact entire colonies as well as subtle and long-term exposures that affect bee behavior, longevity, and colony growth. The health risks for honey bees and other managed pollinators can be exacerbated by interactions among biological threats, chemical exposure, and the interplay of these factors with abiotic stressors stemming from climate change. Overall, commercial and small-scale beekeepers replace more than 40 percent of their colonies annually, a rate that has doubled in the past 2 decades. There is an urgent need to understand and mitigate the biological and abiotic threats faced by honey bees and non-*Apis* pollinators.

Research Focus:

ARS research will focus on identifying and characterizing biological and environmental threats to pollinators and developing solutions to mitigate their effects. ARS will identify and characterize bee pathogens and parasites and use epidemiological approaches to identify the causes of bee declines. ARS will characterize pathogen transmission, host susceptibility, and infection mechanisms, including biotic and abiotic factors. ARS will determine how the native microbiota of bees and beehive materials affect bee susceptibility to parasites and other stressors. ARS will quantify interactions of in-hive treatment chemicals with real-world field rates of agrochemical applications and assess how lethal and sublethal exposure to agrochemicals affect bees.

ARS will identify and develop novel mite treatments and screen novel antiviral and anti-parasitic products, including natural products that modulate the immune response and direct antiviral controls. ARS will conduct research on the impacts of abiotic stressors on pollinator health to develop best management practices. ARS will develop new management strategies and tools that promote queen health and productivity. ARS will develop and preserve genetic resources and breeding strategies to address threats from disease, climate, and other challenges.

Anticipated Products:

- Improved understanding of how climate changes and anthropogenic factors affect bee forage.
- Longitudinal studies addressing how climate change, queen health and resilience, pests and pathogens, forage phenology, and pesticide exposure affect commercially managed honey bees.
- Development of new sampling and diagnostic methods for novel and established bee pests and pathogens using genomics (leveraging AgPest100 and Beenome100 data) and artificial intelligence tools and technologies.
- Development of new treatments, delivery methods of those treatments, therapeutics (including vaccines), and other strategies to combat parasites (including varroa and tropi mites), pathogens, and environmental toxins.
- Determination of the extent of mite resistance to miticides and strategies for mitigating mite resistance.
- Development of breeding stocks for improved honey bee resilience and survivorship.
- Improved knowledge and/or tools, such as breeding bee stocks and traits and their associated management techniques, that provide a foundation for improved integrated pest management strategies for pest and disease control.
- Improved understanding of optimal management of queen and drone production, mating, and quality.
- Development of new strategies for improving and promoting honey bee queen health and productivity.
- Improved understanding of how the microbiome affects bee disease, queen health, social resources, and resilience.
- Improved understanding of pesticide and adjuvant effects (including synergisms) on bees, and development of strategies for reducing bee exposure to these stressors.

Potential Benefits*:*

- Sampling and diagnostic methods applicable for current and emerging pest and pathogen landscapes that swiftly and accurately identify threats.
- Recommendations generated to optimize bee reproduction and improve survivorship.
- Integration of improved honey bee stocks in commercial operations to improve queen health, colony resilience, and colony production, and reduce the need for chemical intervention for pest and pathogen control.
- Improved best management practices for beekeepers and bee breeders, particularly for germplasm optimization and preservation.
- Integrated pest management skills, novel control products and therapeutics, and resistance monitoring programs that allow stakeholders to sustainably manage healthy bees.
- Development and prioritization of mitigation efforts for biotic and abiotic stressors affecting bee populations, and communication of the most relevant solutions to stakeholders.

- Enhanced use of the microbiome to improve bee reproduction, social interactions, and disease mitigation.

Problem Statement 2C: Bee Diversity-- Improving Genomics, Conservation, Systematics, and New Pollination Systems

In the United States, agricultural production and natural ecosystem health depend upon having numerous species and strong bee genetic diversity. Native bee populations are critical natural resources that need to be conserved for pollinating agricultural crops and plants in natural ecosystems. There is growing concern and evidence that these vital resources may be in jeopardy. Recent bumble bee research documents severe declines in some bee species and there is little information on the status of others.

Knowledge of native bee and honey bee genetic diversity is essential. To fully understand bee diversity and how bees respond to biotic and abiotic stressors, high-quality reference genomes are needed, along with data on the pathogens and microbes associated with different bee species. Honey bees with genetically based resistance or tolerance to health threats will provide the most sustainable solution to problems caused by parasites, pathogens, and threats from climate change. Research to support the breeding of improved bees is long-term and multifaceted. Foundational work is needed to identify specific traits or populations of bees with useful phenotypes, and these traits and bees need to be characterized for the physiological, behavioral, genomic, and genetic factors that regulate resilience. The application of research findings requires collaborating with the beekeeping industry to breed and deliver bees that are valuable for the commercial sector. A further aspect of the work is to cryopreserve valuable genetic material for later use by bee breeders and researchers, or to conserve endangered bee strains, subspecies, or species.

Comprehensive inventories, population sustainability assessments, and studies of the effects of altered habitats are needed to determine the extent of species decline. This information is also essential for developing remedial efforts to guarantee the continued presence of these keystone species for agricultural and natural ecosystems. Accurate taxonomic identification is critical given the approximately 4,000 species of bees in the United States. Formal revisions, user-friendly Web-based identification guides, and new identification methods using molecular tools and image recognition using artificial intelligence are in great need.

Understanding the role of bee diversity in pollination of crops and plants in natural ecosystems is essential for sustainable food production and natural ecosystem health. Greater fruit set and seed production can result from the interaction of honey bees and other bee species. Controlled environment agriculture managers have a critical need for information about how different bee species can contribute to these unique cropping systems. Restoring natural ecosystems that have experienced wildfires or other types of environmental harm associated with climate change will also require critical information about how bee species (including the honey bee) can work together as pollinators to help restore ecosystem health, particularly in forests and watersheds.

Research Focus:

The research focus will be in four areas: bee genomics and genetic diversity, conservation of bee species and strains, systematics and phylogeny, and development of pollination systems for sustainable agriculture and natural ecosystems. ARS will help create high-quality reference genomes for native bees and data on pathogens and microbes associated with diverse species. ARS will use molecular markers to quantify genetic diversity for honey bees and bumblebees and develop cryopreservation practices for key bee germplasm. ARS will also characterize honey bee traits and genetic stocks for improved resilience to biotic and abiotic threats and use this information to breed honey bees with improved performance in commercial beekeeping operations. ARS will also select bee strains and species for specialized pollination needs for agricultural crops and systems, such as controlled environment agriculture. In addition, ARS will conduct field surveys in natural ecosystems (i.e., non-agricultural) to sample for the presence of both native and non-native wild bees. Bee diversity will be preserved at the National Pollinating Insects Collection in Logan, Utah. In addition to the curation of pinned specimens, ARS will develop both morphologically-based and DNA sequence-based methods to improve bee taxonomy and systematics and enable stakeholders to more easily identify bees of interest. ARS will contribute expert knowledge to the development of native bee health monitoring systems in collaboration with other government and non-government organizations, as appropriate.

Anticipated Products:

- Improved knowledge of bee genomes (based on Beenome100) and genetics useful for improving bee health, bee breeding, and conservation.
- Reference quality genomes, identification of pathogens/microbes associated with bee species, and genetic databases for identifying and using eDNA in species surveys.
- Improved understanding of population genetics, strain distribution of honey bees and native bees, and genetic basis of bee responses to biotic and abiotic stressors.
- Improved knowledge of bee diversity and habitat carrying capacity to enhance bee conservation through improved understanding of honey bee/native bee interactions.
- A public facing dashboard with bee species distributions that can interface with geospatial tools and other databases to provide insight into the impacts of land-use changes, climate change, and other factors.
- Improved insights into how honey bee and other species can be used to help restore lands after fires and climate/weather disasters to combat climate change.
- Tools for effective cryopreservation of valuable bee germplasm and embryos for industry use, research, and conservation of bee diversity.
- New knowledge of bee systematics and phylogeny, and development of guides for bee identification, including those based on imaging and AI/ML techniques, coupled with improved knowledge of bee biology to create a phylogenetic approach to bee conservation.
- Discovery and development of new pollinators for crops (traditional nut/fruit and seed crops, as well as crops grown in controlled environment agriculture) for sustainable and resilient food production and nutrition.

Potential Benefits:

- Improved knowledge of honey bee diversity and taxonomy that is critical for breeding programs to improve pollinator effectiveness and health.
- Conservation non-*Apis* bee diversity, including bumble bees, alfalfa leafcutter bees, and blue orchard bees, which are essential for pollinating agricultural crops and hundreds of species of native plants.

Component 2 Resources

- Tucson, Arizona
- Davis, California
- Tifton, Georgia
- Baton Rouge, Louisiana
- Beltsville, Maryland
- Poplarville, Mississippi
- Stoneville, Mississippi
- Fargo, North Dakota
- Logan, Utah
- Kearneysville, West Virginia