USDA Agricultural Research Service

National Program 304

Crop Production & Quarantine

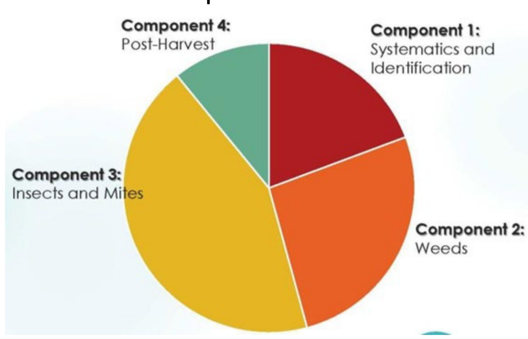
External Panel Retrospective Review: 2018-2023

## Introduction

ARS is a mission-directed, problem-solving agency with the capacity to integrate basic and applied research in response to stakeholder needs. The mission of ARS National Program 304 is to provide technology to manage pest populations below economic damage thresholds by the integration of environmentally compatible strategies that are based on increased understanding of the biology and ecology of insect, mite, and weed pests. The NP 304 Action Plan includes four Research Components:

1. Systematics and Identification
2. Weeds
3. Insects and Mites
4. Protection of Post-Harvest Commodities, Quarantine, and Methyl Bromide Alternatives

The goals of National Program (NP) 304 include to conduct fundamental research to create the knowledge base necessary to develop innovative control methods and IPM strategies, and to conduct applied research to produce informational and material products that improve pest and disease control in agriculture. Improvements include reduced costs, better controlled pests with fewer non-target, human, and environmental effects, and a reduction in the establishment and spread of invasive insects, mites, and weeds. These control strategies are applied in a variety of environments, from the production field to storage, shipping and packing facilities. The development, implementation, and improvements of pest and weed management and control strategies contribute significantly to maintaining the competitiveness and vitality of U.S. agriculture and improving the quality and security of our food and fiber supply. NP 304 is a large, comprehensive program with approximately 54 appropriated projects, distributed across 4 research components as shown below.



The retrospective review panel convened by webinar on December 06, 2023. NP 304 leadership provided overviews of the progress in each of the 4 components as well as the USDA IR-4 program. The presentations highlighted representative project successes accomplishing the goals outlined in the 2018-2023 NP 304 Action plan.

**Summary**

The NP 304 Retrospective Panel was impressed by the breadth of the research presented in each of the 4 research area components. The NP 304 leadership shared high impact projects, both completed and ongoing from each area. These projects clearly demonstrated progress that indicates the ability of the NP 304 to complete the goals in their 2020-2025 Action Plan. The quantity of their research is demonstrated by the production of more than 2500 refereed publications. This represents an average of approximately 3 publications per annum per scientist (187 scientists are leading projects within the NP 304). The quality of their work is supported by the many top tier journals in which these publications appear and the attainment of more than 450 competitive grants awarded to NP 304 scientists in this period.

There are approximately 54 appointed projects within NP 304, conducted at 34 locations within the U.S. and 4 overseas locations (extremely important to the evaluation and successful outcome of classical biological control programs). Much of this research is vital to the continued productivity of American agriculture, but may not necessarily fall into the 'hot button' zone targeted by many funding agencies. The NP 304 hosted IR-4 program, for example, provides research supporting the registration of pest management products in production systems that may lack the acreage to make it cost-effective for agricultural chemical companies to pursue registration.

The NP 304 ensures its research is pertinent to existing stakeholders and to science. While there were multiple examples of direct stakeholder input to the research, also noted was a wide collaborative effort. The scientists in NP 304 collaborate on projects with researchers from industry, University, non-profit, State and other Federal institutions. Collaborations of this sort ensure many views and needs are reflected in the direction, and the potential utility, of their research. Such projects tend to have high impacts on their systems and impart significant benefit to their stakeholders. This collaboration is not only restricted to researchers in the U.S. There are very active international collaborations as well, especially with European, Asian and Central/South American scientists. The program has also taken steps to build for the future of their science. In the review period, NP 304 scientists have trained over 700 post-doctoral fellows, graduate and undergraduate students.

Of particular interest to the Review Panel were the presentations on cross cutting programs. These multi-disciplinary programs are utilizing the best skills and organizational structure of the ARS to address difficult-to-solve pest management problems. Their Citrus Greening program is

an excellent example. The multiple disciplines involved provide different views of the problem, generating fresh interpretations and different, but inclusive options. These have been integrated into an effective solution and delivered to stakeholders. One of, if not the largest potential strengths of NP 304 is the breadth of specialties incorporated in ARS (e.g. foundational and applied research in insects, weeds and pathogens, translational science, economics, social science), all operating within an infrastructure that facilitates direction toward a common purpose. The cross cutting projects demonstrated this as an area of tremendous potential whithin a program such as NP 304.

In summary, NP 304 is a high-impact research program. It is providing results that are both immediately applicable to their stakeholder groups and influence and assist other areas of pest management. The broad, collaborative nature of their research means it is deeply integrated into national and international development of pest management. This research is extremely important to U.S. agriculture, combating invasive species, and remediating huge areas of degraded natural areas. This research has produced results that benefit producers and stakeholders, researchers and students, science and technology, and the taxpaying public. More importantly, this research has global reach and impact, benefitting global agriculture.

**GENERAL COMMENTS**

Research Areas for additional emphasis in the future include:

Training and retaining a talented ARS National Program 304 workforce especially addressing the gaps in pest modeling, data science and AI.

Increase interdisciplinary collaboration where appropriate to understand the combined impact of insects, weeds, and diseases on production agriculture and integrating management across the disciplines. The crosscutting programs were the highlight of the Program and underscore the potential strength of ARS.

Collaborative work with social scientists to evaluate adoption of new technologies and integrated approaches that have been described. Adoption is sometimes lacking in new technologies and methods, identifying and overcoming barriers can advance adoption of pest management strategies.

Similarly, the economics of adopting new technologies in field crops and rangeland systems should be determined as the work goes forward.

Bioherbicides: Further work to determine the selectivity of these novel biologically active compounds and work to determine if and how they could be integrated into weed management strategies for conventional and organic crops.

Harvest weed seed destruction; it should be determined if weed seed destruction at harvest selects for early shattering biotypes of driver weed species. The possibility of integrating the technique into weed management to reduce or delay this selection process should be pursued.

The current regulatory environment is focused on endangered species. EPA registration and registration review requires an assessment of pesticide risk to endangered species and applying mitigation (including exclusion of some uses) to protect endangered species and habitats. NP 304 programs will need to include development of integrated pest management approaches that will provide for successful control without the potential to impact endangered species and their habitat. Interdisciplinary approaches to address this regulatory environment are needed to sustain our production systems and food security.

## Reference Materials

**National Program 304 Crop Protection and Quarantine Retrospective Review Appendices**

- Appendix 1: Current Project Listing
- Appendix 2: Peer-Reviewed Publications
- Appendix 3: Selected Supporting Information and Documentation for Accomplishments and Impact of NP304
    - External Funding Received
    - Mentoring and Editorship
    - International Collaborations
    - Technology Transfer
- Appendix 4: Cooperating Institutions as Co-Author on Peer Reviewed Publications
- Appendix 5: NP 304 Annual Reports (2018-2022)
    - 2018 Annual Report
    - 2019 Annual Report
    - 2020 Annual Report
    - 2021 Annual Report
    - 2022 Annual Report
- Appendix 6: NP 304 Action Plan (2015-2020)
- Appendix 7: NP 304 Action Plan (2020-2025)

**Component 1**

- Comp 1 Systematics and Identification (PowerPoint)

**Component 2**

- Component 2 – Weeds PS 2A, 2B, 2C (PowerPoint)

**Component 3**

- Component 3- Insect Vectors of Plant Pathogens
- Comp 3 – Insects and Mites PS 3A (PowerPoint)
- Comp 3 – Insects and Mites PS 3B (PowerPoint)

- Comp 3 – Insects and Mites PS 3C (PowerPoint)
- Comp 3 – Insects and Mites PS 3b, 3C (PowerPoint)

**Component 4**

- Protection of Postharvest Commodities, Quarantine, and Methyl Bromide Alternatives (PowerPoint)

**IR4 Program**

- IR-4 Program (Comp 2,3,4) (PowerPoint)

**Cross-cut Programs**

- Overseas Labs (PowerPoint)
- New Identification for Weed Identification (PowerPoint)
- FY21_The Sagebrush Sea_ Innovative Restoration (mp4)

**NP-304 NPRA – Panel Orientation-20231113_130850-Meeting Recording (mp4)**

**Introduction from CPP's Deputy Administrator (PowerPoint)**

# REVIEW NOTES ON INDIVIDUAL RESEARCH COMPONENTS

## COMPONENT 1: SYSTEMATICS AND IDENTIFICATION

One of the foundations of successful pest management is the correct identification of pest species. The support of systematic research in applied agriculture is fundamental to building successful management programs that are both environmentally and economically sustainable. Misidentification of insects can have serious consequences ranging from the exclusion of information from other locations that may be pertinent to invasive species to the application of inappropriate and ineffective control techniques. The systematic relationship of various pest species often leads to the development of successful management programs.

The research being conducted in Component 1 was current, applied and novel. *It met the review requirements of being relevant, producing quality results and being highly impactful*. Based on the NP 304 plan of action for this period, it has achieved targets and provided information that can not only be applicable currently but provide the basis for future development. The Ag100Pest program is a valuable addition to the i5K and earth BioGenome projects and demonstrates the potential utility of the information being generated by these efforts. Results from this component will significantly improve resistance management, biological control, monitoring and predicting insect populations and management programs at local, regional and larger scales. It demonstrates a consistent level of productivity over the years reported and promises equally interesting and useful research.

Comments on specific Problem Statements follow:

**Problem Statement 1A: Insects and Mites**

Overall the project used systematic and innovative approaches to identify insects through the generation of the reference genome for arthropod pests, DNA barcoding to assess insect diversity in citrus, assess the global diversity of leafminer flies and the geographical origin of species, comprehensive phylogenetic analysis of the orders, and development of AI technology for recognition of invasive beetles. In addition, extensive work has been done to understand the mechanism of insecticide tolerance and resistance, and the transfer technology of new sources of insecticides and natural enemies of insects from their geographical origins.

One question was raised with regard to the work on the potential for boll weevil resistance to malathion. What is the registration status of malathion for this use - malathion registration was under scrutiny due to potential impact on endangered species. Will this work lead to additional work in component 3 to determine new methods for eradication of the boll weevil?

**Problem Statement 1A: Insects and Mites**

As part of the Ag100Pest initiative (although perhaps now better referred to as the Ag175Pest Project), the USDA_ARS effort to sequence the top 175 agricultural arthropod pests in the U.S., a report was presented on the sequencing of the Boll Weevil's (*Anthonomus grandis*) response to exposure to the insecticide malathion. An excellent example of this ambitious undertaking, the work is providing interesting insights into the genetic development of insecticide resistance (in this case, the lack of that development). It underscores the value of sequencing the genomes of high impact pests; the information gained can provide valuable insight into the management of other arthropod pests.

The development of pesticide resistance presents ongoing challenges to growers, and industry. How resistance develops is not well-understood but has been traditionally thought to involve strong selection for certain homozygous recessive traits that confer resistance. The boll weevil reference genome and resistance potential to malathion addresses an unusual situation with the boll weevil and how it has not developed resistance to malathion, despite its broad use for at least four decades, and potential for resistance to other OP's. Modern genetic/molecular tools have been brought to bear on understanding the resistance mechanisms, population genetics, gene flow and the regional geographical sources of re-infestation of this economically important pest of U.S. agriculture.

Other phylogenomic research on holometabolous insect orders has yielded important insights into the evolutionary development of Hymenoptera, particularly the evolution and speciation of parasitic Hymenoptera. Of particular interest (and importance) is research on geographic origin of invasive insect pests that enables better matching of biological control agents based on geographic matching. The efforts to use AI for pest detection may eventually have application in 'smart trap' technology, there are several traps currently in development using AI trained high resolution cameras to identify trap captures. While there is potential for this research to reap significant rewards by providing quick and accurate pest detection (in some cases more accurate than humans), much work remains to be done in this area.

**Problem Statement 1B: Non-crop plants**

No examples of work were given.

**Problem Statement 1C: Microorganisms**

Research should continue directed at locating and identifying potential new microbial pesticides, particularly ones that have efficacy in dry conditions that otherwise limit their use to very humid conditions. Many microbial insecticides often fail to produce results because of environmental limitations.

The work of the Invasive Insect Biocontrol & Behavior Laboratory in developing and patenting three microbial pesticides based on *Chromobacterium* species was documented as examples of successful technology transfer in this se3ction.

## COMPONENT 2: WEEDS

*Overall, the program's goals in this area were relevant, ambitious and forward thinking. The description of progress was well done and shows that the program has achieved a great deal in five years. Through high quality research, it has produced valuable results which will positively impact work in pest management.* The problems are great and the work needed to understand the biology, ecology and persistence of driver weed species in order to develop sustainable solutions is very long term. The program should be commended for the work completed successfully over the past five years. The cross cutting research to develop new techniques for identifying and controlling weeds in agronomic and horticultural cropping systems using cover crops, integrated management approaches, computer vision and robotic technologies, and harvest weed seed management are particularly relevant and of great need. Project 304 has the unique capability to conduct the long term research and demonstration needed to be able to develop and adapt these cutting edge technologies into cropping system practices in diverse climates.

The research in range and natural systems to understand the impact of invasive weeds as well as the ecology of the system is, again, long term and this program is uniquely positioned for this work. The progress made to date is commendable and relevant to the invasive plant community and land managers. Biological control of invasive plants is uniquely suited to these environments and the work conducted to date is highly relevant and needed. Integration of biological control into these less disturbed management systems is challenging and this program is making excellent progress in this effort. The development of decision support tools is an important addition and will be helpful to those who manage these varied landscapes.

Comments on specific Problem Statements follow:

**Problem Statement 2A: New weed management technology discovery and development**

Weed science has struggled with developing novel weed management techniques, but more importantly, resistance of weeds to herbicides is a major problem in U.S. agriculture. The research being done in this category is high impact and involves pursuing alternative herbicides, such as bioherbicides (including allelopathic chemicals), finding new modes of action, controlling weeds using precision approaches and mapping, and AI and machine learning to identify weeds in the field and control them with precisely applied herbicides.

NP 304 has made significant progress in identifying and evaluating the phytotoxicity of the candidate bioherbicides, khellin and visnagin. Progress was also shown in determining the chemical structure and biological activity of splicesome. This effort should lead to further work to determine the selectivity of these biologically active compounds and work to determine if and how they could be integrated into weed management strategies for conventional and organic crops. The allelochemical sorgoleone has been studied for many years; however, progress has been made in identifying the biosynthetic pathway for this chemical. This effort may lead to further work to develop crop plants with this allelochemical property. The cross cutting work that described real world assays to understand the allelopathic impact of potential cover crops is very exciting and will be of great value going forward.

Cover crops continue to have great potential as part of an integrated weed management strategy; they are being used successfully in some cropping systems. The GROW cover crop trials are a step in that direction, cover crops are being evaluated in integrated systems across the eastern U.S. and this research will yield valuable insights in how they might be used as part of integrated weed management.  More work is needed to find and evaluate the right cover crop species and promises to yield critical information on cover crop performance and crop interactions involving many sites in the U.S. The Planting Green approach to cover cropping is also an interesting extension of this technology, particularly in no-till systems.  In North Central states, research on planting dates of winter cover crops should be refined to avoid the creation of a green bridge for insect pests such as wheat stem sawfly.

Some very novel tools are being developed to identify and remove weed seeds during the harvest process. NP 304 weed science research has made progress through collaborative work to understand the biology at harvest of many weed species and the potential for harvest weed seed destruction as part of an integrated management system. The work conducted to determine seed retention of many species is particularly relevant to determining the utility of this approach. A question that remains is whether the use of weed seed destruction at harvest will select for early shattering biotypes of driver weed species. Future evaluations should address how this tool can be integrated into weed management to reduce or delay this selection process.

The inability to identify weed species and differentiate them from crops or desirable species using AI/ML has been a significant roadblock to using computer vision and robotics for weed control in practice. The NP 304 team is doing the long term work needed to enable the development of this new technology. Of particular importance is the work being done to capture the genetic variation of weed and cover crop/crop species using computer vision technology. The fact that this is resulting in an open access, curated data repository is highly relevant and will have great impact. A question remaining will be to address the cost to adopt this technology in field crops as the work goes forward.

**Problem Statement 2B: Biological control and ecosystem research**

The work on biological control of invasive species was well documented and presented; excellent work is being done in California, Florida, Montana, Maryland, and other states to manage egregious invasive weed populations.  Efforts to find biological agents that can effectively reduce invasive weed populations have seen mixed results with some of our more noxious weed species. Sometimes this is due to environmental mismatching, or genetic factors. The research being done in this area seeks to improve weed biocontrol success by developing support tools to restore degraded areas, and finding biocontrol agents that can perform better (and understanding why some don't).

The work on biological control of species invading a variety of ecosystems are yielding results. In some of these systems, biological control is the primary tool available for management. Will this result in long term selection for resistant biotypes of some species?

The high impact collaboration with the Nature Conservancy on restoration of rangeland that has been invaded by fire prone grasses was very relevant. It is critical to reversing severe ecological degradation involving millions of acres of public and private land throughout the U.S. These collaborations are important in situations in restoration and monitoring efforts which involve long-term commitments of time and funding to be successful. The integration of charcoal coated seed of native restoration species with the use of pre-emergence herbicides is a progressive approach. Questions for future work include whether this approach could be adapted to use on large tracts of land and whether this approach can be made affordable by all land management groups. Other factors that will require attention include the impact of climate on the efficacy of the preemergence herbicides, determining the range of environments within which the technique will work.

**Problem Statement 2C: Integrated approaches to weed management**

Like any pest management system, integrated approaches work best when the right tools are adopted. The research in this area involves developing predictive and modeling approaches to analyze the spread of weeds and invasive plants. Movement of invasive plant species in different environments (aquatic vs. terrestrial vs. agriculture) needs to be quantified and understood in the context of weed management, population ecology, climate change, and competitive interactions with other plant species. Furthermore, the source population of these invasive weed species needs to be understood in the context of biological control. Like any IPM approach, all available tools should be adopted and used, but we need to know how to use these tools effectively. Hence, this research is important to U.S. agriculture.

Decision support tools (web-based and mobile applications) are being developed to consolidate weed management tools to help growers make cover crop decisions and develop management plans. The Development of several Web-based Decision Support Tools to help growers manage weeds was a highlight of NP 304's integrated weed management work. Growers need these region-specific tools for herbicide and nitrogen applications as well as cover crop selection. The innovative advancements in weed image identification by NP 304's interdisciplinary team of weed scientists, engineers and computer scientists will be impactful to the field of precision agriculture and decision support models.

The GROW network of collaborators including industry, universities, and government agencies to transfer these decision support tools is a highly successful effort to provide the information needed across the country. Next steps for this work might include developing means to determine adoption of this network and these decision support tools in different areas of the country. In addition, extension of this integrated work and decision support tools to the semi-arid and arid western states where water availability is a concern will be welcome in future years.

## COMPONENT 3. INSECTS AND MITES

*The research conducted by NP 304 on insects and mites has been relevant, novel and interesting. It has both short and long term potential impacts and has provided results which provide a foundation for current and future pest management.* NP 304 has made significant advancements in monitoring using chemical signaling, remote sensing techniques, and molecular tools. They have developed, enhanced and evaluated new management tactics in areas such as insecticides, biological control, host plant resistance, the disruption of population dynamics, and examined the management of arthropod vectored plant disease. The research also demonstrates the strength of the program in the development of an outstanding multi-disciplinary, integrated pest management program for Citrus Greening. It is important to note that much of the research has been developed with input from stakeholder groups and the agricultural industry.

The program is relevant, innovative and of high quality. The results carry significant impact for multiple production systems and are definitely meeting the needs of their stakeholders.

Comments on specific Problem Statements follow:

**Problem Statement 3A: Early detection, prediction, and monitoring of beneficial and pest arthropods**

Novel approaches were successfully developed to detect, monitor and predict insect species. This includes the development of semiochemical attractants, baits, the use of remote sensing techniques, models to improve trapping efficiency and prediction, and genetic techniques to monitor regional populations.

The exploitation of chemical signaling in insect management was a focus of NP 4304 research in this component. These accomplishments included the development of an aggregation pheromone for cucurbit pests for monitoring and 'attract and kill' applications. Chemical lures and a patented bait station for fruit flies were also developed. And the refinement of specialized pheromone and lure technology (SPLAT technique for detection and annihilation of invasive species) all reflect a serious research effort into the use of chemical communication for pest management.

Another development of monitoring technologies was demonstrated with a project that is a 'proof of concept' for a 'photonic' fence. Insect silhouette, wing beat and oscillation is measured and tracked across a specific entry point by an InfraRed beam. If these species specific traits identify an insect pest, it is tracked and killed by a laser. It is harder to imagine a more novel pest management technology than insects meet Star Wars.

Improvement of existing predictive methods was also accomplished. Research was conducted to improve predictions from trap catches, to further incorporate genetic and climatic information to pest predictive distribution models and on the incorporation of vegetative and climatic data to improve grasshopper population predictions. Refining the use of genomics tools to predict pest populations was also accomplished through development of molecular and real-time pest identification tools using biomarkers.

These tools will give researchers more comprehensive datasets than have ever been achieved before. In addition, future research to keep invasive pests from entering and establishing within the U.S. will involve the development of detection and monitoring tools to enable rapid and accurate invasive pest detection on incoming commodities.

**Problem Statement 3B: Develop new or improved management tools and knowledge to control arthropod pests**

There is a literal arms race occurring between insect and mite pests and the tools that we deploy to manage them. Ongoing research in this area is critical to keep pace with arthropod evolution under intense selection pressures (i.e., development of resistance in all its forms). It is encouraging to see research directed at manipulating arthropod behavior by developing attractants (including artificial sweeteners) and unique repellents, refining the use of receptor interference (receptor-i) as disruptors of biological processes, alternatives to neonics (sucking pests), biological control (EAB), plant resistance to Lepidopteran and Coleopteran pests (FAW, corn rootworm), improved nanoparticle formulations, entomopathogenic fungi genomics discovery, understanding basis of Bt resistance and discovering ways to disable (knockout) genes for resistance, applying genomic tools to understand gene flow and population variability in the European corn borer.

The development of receptor-i as an insecticide is an important accomplishment. Like RNAi, this technique will be very target specific, be rapidly screened and have a wide range of applicability. It has received 4 patents and there are currently applications targeting 8 separate arthropod pest species. The use of RNAi is also being researched in Citrus Greening disease in a unique management tactic, with two separate dsRNA products, one targeted against the vector and the other against the pathogen.

Traditional proactive control tactics have been developed under NP 304 research. Biological control efforts are well represented; for example, 4 parasitoids have been released targeting Emerald Ash Borer, the genomics of 100 strains of entomopathogenic fungi have been sequenced, and a new nanoparticle delivery system developed to increase the efficacy of entomopathogen applications.

These efforts have supported precision application of management tools, enhanced suppression of pathogens of plants and of beneficial insects, and assisted pest management in conventional and organic systems.

**Problem Statement 3C: Integrate management strategies to control arthropod pests**

The integration of pest management programs is one of the strengths of the NP 304 program. There were several integrated research initiatives noted in the presentation, including: the use of carn varieties to improve biological control results, soybean flavonoids which improved the virulence of an insect pathogen, combining repellents and attractants in a push-pull management strategy for spotted wing drosophila, and using aphid honeydew to extend the longevity of parasitoids of wheat stem sawfly. The value of cover crops to biological control is demonstrated with improved wheat stem sawfly biocontrol. Insect decline has been a major facet of research in entomology and ecology for some years now, but there are a lot of unanswered questions that will require dedicated funding and research on long time scales. Documented ladybug declines in field crops adds to the already grim picture of arthropod population health over spatial and temporal scales. Also presented were area-wide scale management programs to eradicate pink bollworm, protect pollinators and restore monarch habitat in agroecosystems.

The effects of decreased natural biological control on pest management practices was presented as was the performance against soybean aphid of aphid resistant genes isolated in soybeans. Further development of host plant resistance solutions, a technique requiring collaborative efforts from multiple disciplines, was highlighted in projects where resistant traits from small grains and sorghum were identified and genotyped and provided to stakeholders for further development. This has resulted in an increase in acreage of resistant hybrids.

But perhaps the best examples of integration of pest management research were the cross-cut programs.

Dr. Michelle Heck's crosscutting research on combating citrus greening disease or Huanglongbing (HLB) highlights both novel and applied research that directly address citrus stakeholders' needs for near term solutions to this devastating vector-transmitted plant pathogen. It truly integrates the research from several different Problem Statements. From 3A: The genomic analysis of grove collected Asian citrus psyllids indicated that multiple genes are involved in the transmission of HLB to commercial citrus. As such, gene medication of the vector to block transmission is unlikely to stop the spread of HLB. These findings have informed NIFA's Emergency Citrus Disease Research and Extension Program, as this competitive grant program no longer prioritizes modifying the insect vector to prevent HLB transmission. From 3B: The "Grove-First"model for testing commercially available therapeutic molecules is a big step forward for combatting HLB in FL's few remaining commercial orchards. And from 3C: The modified agrobacterium symbiont delivery biotechnology is a truly novel approach to treating HLB infection across the entire citrus tree. If successful this biotechnology could also treat other fruit tree pathogens. Some of these solutions came about almost by accident, or serendipity. This important research is a model for overcoming intractable research challenges in U.S. agriculture, involving improved invasive pest and disease (pathogen) management, understanding plant disease vector biology and ecology, fostering research collaborations among multiple stakeholder groups, and pushing the frontier of therapeutic tools (symbionts).

Another outcome of this crosscutting research is the demonstration of the benefit of understanding and using grower-led involvement in the research, development, and integration of new tools to manage a complex pest problem in perennial crops. Another outcome is the potential to apply this framework to other insect/disease complexes in perennial crops.

A regulatory question is the issue of using oxytetracycline in this system - what are the implications for microbial resistance? This issue is under scrutiny in the regulatory system. The potential for the new delivery symbiont strategy will be of great benefit to alleviate this risk.

Although significant advances have been made in citrus greening research, it is nevertheless astounding how little we still know about this pathogen and vector, and how to control them. However, it is anticipated that numerous novel tools and approaches to disease vector and plant disease management will result from this citrus greening research that will translate to other issues in U.S. agriculture. The effect of transgenic plants on aphid dispersal and virus incidence is interesting and should be studied more closely and replicated in other cropping systems that allow transgenic plants.

Other cross-cutting also addressed insect vectors of plant pathogens, including zebra chip disease, which is similar in many respects to citrus greening, and involved the dedicated work of numerous ARS scientists in multiple states working together with academia and industry to solve a major threat to the U.S. potato industry. Other plant diseases that are vectored by insects, such as Little Cherry Disease by leafhoppers, involved similar problem-solving approaches as seen with HLB and ZC. Viruses transmitted by whiteflies and aphids continue to present a global problem, but research by ARS scientists is yielding new insights and tools to stay ahead of these pernicious pests.

## COMPONENT 4. PROTECTION OF POST-HARVEST COMMODITIES, QUARANTINE, AND METHYL BROMIDE ALTERNATIVES

Many high-value commodities require intensive inputs to manage pests and diseases. Enormous losses are often incurred by ornamental growers and other fresh horticultural crops. Management in these systems traditionally tended to be reliant on multiple applications of broad spectrum insecticides. The research in this Problem Statement focuses on alternatives that are more ecologically and economically sustainable. While perhaps not as glamorous, or as well-known as some other areas of pest management, the economic impact of post-harvest loss makes this an extremely important area of research (the cost of Naval Orangeworm management in California almonds and pistachios alone exceeds $700M per year). *This research includes both new tactics and novel applications of established techniques. The work is immediately relevant given stakeholder needs, and benefits from input from those groups. It has a high potential for immediate and long-lasting impact and represents collaborative and independent research.*

**Problem Statement 4A: Manage Pests Affecting Fresh and Durable Commodities**

Applications of multiple management technologies to manage Naval Orangeworm (NOW) in tree nuts has provided some relief to California almond and pistachio growers. An area-wide program of mating disruption, similar to the programs for apple coddling moth in the Pacific Northwest, has been established. In addition, a collaborative pilot program using the sterile insect technique to manage NOW found in low recoveries of sterilized insects, resulting in improvements in establishing a new strain for release.

Keeping stored product pests from infesting stored commodities and 'finished food products' saves these products from insect damage and spoilage. Monitoring and identifying stored product pests quickly using AI techniques is an important area of research that can have far-reaching applications within entomology. Keeping stored product pests from infesting stored commodities in the first place by deploying deltamethrin-treated netting (Long-lasting insecticidal netting - LLIN) is a cost-effective way to protect valuable stored commodities, but if this is not possible, research has shown a way to disrupt stored product pests from reproducing and building up damaging population levels through mating delay/disruption. Genome sequencing is being used to elucidate the feeding histories and alternate hosts of Lesser Grain Borer, which is an insect pest of stored grain whose relocation throughout the country is facilitated by post-harvest transport of grain. Surprising results of the research indicated the insect is a wood borer and may find shelter in woody areas and that some grass species may act as both feed source and travel corridors between infestation sites. These results may provide valuable management insights during post-harvest movement, storage and processing.

**Problem Statement 4B: Improve and Develop Postharvest and Quarantine Treatments**

The loss of methyl bromide as a fumigant opened research opportunities to find alternatives. This research is critical to keep commodities pest-free during shipment to foreign export markets and prevent movement of invasive species to new areas of the globe.

New phytosanitary treatments were developed for NOW, psyllids, stink bugs, and mites. New potential products such as nitric oxide and sulfur dioxide were evaluated and their usage refined. And new products, including essential oils, were assessed for horticultural use.