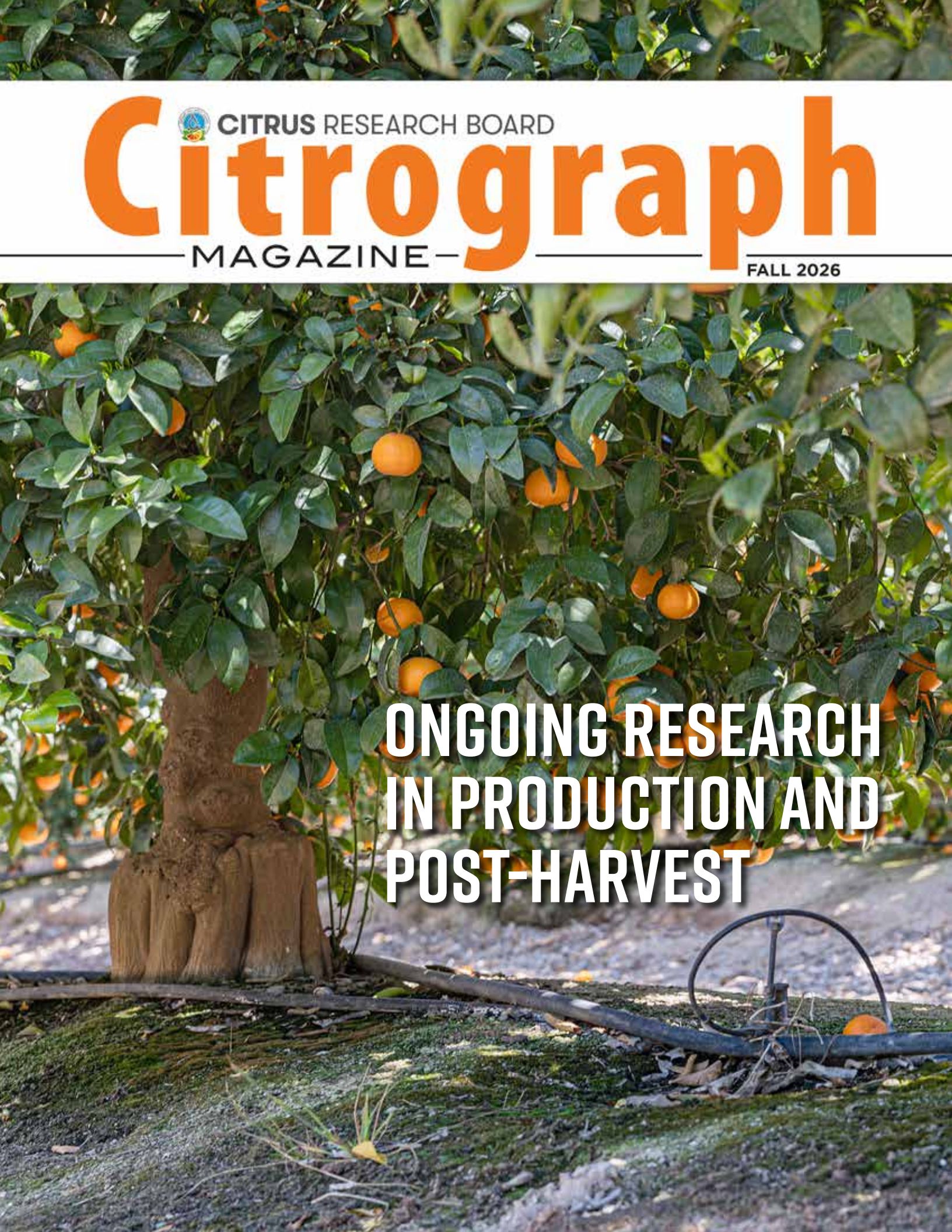
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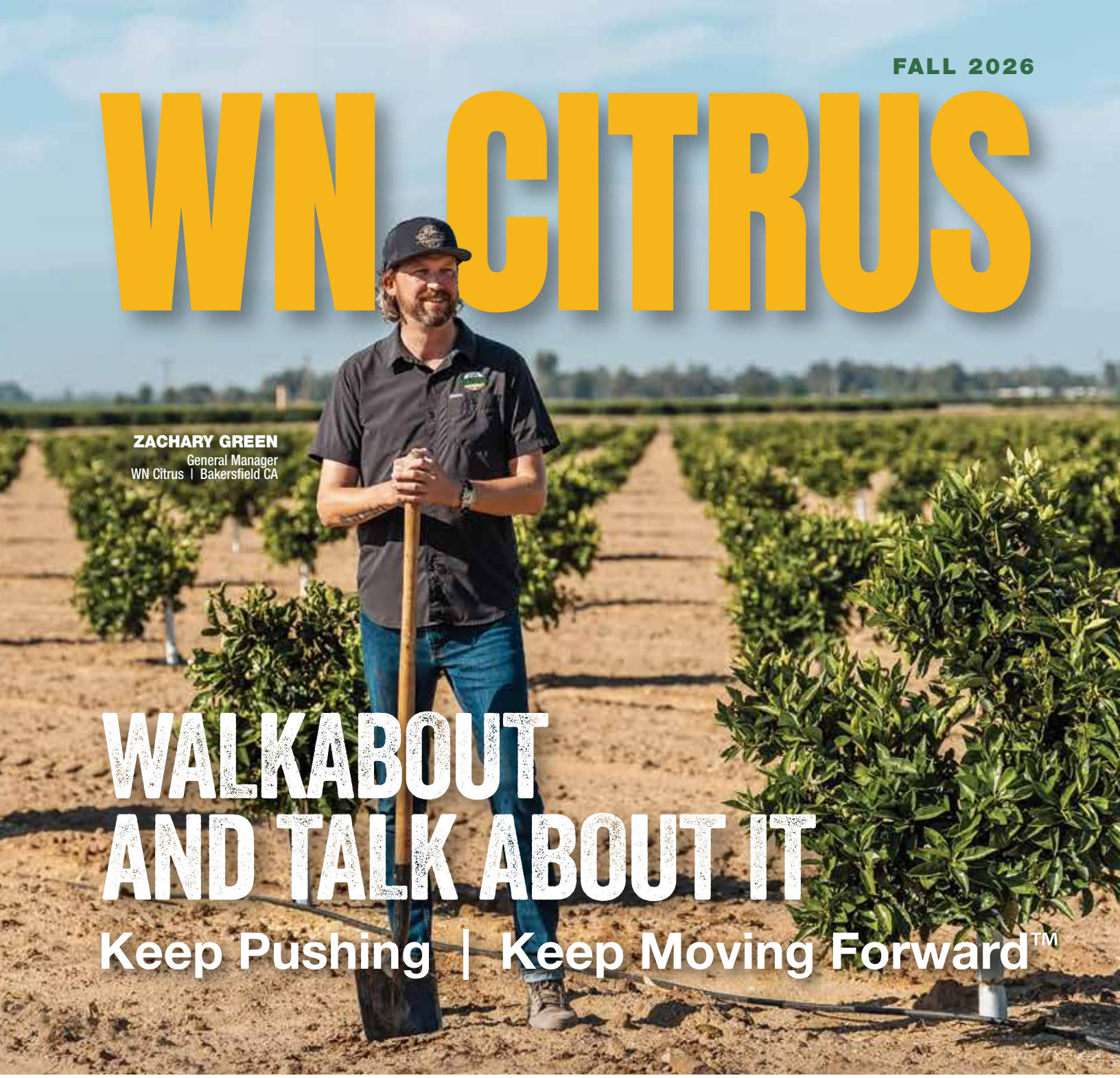
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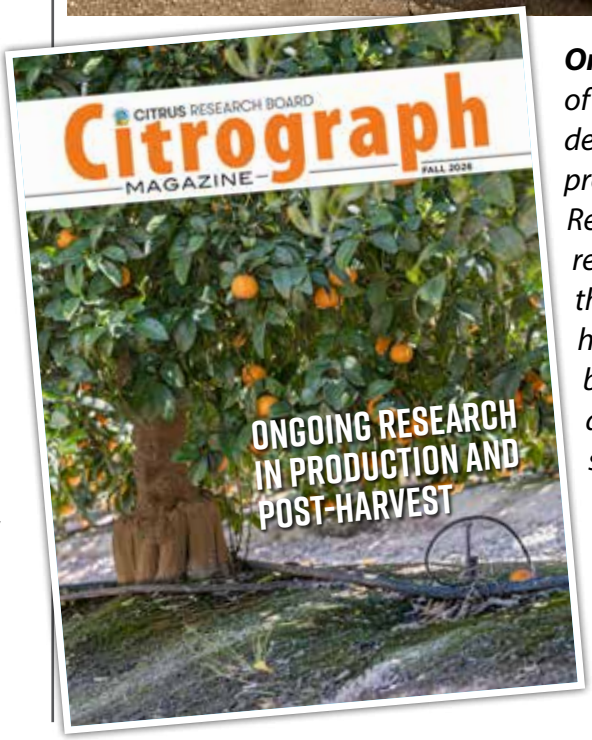
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On the Cover: *The fall 2026 issue of* Citrograph *highlights the latest developments in post-harvest and production efficiency that the Citrus Research Board is funding. The research and innovations featured throughout the issue demonstrate how science and technology are being applied to improve efficiency, address emerging challenges and support a more sustainable and resilient California citrus industry. We hope you enjoy this issue.*



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THE MISSION OF THE CITRUS RESEARCH BOARD

Ensure a sustainable California citrus industry for the benefit of growers by prioritizing, investing in and promoting sound science.

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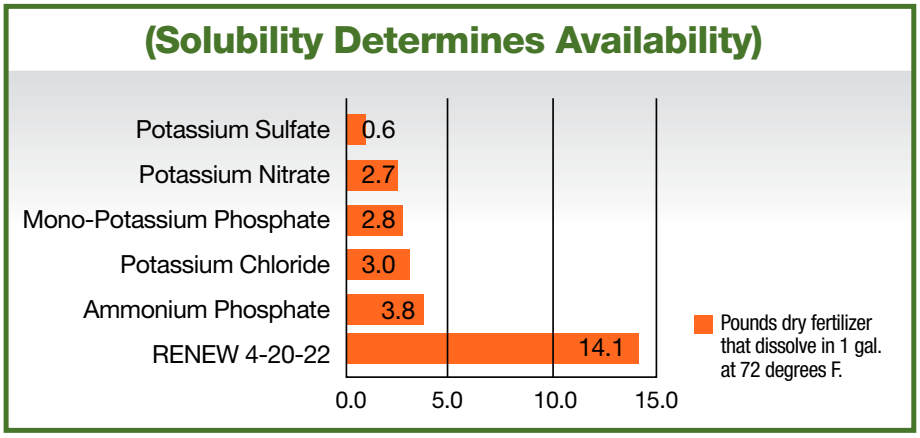
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NOVEMBER 18
CITRUS PEST AND DISEASE PREVENTION COMMITTEE (CPDPC) MEETING
For more information, visit *www.cdfa.ca.gov/citruscommittee*

JANUARY 28
CITRUS RESEARCH BOARD (CRB) BOARD MEETING
For more information, contact the CRB at (559) 738-0246 or visit *www.citrusresearch.org*

MARCH 10
CALIFORNIA CITRUS MUTUAL (CCM) CITRUS SHOWCASE
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From the PRESIDENT'S DESK

Marcy L. Martin

As we begin a new fiscal year, our commitment to California's citrus industry remains stronger than ever. While the challenges facing our growers continue to evolve, so do the opportunities to develop innovative, science-based solutions. Through collaboration with researchers, growers, industry partners, and government agencies, the Citrus Research Board (CRB) will continue investing in research that delivers practical tools and meaningful results. Together, we are building a more resilient, sustainable future for California citrus—one that will benefit not only today's growers, but the generations that follow.

This year, we have focused on several important production and post-harvest issues, including lemon pitting, water-use efficiency, Sweet Orange Scab, and other emerging challenges. Many of these research efforts are highlighted in this issue of *Citrograph*. CRB remains steadfast in its commitment to funding high-quality research and supporting internal programs that help California citrus growers remain productive, competitive, and resilient. One of our most significant initiatives is the California Citrus Research and Field Trials (CA-CRaFT) Program, launched in 2023 to improve the management of Asian citrus psyllid (ACP) populations in Southern

California. Supported by the United States Department of Agriculture's Huanglongbing Multi-Agency Coordination (HLB-MAC) Group, the program evaluates both preventative and threshold-based management strategies designed to reduce ACP populations and ultimately minimize the spread of huanglongbing (HLB).

Much of the program's work has focused on the Imperial and Coachella valleys, where intensive monitoring using traps, tap sampling, visual inspections, and canine detection has helped detect ACP populations at very low levels. These efforts allow infestations to be identified and treated early, reducing the potential for population growth and protecting California's commercial citrus industry. Results from the desert region continue to demonstrate that consistent monitoring combined with timely treatments is essential for effective ACP suppression.

Building on these successes, CRB is expanding the CA-CRaFT Program into Ventura County, where distinctly different growing conditions present new opportunities to evaluate additional management approaches. Because ACP is already well established in Ventura County's coastal environment, the detection methods and mitigation strategies that have proven effective in the desert may not achieve the same results there.

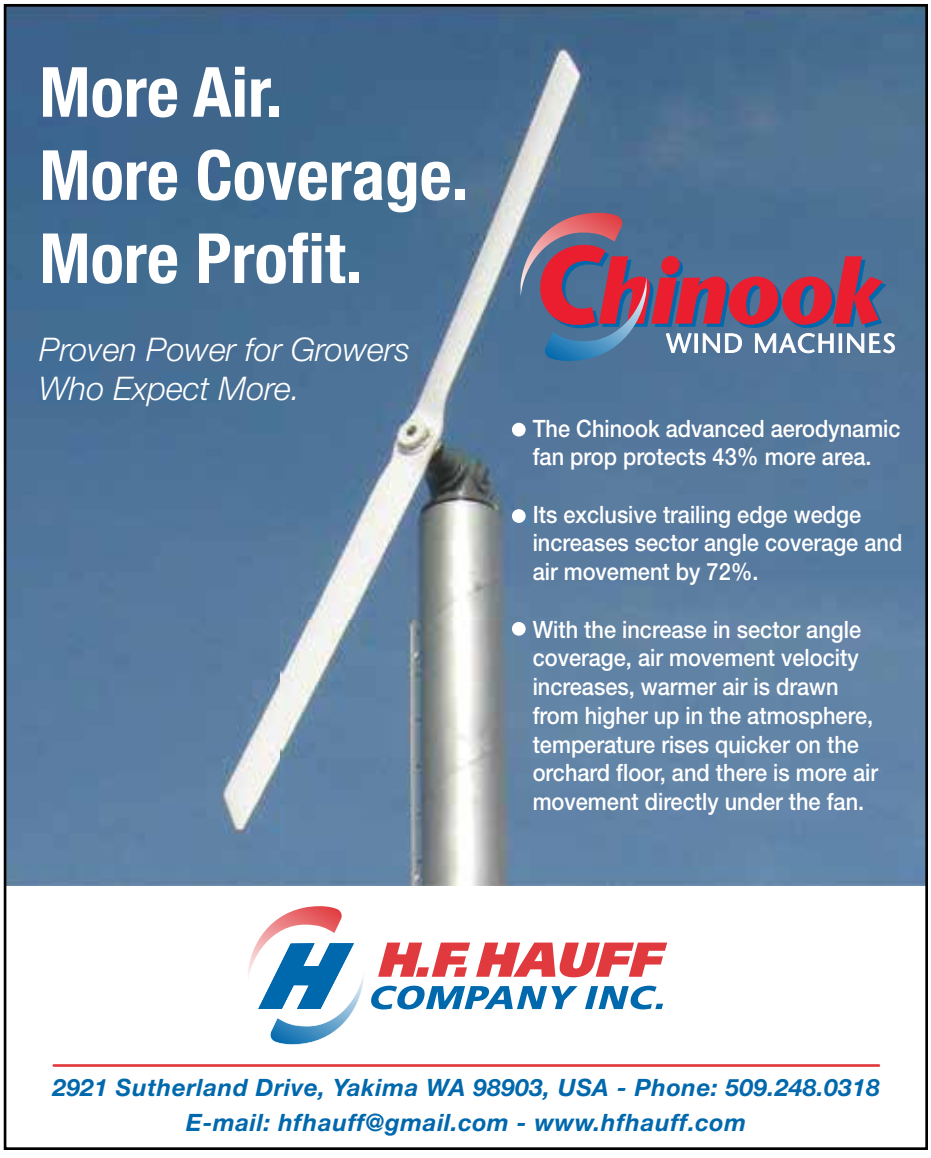
The Ventura County phase of the program will emphasize biological control, initially targeting approximately 2,000 acres. For many years, CRB has supported research on *Tamarixia radiata*, a beneficial parasitic wasp that attacks ACP nymphs and helps suppress psyllid populations. Researchers have developed an innovative self-release cage that allows *Tamarixia* to emerge naturally into surrounding groves while continuing to reproduce and disperse. Selected citrus blocks will receive self-release cages, while comparable blocks will serve as untreated controls. The initial phase will focus primarily on organic and low-input integrated pest management (IPM) groves, although conventional production sites are also being considered.

Growers interested in participating in the Ventura County CA-CRaFT Program are encouraged to visit ***citrusresearch.org*** for additional information and application details. We look forward to sharing updates on the program's progress in the Winter 2027 issue of *Citrograph*.

None of these accomplishments would be possible without the dedication of our grower Board and committee members, who generously contribute their time and expertise to review research proposals, identify industry priorities, and recommend investments that will benefit California citrus growers for years to come. Their commitment, together with the efforts of our research partners, staff, and growers, continues to strengthen California's citrus industry.

As we begin a new fiscal year, we remain focused on advancing science-based solutions that address today's challenges while preparing our industry for tomorrow's opportunities. Thank you for your continued partnership and support as we work together to ensure a strong, sustainable future for California citrus.

***Marcy L. Martin serves as the president of the Citrus Research Board, based in Visalia, California. She also is the executive editor of* Citrograph. *For more information, please contact* marcy@citrusresearch.org**



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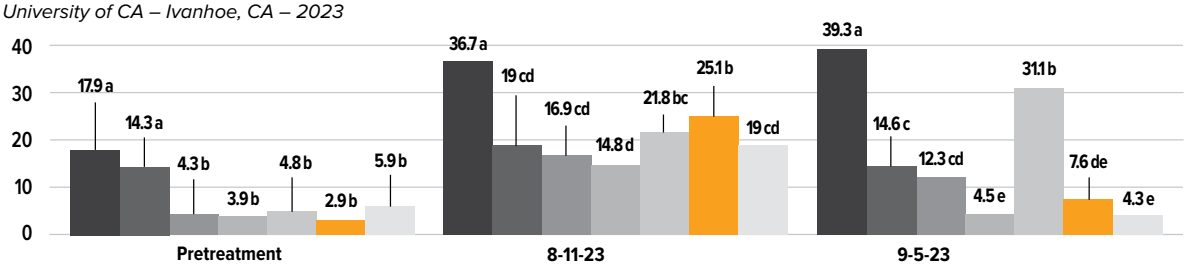
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University of CA – Ivanhoe, CA – 2023



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Research Updates to be Shared at the CALIFORNIA CITRUS CONFERENCE in October

Caitlin Stanton

At the 2024 California Citrus Conference, CRB's IPM entomologist, Ivan Milosavljević, Ph.D., provided an update on the CA-CRaFT Program as well as his ongoing work on Argentine ants.

The California Citrus Conference will return to Visalia, California, on October 21, 2026, and feature a variety of citrus research speakers. Growers, PCAs, packinghouse professionals, and affiliated industry personnel are invited to participate in this conference which will be held at the Visalia Convention Center and will showcase the best of the best in citrus research. Highlighted topics include updates on the fight against the Asian citrus psyllid (ACP) and huanglongbing (HLB), integrated pest management strategies, production technology, post-harvest food safety, and more. The last California Citrus Conference was held in 2024 and welcomed nearly 350 attendees for a full day of research talks and scientific poster presentations.

"The California Citrus Conference is an important venue to connect those in the field with CRB-supported researchers," said CRB President, Marcy L. Martin. "We look forward to sharing research updates with the industry at the 2026 conference."

Scheduled speakers include:

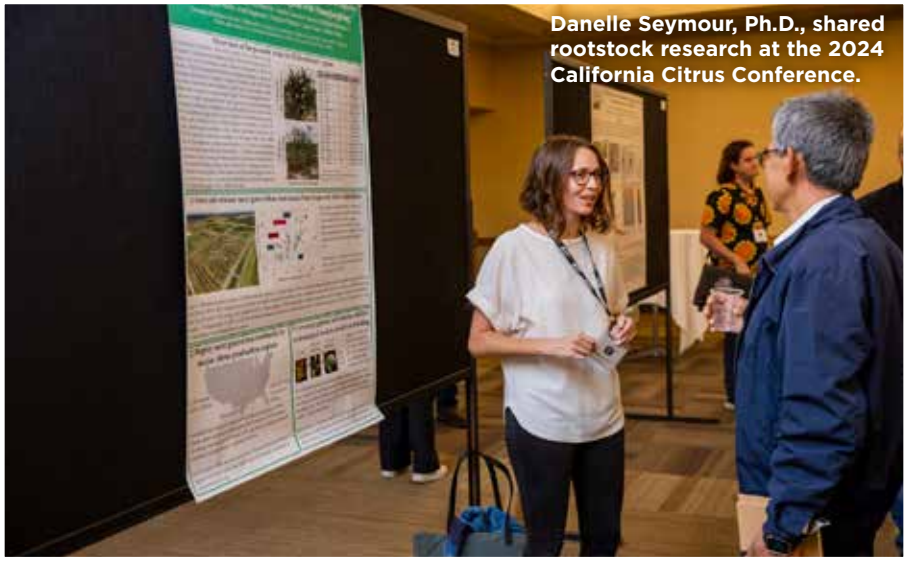
- David Haviland, University of California Agriculture and Natural Resources
- Ivan Milosavljević, Citrus Research Board
- Sandipa Gautam, University of California Agriculture and Natural Resources
- Danelle Seymour, University of California, Riverside
- Amanda Zito, Fresno County Agricultural Commissioner
- Jim Adaskaveg, University of California, Riverside
- Melinda Klein, Citrus Research Board
- Plus more speakers to be announced!



Jim Adaskaveg, Ph.D., spoke to attendees about ongoing Sweet Orange Scab detections at the 2024 California Citrus Conference.



The California Citrus Conference presented an opportune time for industry members to hear updated research on topics from integrated pest management to production practices and post-harvest research.



Danelle Seymour, Ph.D., shared rootstock research at the 2024 California Citrus Conference.

In addition to the scheduled speakers, posters featuring CRB-supported research will be displayed, and researchers will be available to answer questions. Continuing education units have been applied for and will be available to conference attendees, pending approval by the California Department of Pesticide Regulation (CDPR) and Certified Crop Advisors (CCA).

Registration for the conference is now open and highly recommended, as attendance has increased each year, and space is limited. To register or learn more about the conference, please visit ***citrusresearch.org***. Registered attendees will receive conference materials and admission to all sessions, along with a complimentary hot breakfast, lunch and break refreshments.

The CRB is pleased to once again hold the California Citrus Conference at the Visalia Convention Center. The convention center is located at 303 E. Acequia Avenue, with the Visalia Marriott at the Convention Center and Comfort Suites conveniently located nearby. Please contact the CRB Communications Department at *events@citrusresearch.org* with any questions about the California Citrus Conference.

We are thrilled to showcase the best of the best in citrus research and look forward to seeing you all in October.

***Caitlin Stanton is the director of communications with the Citrus Research Board and also serves as the editorial assistant of* Citrograph. *For more information, please contact* events@citrusresearch.org**



REGULATORY PARTNERSHIPS PROTECTING CALIFORNIA CITRUS: FROM GROVE TO PACKINGHOUSE

Dahmoon Maeesomy

California citrus growers understand that protecting citrus requires more than sound production practices. As invasive pests and diseases continue to threaten commercial citrus production, regulatory compliance and industry collaboration remain critical to safeguarding the future of California citrus. The California Department of Food and Agriculture's (CDFA) Citrus Pest and Disease Prevention Division (CPDPD) is mandated to protect California citrus from pests and diseases through early detection programs, timely and robust response activities, and science-based regulations. The CPDPD partners with growers, packers, processors, haulers, nurseries, County Agricultural Commissioners (CACs), researchers, and industry organizations to reduce the risk of pest and disease introduction and establishment, while supporting the efficient movement of citrus throughout





Figure 1 and 2. Proper safeguarding in transit

the state. While much attention is focused on the Asian citrus psyllid (ACP) and huanglongbing (HLB), regulatory programs extend across the citrus supply chain—from grove management to post-harvest handling and transportation.

Production Practices and Regulatory Responsibility

ACP remains the most significant insect threat to California citrus because it transmits HLB, the disease that has devastated citrus industries worldwide. HLB has no known cure, renders fruit unmarketable, and leads to tree decline and death. As a result, regulatory efforts focus on early detection, rapid response, quarantine enforcement, and coordinated suppression activities.

For growers, compliance with quarantine requirements and movement restrictions is an important part of statewide disease prevention. These measures protect not only individual operations but also neighboring groves and the broader citrus industry. The CPDPD maintains statewide trapping and survey programs to quickly identify pest and disease introductions before they become established. The regulatory decisions are informed by collaboration among the CDFA scientists, CACs, the United States Department of Agriculture, university researchers, and industry stakeholders. Growers also play a key role by monitoring groves and maintaining best management practices, reporting suspicious symptoms or pest detections, and following treatment and quarantine requirements when necessary.

Quarantines as a Prevention Tool

Quarantines remain an effective tool for preventing the spread of invasive pests and diseases. While they can create operational challenges, quarantines help protect commercial production regions from human-assisted movement pathways that can accelerate pest dispersal. California maintains regulatory programs addressing ACP, HLB, and other significant citrus threats. These programs establish requirements for moving fruit, nursery stock, equipment, and other regulated articles within and from affected areas. The goal is simple: reduce opportunities for pests and pathogens to spread while allowing growers and handlers to continue operating efficiently. As pest distributions and scientific knowledge evolve, regulatory requirements are reviewed and adjusted to ensure they remain effective while minimizing unnecessary burdens on industry operations.

The Critical Role of Packinghouses and Post-Harvest Operations

Protecting California citrus does not end at harvest. Packinghouses, processors, and transportation partners play a critical role in preventing pest movement by maintaining compliance with quarantine requirements. Post-harvest pathways represent some of the highest-risk opportunities for accidental pest spread. With large volumes of fruit moving throughout California and beyond, following proper safeguarding procedures is essential. Regulated facilities must follow protocols designed to reduce the likelihood of ACP movement during handling and transportation. Depending on the origin and destination of fruit, these requirements may include approved post-harvest mitigations, safeguarding measures, documentation, and compliance with quarantine restrictions. Recent regulatory updates demonstrate how science-based decision-making can improve operational efficiency while maintaining protections. In 2024, the CPDPD revised requirements governing certain bulk citrus movements between ACP and HLB quarantine areas. Under the revised framework,

restrictions were loosened on fruit moving from an ACP quarantine zone and HLB quarantine area to packers or processors located within HLB quarantine areas. However, safeguarding measures for fruit in transit, such as enclosed transportation or complete tarping of loads, remain mandatory (**Figure 1** and **2**). These adjustments reflect the Division's commitment to balancing risk management with practical industry needs while maintaining strong protection against artificial pest spread.

Looking Ahead

Protecting California citrus requires a comprehensive approach that integrates production management practices, scientific research, regulatory oversight, and industry collaboration. No single strategy can safeguard the industry alone. From grove inspections and detection surveys to packinghouse safeguards and transportation requirements, every component of the regulatory system contributes to reducing risk and protecting market access for California citrus. The CPDPD remains committed to working alongside growers, handlers, processors, nurseries, researchers, and industry partners to ensure California citrus continues to thrive despite increasing pest and disease pressures. Success depends on shared responsibility. Every stakeholder—from growers monitoring groves to packers implementing safeguarding procedures—plays a role in preserving the long-term viability of California's citrus industry. As threats continue to evolve, strong partnerships between industry, academia, and regulatory agencies will remain essential in protecting California citrus.

***Dahmoon Maeesomy is an agricultural pest control supervisor and statewide outreach coordinator for the CPDPD of the CDFA. For additional information, please contact* Dahmoon.Maeesomy@cdfa.ca.gov**

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CITRUS DWARFING TRIALS: Updates from Screening and Focused Experiments

Irene Lavagi-Craddock, Abigail Frolli, Bharani Manoharan, Alaaeldin Rezk, German Villalba-Salazar, Ashraf El-Kereamy, Carol Lovatt and Georgios Vidalakis



Measuring vegetative growth of trees in the dwarfing trial.

Project Summary

Building on the long-term transmissible small nuclear ribonucleic acids (TsnRNAs) field results (Lavagi-Craddock et al. 2025), this Citrus Research Board (CRB)-funded project expanded the evaluation of TsnRNAs as tools for citrus dwarfing across a wide range of commercially relevant rootstock-scion combinations. This effort included two complementary components:

1. ***A large screening experiment*** *including nine scion and eight rootstock varieties designed to identify promising combinations responsive to TsnRNA-induced dwarfing.*
2. ***A focused experiment*** *centered on Tango mandarins propagated on trifoliate-related rootstocks, selected based on industry interest.*

This article summarizes the progress made in these second-phase experiments and complements the long-term orchard performance data presented earlier.

California citrus faces mounting pressures, from rising production costs, limited water resources, labor shortages, and the ongoing threat of huanglongbing (HLB). These realities demand orchard designs that deliver greater efficiency and adaptability. One promising strategy to address this need is the development of smaller, more manageable citrus trees that can be planted at higher densities and more easily integrated into screenhouse production systems (Webster 2002).

For over three decades, researchers at the University of California have studied TsnRNAs—regulatory RNA molecules originally identified as viroids[1]—as biological tools for citrus dwarfing (Lavagi-Craddock et al. 2025; Semancik et al. 1997). Early field trials demonstrated that trees treated with TsnRNAs could achieve canopy volume reductions of up to 50%, without compromising fruit quality (Vidalakis et al. 2010, 2011). These reductions translated into real orchard benefits, including improved light penetration, easier pest

Table 1. High-priority scion and rootstock varieties selected for inclusion in the screening experiment.

SCIONS		ROOTSTOCKS	
Tango	mandarins (3)	16-6 Rich	trifoliate (1)
Nules Clementine		Carrizo	citranges (trifoliate x sweet orange hybrid) (1)
Shiranui		X639	trifoliate hybrids (other) (4)
Parent Washington navel	sweet oranges (3)	US 802	
Cara Cara navel		US 897	
Fukumoto navel		US 942	
Limoneira 8A Lisbon	lemons (1)	Schaub rough lemon	lemon (1)
Rio Red	grapefruit (2)	Sour orange	other (1)
Star Ruby			

Table 2. Canopy volume reduction in TsnRNA-treated trees relative to their non-treated controls (set at 100%) observed in four-year-old plantings in 2025. Each rootstock-scion combination consists of at least three treated and three untreated trees. Tree size measurements were taken in May 2025. Values are canopy volume reduction percentage in comparison to non-treated control. N.D. indicates no measured canopy difference from untreated control observed at four years.

	CARRIZO	RICH 16-6	SCHAUB ROUGH LEMON	SOUR ORANGE	US-802	US-897	US-942
Mandarin							
Fukumoto				N.D.			
Nules Clementine		**39.9**				N.D.	N.D.
Shiranui	**31.8**	**25.6**	N.D.	N.D.		N.D.	N.D.
Tango		N.D.					
Lemon							
Limoneira 8A		N.D.					N.D.
Sweet Orange							
Parent WA		**30.8**					
Grapefruit							
Rio Red		**49**	N.D.				
Star Ruby		**40**	N.D.		N.D.		

management, and reduced labor requirements (Lavagi-Craddock et al. 2022, 2025). Building on these foundational results, the final years of this CRB-funded project had three objectives:

1. **A large screening experiment** designed to evaluate the effect of TsnRNAs across more than 50 commercially relevant rootstock–scion combinations.
2. **A focused experiment** that narrows in on Tango mandarins on trifoliate-related rootstocks, reflecting industry interest in this high-value variety and its potential suitability for high-density systems.
3. **An evaluatation** of the long-term impacts and potential economic benefits using TsnRNAs.

Together, these trials intended to identify which combinations respond most strongly to TsnRNA treatments and were geared to supply the industry with actionable data on the long-term potential of TsnRNA dwarfing technology. This article provides an update on the second portion of the project, highlighting progress in both the large screening and focused experiments and setting expectations for the years ahead.

Large Screening Varietal Evaluation

The large-scale screening experiment was established at the Lindcove Research and Extension Center (LREC) in 2021 and is the most extensive evaluation of TsnRNA dwarfing conducted to date. The CRB Production and Post-Harvest Technology Research Committee refined the project's original design of 16 scions × 18 rootstocks, to a high-priority set of nine scions and eight rootstock varieties. Varieties were chosen to capture both industry-standard selections and emerging materials of commercial interest (**Table 1**).

Two sets of plantings were completed; the first in 2021, and a second in 2024. The field plantings encompass the majority of the possible rootstock-scion combinations (53 out of 78) from the nine different scion varieties grafted onto eight different rootstocks (**Table 1**), which provides an excellent opportunity to explore the dwarfing potential of TsnRNAs on a wide range of rootstocks and scions of high commercial value for California producers.

Each rootstock-scion combination was represented by trees inoculated with a mixture of

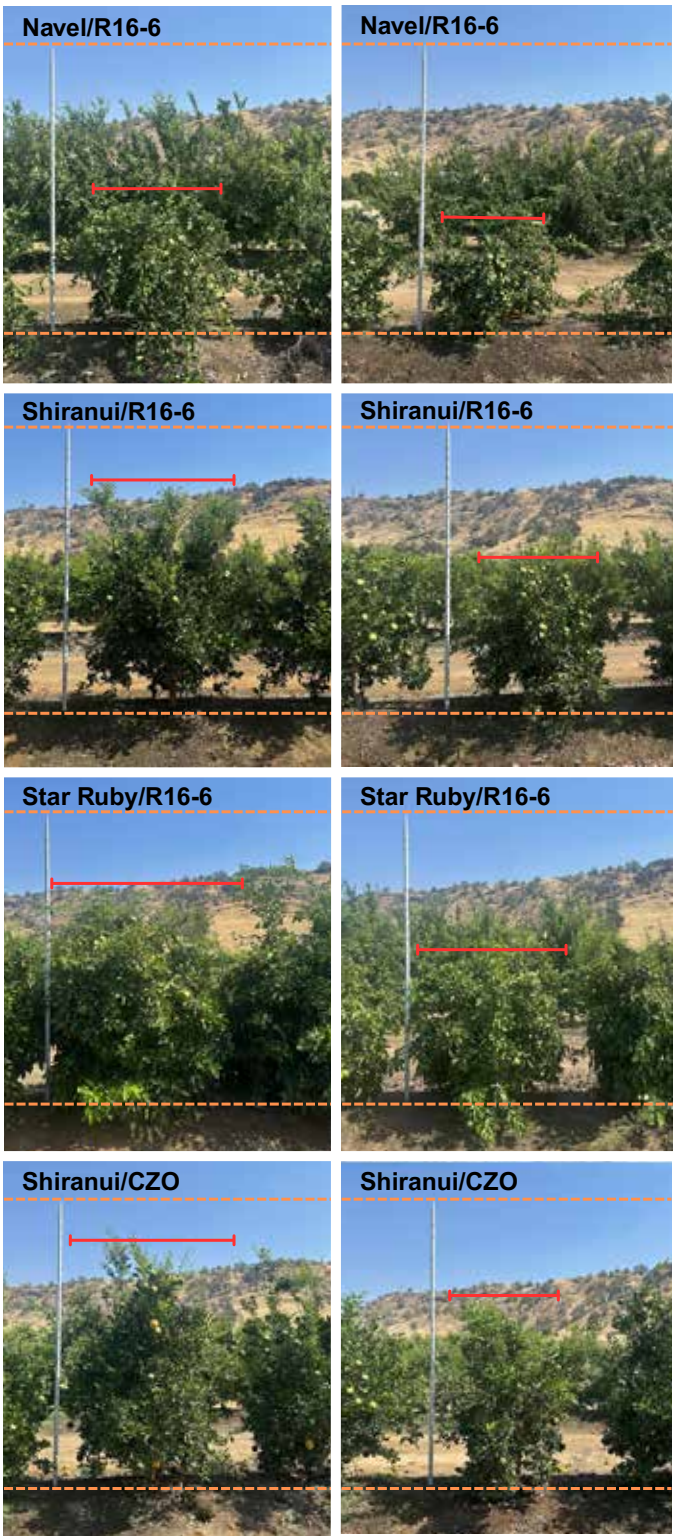


Figure 1. Early reduced canopy volume effect of TsnRNA mix (Ia, IIa, IIIb) on four-year-old navel (Parent Washington), mandarin (Shiranui) and grapefruit (Star Ruby) trees on Rich 16-6 (R16-6) trifoliate rootstock, and mandarin (Shiranui) on Carrizo (CZO) rootstock (2021-2025) in an experimental block (planting density 6 x 10 ft). TsnRNA-mix-treated trees (right) displaying reduced canopy volume compared to the non-treated controls (left). Photos taken in September 2025.

TsnRNAs (Ia, IIa, IIIb), which had been previously shown to dwarf citrus trees, or left untreated as controls, allowing for side-by-side preliminary tree size comparisons. The goal of this trial was not only to document whether dwarfing occurs, but also to determine which combinations consistently respond, how strongly they respond, and whether the effect holds across citrus types—mandarins, navels, grapefruit, and lemons.

As previously shown in long-term trials, phenotypic dwarfing requires four to five years to emerge (Vidalakis et al. 2010, 2011). For this reason, most combinations planted in 2021 still appear similar to their untreated counterparts. Even so, early divergence is beginning to appear in a few rootstock–scion combinations including mandarins, sweet orange, and grapefruit (**Figure 1** and **Table 2**).

Several scion varieties grafted on Rich 16-6 are exhibiting clear canopy volume reductions following TsnRNA treatment compared to untreated control, including Nules Clementine mandarins (39.9%), Rio Red grapefruit (49.0%), Star Ruby grapefruit (40.0%), Shiranui mandarins (25.6%), and Parent Washington navel oranges (30.8%). At this early stage, Shiranui is the only scion propagated on Carrizo rootstock that shows a canopy-volume reduction compared to the untreated control (31.8%). These early responses align with the dwarfing patterns documented in the long-term Field 41 trial, providing independent confirmation from a separate planting (Vidalakis et al. 2010).

The 2024 planting included additional high-priority rootstock-scion combinations treated with the same TsnRNA mix (Ia, IIa, IIIb) or left untreated as controls, allowing for side-by-side comparisons as these combinations became available. The first canopy volume measurements, collected in September 2025, approximately one year after planting, provided valuable baseline data. As expected for one-year-old trees, no phenotypic dwarfing is yet visible; meaningful canopy differences typically emerge only after the fourth or fifth year and are therefore not expected to be observed until approximately 2028–2029. A complete list of these one-year-old rootstock-scion combinations is provided in **Table 3**.

This TsnRNA screening trial provides a crucial foundation for identifying which scion–rootstock combinations respond best to TsnRNA-induced dwarfing, enabling the selection of appropriate combinations for subsequent trials that can include identification of the critical TsnRNA treatment, as well as evaluation of flowering, yield, and fruit quality under high density or screenhouse plantings. While most of the trees are still too young to show visible reductions, the first canopy differences observed in grapefruit and mandarins echo the patterns reported in earlier long-term studies (Vidalakis et al. 2010, 2011; Semancik et al. 1997). Over time, these findings will guide the industry toward combinations that combine commercial relevance with reliable dwarfing. The ultimate goal is to support high-density orchard systems, reduce input costs, and provide options that are more easily adapted to future challenges such as HLB management and the potential expansion of screenhouse production systems.

Table 3. Canopy volume reduction in TsnRNA-treated trees relative to their non-treated controls observed in one-year-old plantings in 2025. Each rootstock/scion combination consists of at least three treated and three untreated trees. Tree size measurements were taken in September 2025. N.D. indicates no measured canopy difference from untreated control observed at one year.

	CARRIZO	RICH 16-6	SCHAUB ROUGH LEMON	SOUR ORANGE	US-897	US-942	X639
Mandarin							
Fukumoto	N.D.	N.D.	N.D.		N.D.	N.D.	N.D.
Nules Clementine	N.D.		N.D.	N.D.			N.D.
Tango	N.D.		N.D.	N.D.	N.D.	N.D.	
Lemon							
Limoneira 8A	N.D.		N.D.	N.D.			N.D.
Sweet Orange							
Cara Cara	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Parent WA	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	
Grapefruit							
Rio Red	N.D.			N.D.			
Star Ruby				N.D.			

Table 4. Experimental design of the focused experiment of Tango mandarin on Trifoliate rootstocks. The TsnRNA mix (Ia, IIa, IIIb) and the single-component TsnRNA-IIIb were included in this experiment as required depending on the rootstock/scion combination used as control. Each treatment consists of at least three treated and three non-treated trees. Appropriate biological controls were selected based on known responsiveness.

ROOTSTOCK	SCION	TSNRNA	TREATMENT
Carrizo	Tango	Mix	Tests whether the TsnRNA mix induces dwarfing in the Tango/Carrizo combination.
Carrizo	Algerian Clementine	Mix	Included only under Mix because this combination responds to the TsnRNA mix, not to IIIb; serves as a concurrent positive biological control for Tango/Carrizo.
Rich 16-6	Tango	Mix	Evaluates Tango on trifoliate under the TsnRNA mix.
Rich 16-6	Navel	Mix	Concurrent positive biological control for Tango/Rich 16-6 under the Mix treatment.
Rich 16-6	Tango	TsnRNA-IIIb	Tests Tango on trifoliate under the IIIb treatment.
Rich 16-6	Navel	TsnRNA-IIIb	Concurrent positive biological control for Tango/Rich 16-6 under IIIb; helps distinguish treatment vs. scion effects.

Focused Experiment: Tango on Trifoliate Rootstocks

While the screening experiment provides a broad survey across varieties, for the identification of TsnRNA responsive scion-rootstock combinations, the focused experiment was designed to take a closer look at a high-value scion–rootstock system identified by growers, Tango mandarin on trifoliate-related rootstocks. This smaller Tango trial, with all related control treatments (**Table 4**), complements the large screening block by focusing on a combination that is commercially relevant and worthy of closer attention, as identified through grower surveys and committee input. This design allows researchers to collect in-depth data on additional horticulturally important traits beyond tree size, such as precocity[2] and fruit quality evaluations.

The focused experiment was planted in 2024, and, in addition to Tango, the design included Algerian Clementine grafted onto Carrizo and navel grafted onto Rich 16-6 as concurrent positive biological controls. These combinations were selected based on previously reported TsnRNA-induced dwarfing responses (Vidalakis et al. 2010, 2011; Semancik et al. 1997). These materials provided important comparisons for understanding whether the dwarfing response in Tango was unique or whether mandarins and navels would behave in a similar way. Treatments also included both TsnRNA-treated and non-treated controls, allowing direct evaluation of canopy volume, as well as flowering and fruiting patterns over time (**Table 4**).

In consultation with the CRB Production and Post-Harvest Technology Research Committee, it was agreed that canopy volume would serve as the primary early parameter to monitor. Field inventories conducted in 2025 confirmed that a sufficient number of trees remained alive and healthy for meaningful evaluation, despite planting losses of a few individuals. The first tree measurements performed in September 2025, approximately one year after planting, served as an essential baseline, but were not yet predictive of long-term dwarfing. At this early stage, no differences in tree size were recorded in any of the rootstock/scion/TsnRNA combinations. This outcome was expected. As with the younger trees of the

screening trial, trees planted in 2024 are too young for visible dwarfing to emerge.

Looking Ahead

This project established key early benchmarks for TsnRNA-induced citrus dwarfing under California conditions. Although definitive canopy effects will require several more years to emerge, the early reductions observed in grapefruit and mandarin support further monitoring as the trials mature. Together, the screening and focused trials will provide the California citrus industry with more information about the dwarfing potential of TsnRNAs across commercially relevant California varieties, including Tango on trifoliates.

CRB Research Project #5100-154

Glossary

[1]Viroids: Infectious small RNA species, typically 300-600 nucleotides that do not encode any protein and can only be transmitted and replicated in plants.

[2]Precocity: The degree to which a tree begins fruiting earlier than normal for its variety and rootstock.

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HOW MUCH WATER ARE YOUR CITRUS TREES REALLY USING?

Satellites Have an Answer - But Is It Accurate?

Daniele Zaccaria and Pasquale Steduto

Project Summary

How much water do your citrus trees actually use in a season? And can satellite model tools—now widely used by several water agencies—give you accurate enough numbers to rely on? This research project sets out to answer those questions. Our UC Davis research team surveyed growers, orchard managers, certified crop advisers (CCAs), irrigation specialists and practitioners, and water managers to understand what level of evapotranspiration (ET) accuracy is considered acceptable for real water-accounting decisions. We then measured actual ET in well-managed commercial citrus orchards in Tulare, Kern, and Riverside counties using advanced micrometeorological methods and equipment. These field measurements allowed us to compare real citrus water use against ET estimates produced by satellite remote-sensing (SRS) models, specifically available through the OpenET web platform. We learned that OpenET models currently overestimate citrus ET by 30% or more, mainly because they miss important daily changes in how citrus trees regulate water use under hot, dry afternoon conditions. Our findings give the California citrus industry a clear, science-based assessment of current ET tools and point to practical steps for improving satellite ET estimates to support more efficient and sustainable water management under growing scarcity and climate uncertainty.

Addressing Water Challenges in California Citrus Production

California produces nearly 80% of all citrus in the United States, yielding 4.15 million tons of fruit in 2023, worth more than $2.5 billion (United States Department of Agriculture, 2024). The citrus acreage is dominated by oranges and mandarins, respectively with 137,663 and 68,830 acres (California Department of Food and Agriculture, 2024).

But the major citrus-growing regions, especially the San Joaquin Valley and the desert areas of Riverside County, face increasing water restrictions driven by drought, groundwater depletion, and tighter environmental regulations.

As climate conditions become more variable, accurate evapotranspiration (ET) information is essential for managing irrigation, verifying water use under the Sustainable Groundwater Management Act (SGMA), planning sustainable citrus acreage, and supporting groundwater sustainability and long-term water allocation decisions.

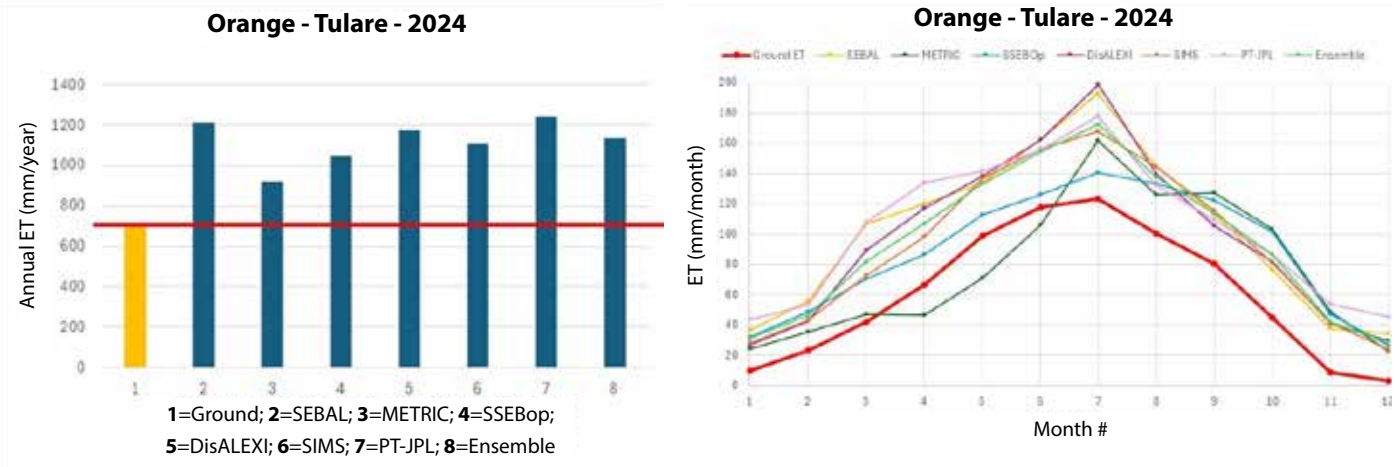


Figure 1. Annual Ground-measured ET and SRS-based ET estimates by the seven models of OpenET (left graph). The dark red line provides reference to Ground-measured ET for comparison to model estimates. Monthly variation of Ground-ET and SRS-ET by the OpenET models (right graph). Data refers to the orange orchard study in Tulare County in 2024.

Yet much of the existing citrus ET information for microirrigated orchards is outdated or inconsistent. Citrus water use varies widely depending on citrus species, tree age and density, row orientation, canopy size, and local climate —factors that most current datasets do not fully represent. At the same time, groundwater sustainability agencies (GSAs) and other water management entities (e.g. irrigation districts, water storage districts, reclamation districts, water conservation districts, etc.) are adopting satellite-based model tools like OpenET (etdata.org), even though these models have had little validation in real citrus production orchards. This project directly addressed those knowledge gaps by measuring citrus ET in the field and comparing it with satellite estimates.

Survey Results and Field Measurements

To better understand how crop ET information is used across California's citrus industry and to assess stakeholders' expectations regarding its accuracy, a statewide bilingual (English-Spanish) survey was conducted. Forty-three growers, crop advisors, and irrigation and water-agency professionals responded to the Citrus ET survey. More than 80% said they use ET information regularly—many on a weekly or even daily basis—and nearly 70% felt that satellite-based ET estimates should stay within 10% error. At the same time, many believed current tools often miss that mark. Most participants said inaccurate ET estimates pose a significant economic risk, and over 85% rated accurate ET information as essential for water planning and for keeping California citrus operations profitable. Overall, the Citrus ET survey responses point to a strong need for better accuracy, clearer methods, and more transparent communication about satellite-derived ET products.

Using eddy covariance[1] towers installed in seven commercial orchards, mandarins and oranges in Tulare and Kern counties, and young and mature lemons in Riverside County, we measured actual citrus ET across the 2023-2025 seasons. Key findings showed that the seasonal actual ET of mandarin orchards in Tulare County (20-year-old trees) ranged from 28 to 47 inches per season (April-October), whereas mandarin orchards in Kern County (6-year-old trees) ranged from 17 to 21 inches per season. For orange orchards, seasonal actual ET ranged from 24 to 26 inches per season in Tulare County (25-year-old trees) and from 26 to 30 inches per season in Kern County (25-year-old trees).

In the Coachella Valley, mature lemons (14-year-old trees) used the most, (i.e., 36-42 inches of water), due to hotter, drier desert conditions, whereas young lemons (6-year-old trees) used less (27-35 inches of water) than mature lemons but still more than mandarins and oranges in Kern County and oranges in Tulare County. These differences in actual ET primarily reflect variations in citrus species, orchard age, canopy development, local growing conditions, and management practices. The consistent multi-year measurements provided a reliable benchmark for evaluating satellite models.

We then compared ground ET measurements with the ET estimates produced by seven satellite remote sensing-based (SRS) models encompassed in the OpenET Platform (version 2.1)*. Examples of these comparisons are shown in **Figure 1** for the orange orchard study in Tulare County and in **Figure 2** for the mandarin orchard study in Kern County. To evaluate how closely satellite-based ET estimates matched field measurements, researchers calculated the Normalized Root Mean Square Error (NRMSE), a statistical indicator that expresses the average difference between estimated and measured ET as a percentage. Lower NRMSE values indicate greater accuracy of ET estimates, while higher values indicate

Platform models included eeMETRIC (earth engine Mapping Evapotranspiration at High Resolution with Internalized Calibration), geeSEBAL (google earth engine Surface Energy Balance Algorithm for Land using), SSEBop (Operational Simplified Surface Energy Balance), ALEXI/DisALEXI (Atmosphere-Land EXchange Inverse/Disaggregation of the Atmosphere-Land EXchange Inverse), SIMS (Satellite Irrigation Management Support), PT-JPL (Priestley-Taylor Jet Propulsion Laboratory), and OpenET Ensemble.

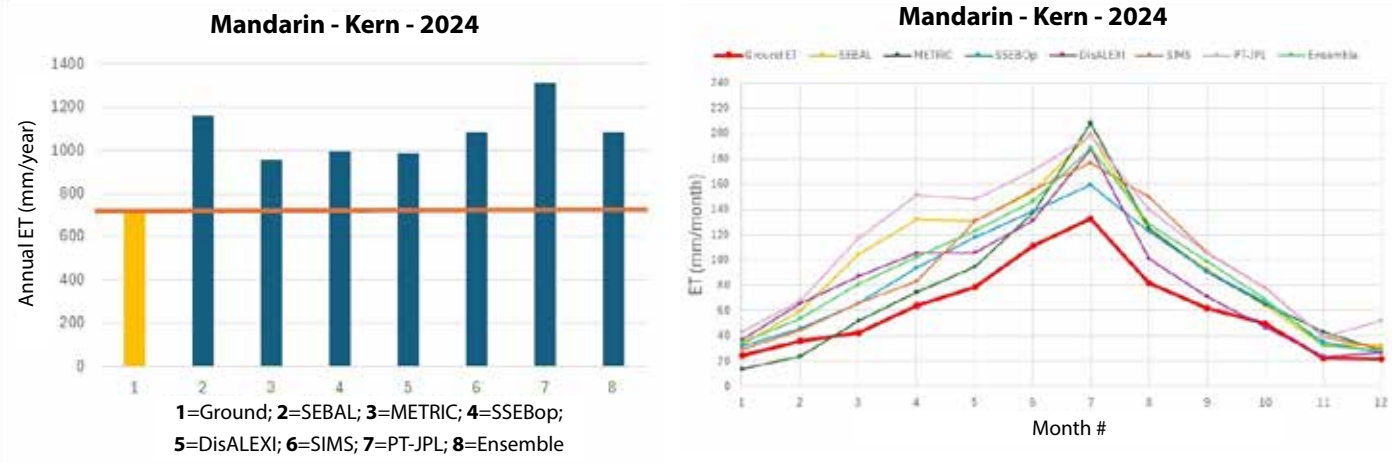


Figure 2. Annual Ground-measured ET and SRS-based ET estimates by the seven models of OpenET (left graph). The dark orange line provides reference to Ground-measured ET for comparison to model estimates. Monthly variation of Ground-ET and SRS-ET by the OpenET models (right graph). Data refers to the mandarin orchard study in Kern County in 2024.

larger estimation errors. **Table 1** presents the set of errors, expressed by NRMSE, for the SRS-ET estimates from the OpenET Ensemble model for all study orchards over the 2023-2025 period. Across all orchards and years, we found that:

i. ***Satellite ET is consistently too high.*** Most SRS-based models overestimated citrus ET by 12% to 80%, with the largest errors occurring for oranges and mandarins and the smallest in lemons. **Figures 1** and **2** show examples of this overestimation.

ii. ***Errors vary by location and year.*** In Tulare County, oranges showed some of the highest overestimation. In Kern County, mandarins tended to show larger errors. Lemons had the lowest overestimation errors (typically 20% to 30%). Errors tended to increase during hotter, drier years (i.e., 2023 in Tulare County; 2024 in Kern County; 2025 in Coachella Valley).

iii. ***Why did overestimation occur?*** A key citrus trait explains it. Satellites pass over California around 10:00 - 10:15 a.m. local time, when the air is still relatively humid. Since citrus trees are highly sensitive to air dryness (known as vapor pressure deficit, or VPD) (Fereres et al. 2012), as the day heats up and the air dries, citrus leaves progressively close their stomata, reducing transpiration, especially in late morning and afternoon. As such, satellites capture the trees when they are using more water than they would for most of the afternoon. As a result, the daily water-use estimate ends up too high. Air turbulence around the trees due to wind can also affect the microclimate in the orchards by breaking up the leaf's boundary layer and carrying away the stagnant shell of humid air. While moderate turbulence helps the plant release heat and enhances water vapor diffusion, high winds can cause excessive moisture stress, triggering the stomata to close. In detail, to prevent critical water loss during high winds or excessive turbulence, citrus stomata—especially on exposed canopy leaves—partially close. This restricts both gas exchange and transpiration during hours when the trees are exposed to windy conditions and high air turbulence. The daily tree transpiration behavior was confirmed by measuring leaf stomatal conductance collected throughout the daylight hours on multiple dates over the crop seasons, using a portable photosynthesis and gas exchange measuring device (CIRAS 3, PP Systems). Stomata opened in the morning and gradually closed as VPD increased over the course of the day. This daily pattern is not reflected in satellite data unless the models are specifically calibrated for citrus.

These findings align with previous results comparing SRS-based ET estimates with ground-based eddy covariance measurements of actual ET in California citrus systems by Dhungel et al. (2024). That study reported average overestimations of 30% or more from the OpenET Ensemble model for orange and mandarin orchards in Tulare County during 2021-2022.

Without adjustment, satellite-derived ET values may give an inflated picture of citrus water use. This can affect irrigation management and perceived crop water needs, water use reporting for SGMA and groundwater budget calculations, evaluation of district or regional water demand, and decisions about sustainable citrus acreage.

Our findings demonstrate that ground measurements of ET remain essential for validating and improving satellite models. We believe that this also points to the need for:

- Better calibration of satellite ET algorithms for microirrigated citrus production systems;
- Adjustments for citrus sensitivity to VPD;
- Improved handling of orchard canopy structure and air turbulence; and
- Local validation before applying ET estimates for regulatory or management purposes.

Table 1. Normalized Root Mean Square Errors (NRMSE) values determined for the OpenET Ensemble model for orange, mandarin, and lemon study orchards in Tulare, Kern, and Riverside counties over the 2023-2025 period.

ORCHARD	COUNTY	YEAR	NRMSE (%)
Orange	Tulare	2023	–
		2024	62
		2025	36
	Kern	2023	27
		2024	44
		2025	56
Mandarin	Tulare (two orchard blocks)	2023	29
		2024	23
		2025	19
	Kern	2023	53
		2024	59
		2025	76
Lemon, young	Riverside	2023	22
		2024	22
		2025	20
Lemon, mature	Riverside	2023	21
		2024	20
		2025	25

Until these refinements are adopted, SRS-based ET values for citrus should be used with caution.

Conclusion

The project results provide the California citrus industry with a clear, science-based assessment of current ET tools and practical guidance for improving SRS-based ET estimates to support more efficient and sustainable water management under growing water scarcity and climate uncertainty. This information is critical for quantitative assessments of sustainable citrus acreage, groundwater extractions, and surface water allocation necessary to maintain high-quality citrus production in regions with declining aquifers and highly variable surface supplies. It also supports efforts to improve water management, maintain fruit yield and quality, and strengthen the long-term competitiveness of California's citrus sector.

The project findings show that current SRS-based ET models can significantly misrepresent the actual citrus water use when not calibrated for local air dryness and air turbulence conditions across the orchards. As a result, existing satellite-derived ET values should be used cautiously and critically by growers, crop and irrigation consultants, water managers, and agencies to avoid unintended impacts on various decision-making processes related to irrigation and water-management planning.

CRB Research Project #5400-170

Glossary

[1]Eddy covariance: Micro-meteorological method to directly measure energy fluxes between ecosystems and the atmosphere.

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UPDATE ON LEMON PEEL PITTING IN THE CENTRAL VALLEY

Ashraf El-kereamy, Meagan Iott, Antonio Gonzalez, Sandipa Gautam, James Adaskaveg and Mary Lu Arpaia

Project Summary

This project continues to study the potential factors causing lemon pitting in Central Valley orchards. During the 2025 season, research efforts focused on identifying pitting locations in-field and measured fruit growth and insect presence over the course of the growing season to explore a potential connection between pitting and mite damage suggested from previous seasons. Fruit evaluation at harvest revealed greater pitting severity within orchards, on outer rows and facing southern exposures. Fruit position within the tree canopy (e.g. upper vs. lower canopy fruit) did not demonstrate a significant effect on lemon pitting incidence or severity. Weekly insect monitoring in 2025 showed a strong positive relationship between two-spotted spider mite pressure, particularly during March through May, and pitting severity at harvest. Thrips populations were not associated with pitting incidence. Current season activities include intensive monitoring in eight of the 12 orchards, with insect and fruit development surveys starting earlier with more data collection to better refine potential correlations to pitting. Ongoing analyses will further evaluate the relationships between commercial field activities, orchard microclimate, pest pressure, fruit growth, nutrition, pruning practices, and lemon pitting development.

Introduction

Lemon pitting continues to be a key problem affecting Lisbon lemon production in California's Central Valley. Since the initiation of this project in 2023, a comprehensive effort has been underway by University of California researchers, in conjunction with the Citrus Research Board staff, to identify the factors associated with pitting in order to provide growers with science-based management recommendations to reduce its incidence and economic impact. The project is examining orchard management inputs and practices, weather, pests, pathogens, nutrition, and phenological development of flowers and fruit in 12 commercial lemon orchards in Fresno, Tulare and Kern counties representing a wide range of pitting incidence and severity. Participating growers have provided detailed records of their fertilization, irrigation, pest management, and cultural practices, while localized weather stations installed in each orchard collect site-specific environmental data, including air temperature, relative humidity, and wind speed and direction. Field surveys are ongoing to monitor insect populations, fruit growth, pruning intensity, nutritional status, and fruit damage throughout the growing season. As reported in previous *Citrograph* articles (Mayorquin and Klein 2023; El-Kereamy et al. 2024), several hypotheses are being investigated. This article provides an update on recent findings from the 2025 and 2026 seasons.

Lemon Pitting and Harvest

The goal for the 2025 harvest was to answer a fundamental question: Is lemon pitting driven by the spatial architecture of the orchard? We evaluated more than 15,000 individual fruits across the 12 ranches using a zero-to-five damage scale developed by Dr. Mary Lu Arpaia. On this scale, a score of two indicated that 20% to 40% of the fruit surface was covered with pitting damage, allowing us to uncover a significant spatial pattern. Fruit facing the eastern sides and fruit on the outermost rows consistently bore the highest pitting counts and worst surface damage (**Figure 1** and **2**). Row position did not necessarily impact whether a fruit was damaged or not, but rather amplified symptom severity, suggesting that environmental conditions could exacerbate an initial factor. Interestingly, when Dr. Arpaia's team collected fruit in the upper versus lower canopies across 3,000 fruits, they found no difference in damage. The orchard's macro-layout and directional exposure mattered far more than fruit height in the canopy. Physiologically, this exposure may be intimately tied to fruit growth. By tracking fruit length and width throughout the season and translating the data into calculated volume, future analyzes will evaluate the hypothesis that rapid fruit expansion, compounding with orchard directional position, may have a relationship with the development of pitting.

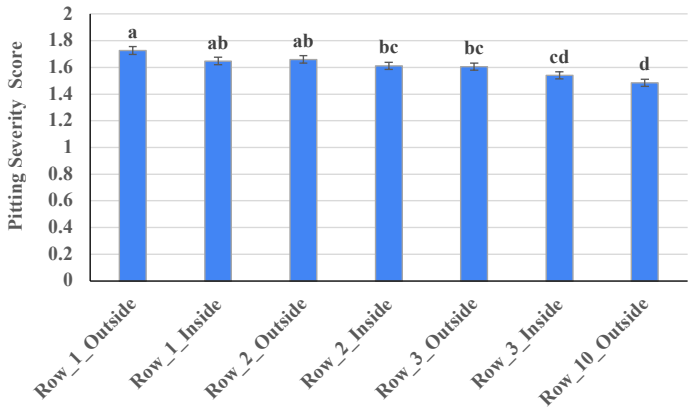


Figure 1. Average pitting severity score with standard error across row positions, across all ranches during the 2025 harvest. Pitting severity score ranges from zero to five. A severity score of two has 20% to 40% fruit surface covered with pitting damage. Statistical analysis was performed using Tukey HSD. Different letters signify statistical difference between treatments.

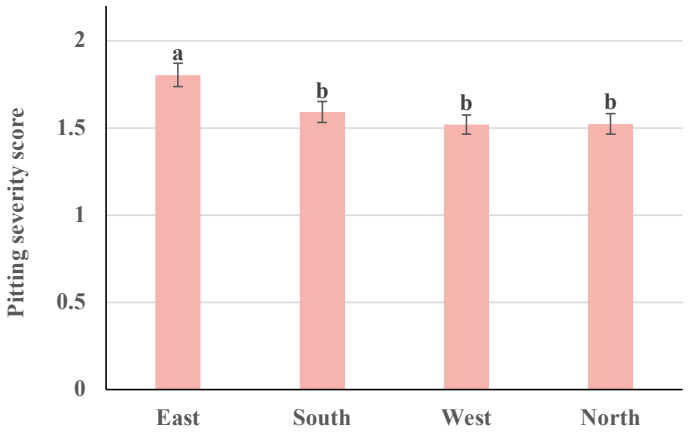


Figure 2. Average pitting severity score with standard error across the four orchard directions, across all ranches during the 2025 harvest. Pitting severity score ranges from zero to five, with five being the most severe. A severity score of two has 20% to 40% fruit surface covered with pitting damage. Statistical analysis was performed using Tukey HSD. Different letters signify statistical difference between treatments.

Lemon Pitting and Insects

Insect survey data collected during the 2025 season showed no real connection between thrips and pitting, but two-spotted spider mites (TSSM) emerged as a possible culprit. Annual TSSM pressure (measured bi-monthly between March and June 2025 and monthly between July and September 2025) shared a strong positive correlation with levels of damage seen at harvest (R^2 value of 0.82), meaning those ranches where high mite populations were surveyed were likely to also have fruit that was more severely damaged by pitting (**Figure 3**). Further data analysis of the relationship between mite pressure and pitting damage by direction in the orchard is ongoing.

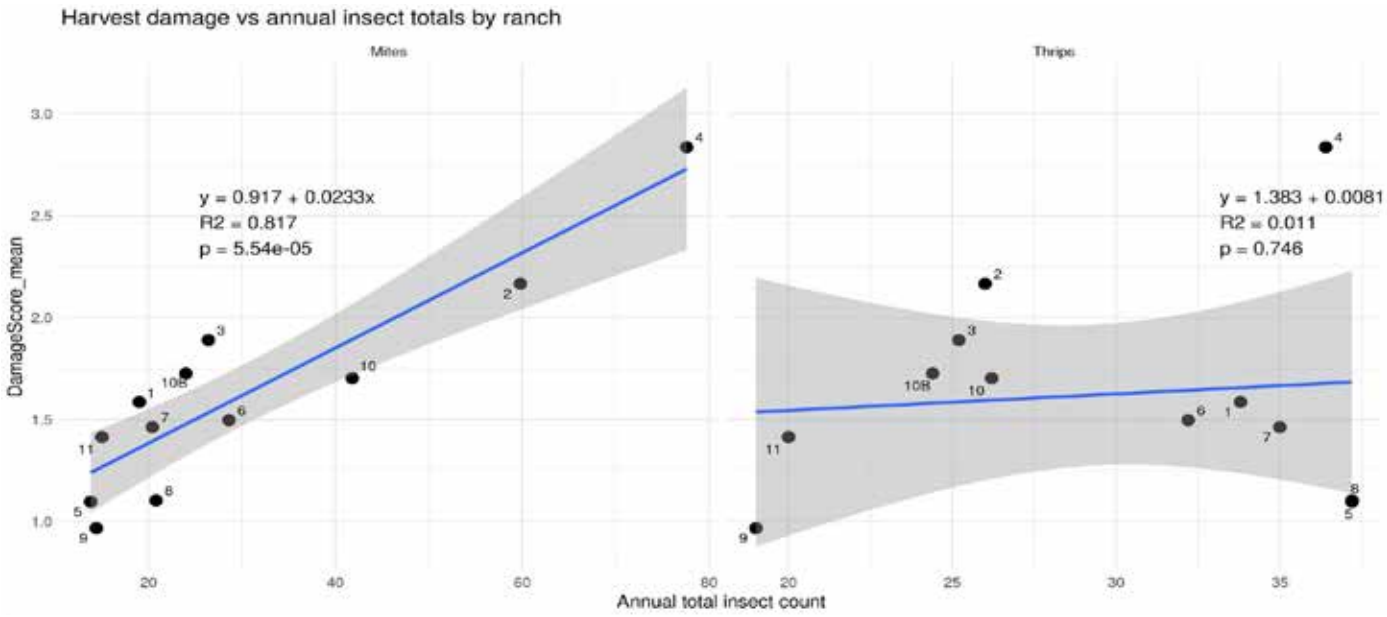


Figure 3. Correlation between total insect counts of two-spotted spider mite (left) and thrips (right) during the 2025 season and overall average lemon pitting damage severity score at harvest for each ranch. Strong correlation is provided by R^2=0.82 with p-value < 0.05.

Survey Activities in the 2026 Season

A major focus during the current season has been evaluating the impact of pruning severity due to previous visual observations in the 2025 growing season of ranches with high volumes of pruning seemingly to have less pitting damage. By tracking tree canopy volumes before and after pruning in the 2026 growing season, we hope to capture widespread differences in grower strategies for canopy architectures which will be cross-referenced with 2026 harvest data to determine if pruning intensity has any relationship with the amount or severity of pitting damage in the orchard. Fruit development and overall fruit damage are being mapped through rigorous weekly sampling. Since classification of damage as pitting damage cannot be completed until color break, all fruit damage is being captured. By monitoring length and width, we calculate total fruit volume to track growth rates.

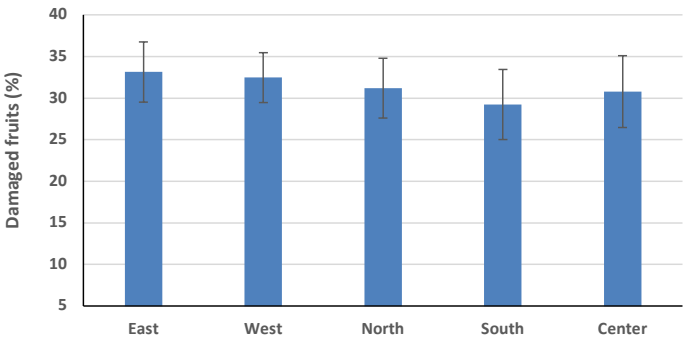


Figure 4. Overall average and standard error of percent fruit damage across the different orchard directions as of May 14, 2026.

During the first three weeks of monitoring fruit development (April 3 – April 16), fruit expansion remained slow across all sites. However, a rapid growth surge occurred between weeks nine and 11 (April 30 – May 14), during which differences in growth rates within the ranches emerged. Spatially, fruits growing on the south and east sides of the orchards developed noticeably larger volumes (data not shown). This rapid fruit enlargement window will be further examined to determine its relationship to fruit damage. Fruit damage assessments during this window show a range between 10% and 40%, with damage escalating sharply from April 23 and onward (data not shown). The current percentage of fruit damage is higher on the eastern sides of the groves, with southern sides of the groves currently showing the least percent damage with no significant differences among directions (**Figure 4**). We will keep following this percentage of pitting throughout the 2026 season.

Pest dynamics and biological timeline of the TSSM are being documented this season across both leaves and flowers (**Figure 5**). On leaves, mite populations statistically did not change over time, though a significant decrease in population was seen between the last two weeks in April. Mite pressure was heavily dictated by grove location and tree orientation. Ranch 6 supported the highest leaf density and southern exposures across all orchards, hosting significantly more leaf mites than any other direction. On flowers, TSSM populations peaked a bit earlier, spiking sharply on April 10, 2026, with Ranches 4 and 6 suffering the highest floral infestations. Unlike the leaves, directional orientation did not statistically change flower mite density, though TSSM adults and eggs

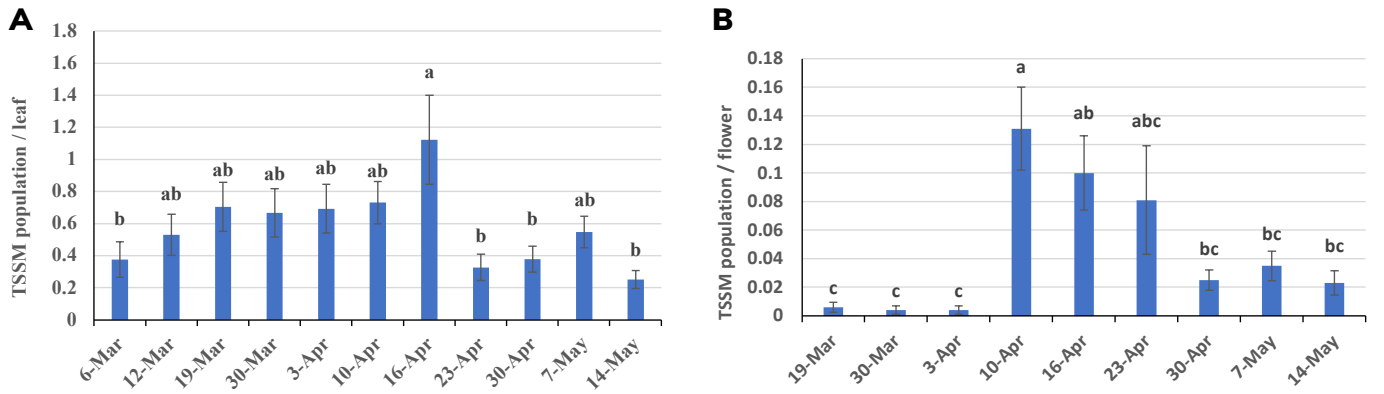


Figure 5. Seasonal changes in the population of two-spotted spider mite found on leaves (graph A) and flowers (graph B) from March to May 2026 across eight orchards in the project. Statistical analysis was conducted using Tukey HSD with different letters signifying statistical difference.

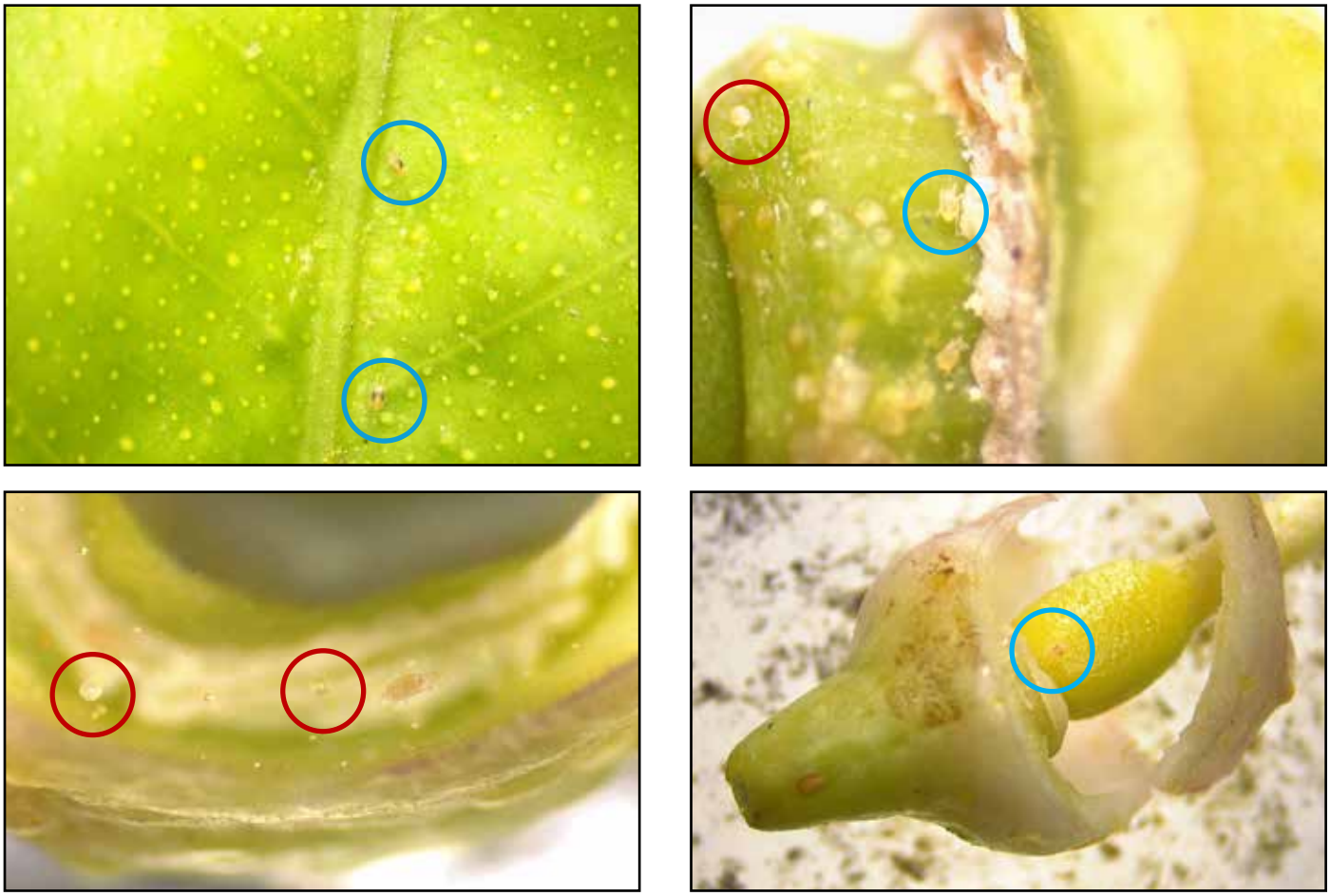


Figure 6. Detection of two-spotted spider mite (TSSM) eggs (red circles) and adults (blue circles) on the leaves, calyx, and fruit during petal fall in the 2026 growing season.

were actively detected at petal fall on the calyx, leaves, and developing fruitlets (**Figure 6**).

To wrap up the comprehensive study, researchers are currently analyzing 24-hour weather data (temperature, humidity, wind speed and direction) and spring leaf nutritional assays, which showed wide grove-to-grove variations in critical elements like nitrogen and calcium.

Conclusions

The results from the 2025 season and a review of the initial survey efforts in the 2026 season continue to demonstrate that lemon pitting is a complex disorder influenced by multiple interacting factors. Significant differences in pitting severity were observed by orchard direction, suggesting that orchard direction could play an important role.

Damage incidence increased during periods of rapid fruit enlargement and was generally greater on the east and south sides of orchards, though further analysis is needed. TSSM populations were strongly associated with pitting severity on the fruit, whereas thrips showed no consistent relationship with the disorder. Ongoing studies on weather conditions, pruning practices, nutrition, and mite management will help identify the key factors contributing to pitting development and support the development of effective management strategies for California lemon growers.

CRB Project #5400-172

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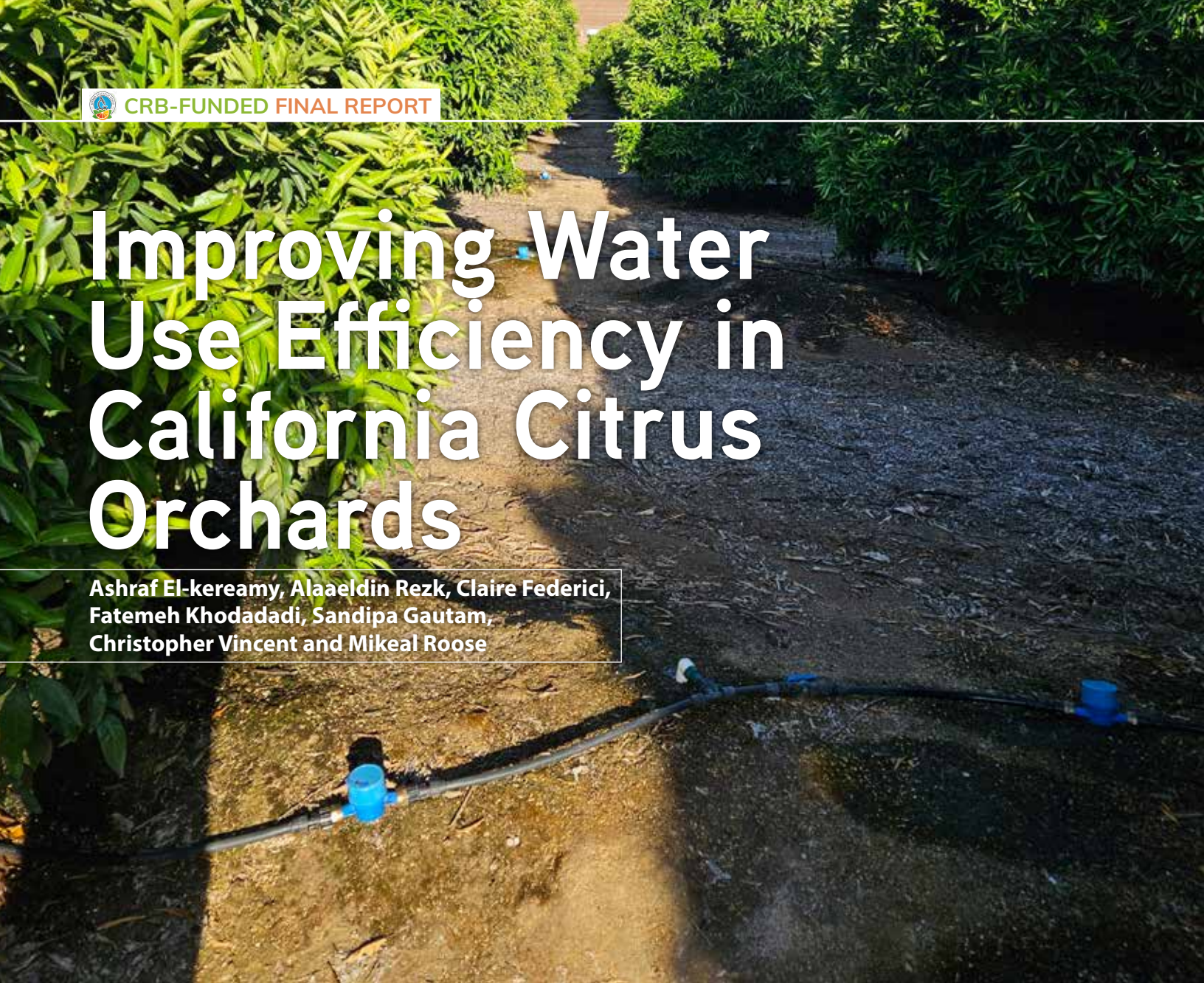
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CRB-FUNDED FINAL REPORT

Improving Water Use Efficiency in California Citrus Orchards

Ashraf El-kereamy, Alaaeldin Rezk, Claire Federici, Fatemeh Khodadadi, Sandipa Gautam, Christopher Vincent and Mikeal Roose

Project Summary

This project evaluates multiple strategies to improve water use efficiency in citrus production under limited water conditions. A trial of mature 'Nules' Clementine mandarin trees at the Lindcove Research and Extension Center in Exeter, California, was used to evaluate the response of 20 rootstocks to late-season deficit irrigation at 75% of predicted evapotranspiration (ET). Only a few traits differed significantly among rootstocks, and high variation in water applied to different plots make the results difficult to interpret. A range of irrigation technologies and cultural practices were evaluated on 'Parent Washington' navel orange and 'Tango' mandarin trees, with the goal of maintaining orchard yield and fruit quality while reducing water use during the 2024 and 2025 seasons. Results suggest that some irrigation technologies have the potential to reduce water use while maintaining citrus production. Longer-term, multi-year trials are needed to draw a conclusion.

Introduction

Water is quickly becoming the most limiting factor for citrus production in California. With ongoing drought and new requirements under the Sustainable Groundwater Management Act (SGMA), growers must find ways to use less water while maintaining yield and fruit quality. Fan-jet irrigation has long been the standard system in citrus orchards, but it can also lead to water loss through evaporation and wind drift. In addition to irrigation practices, rootstock selection plays an important role in how efficiently trees use water and tolerate stress. This project evaluated practical irrigation strategies, cultural practices, and rootstock selection to improve water use efficiency and support tree performance under limited water conditions.

Project Goals

1. Determine the effect of various rootstocks on the response of 'Nules' Clementine mandarin to water limitation.
2. Determine the effect of various cultural practices on 'Parent Washington' navel orange and 'Tango' mandarin water use.
3. Determine the cost of each irrigation system and the water savings.

Current Results

The first objective was to test drought tolerance of mature trees on various citrus rootstocks to provide growers with new information on existing rootstocks and guide breeding for more water efficient rootstocks. Differential irrigation treatments were applied to a previously reported 2012 trial (Roose and Federici 2023) of Nules Clementine on 22 rootstocks at the Lindcove Research and Extension Center (LREC) (**Table 1**). Two rootstocks were eliminated from the data analysis. Trees on Sun Chu Sha were likely budded with the wrong scion, and Tosu had too few surviving trees. Adjacent replicate plots were paired with one plot receiving normal irrigation and the other receiving reduced irrigation

Table 1. Rootstocks used in the drought tolerance study, whether currently released or still experimental, the number of trees on each rootstock in the trial when drought treatments were imposed in September 2024, and comments on whether the rootstock is used for commercial citrus production anywhere in the world. For experimental rootstocks, the comment indicates whether current information indicates it is likely to be released.

ROOTSTOCK	STATUS	TOTAL TREES	COMMERCIAL USE OR POTENTIAL
African Shaddock x 'Rubidoux' trifoliate	Released	12	Limited by CTV susceptibility
'Australian trifoliate #22'	Experimental	12	Good (standard in Australia)
'Bitters' (C22) (Sunki x Swingle trifoliate)	Released	12	New, some use
'Brazilian' Sour Orange	Released	12	Used, but limited by CTV
'C146'(Sunki x Swingle trifoliate)	Released	12	New, little use yet in CA
'C35' citrange	Released	12	Commercial Use
'Carrizo' citrange	Released	12	Commercial Use
'Cleopatra' mandarin	Released	12	Commercial Use
'Furr' (C57) (Sunki x Swingle trifoliate)	Released	12	Little use so far but new
Macrophylla	Released	12	Commercial Use
'Pomeroy' trifoliate	Released	12	Commercial Use
'Rich 16-6' trifoliate	Released	12	Commercial Use
'Rubidoux' trifoliate	Released	12	Commercial Use
Rangpur x 'Marks' trifoliate	Experimental	12	Release possible
Rangpur x Shekwasha	Experimental	11	Release unlikely
Rangpur x 'Swingle' trifoliate	Experimental	12	Release unlikely
Shekwasha x 'English' trifoliate	Experimental	12	Release possible
'Schaub' rough lemon	Released	12	Commercial Use
'Swingle' citrumelo	Released	12	Commercial Use
'Volkameriana'	Released	11	Commercial Use

Table 2. Yield and packline data summed (yield and fruit number) or averaged (all other traits) over the two years of treatment.

TRAIT	IRRIGATION TREATMENT	100% ET	75% ET	IRRIGATION X ROOTSTOCK	ROOTSTOCK
Statistic	(p value)	Mean	Mean	(p value)	(p value)
Fruit Weight (g)	0.08	89	83.7	0.32	<0.0001
Fruit Density (g/ml)	0.23	0.87	0.88	0.26	<0.0001
Yield per Tree (lb)	0.5	345	328	0.17	<0.0001
Number of Fruit/Tree	0.84	1799	1819	0.06	<0.0001
Fruit Size Class	0.1	3.88	3.69	0.4	<0.0001
% Grade E (under or small)	0.77	3.24	3.35	0.41	0.0005
% Best Size (large,jumbo,mamm)	0.2	55.8	51.1	0.28	<0.0001
% Small or Under Size	0.14	15.5	19.2	0.37	<0.0001
Rind Color Index (mean)	0.037	6.92	6.79	0.0068	<0.0001
% Best Color (% orange or better)	0.35	44.5	43.5	0.14	<0.0001
Rind Texture (larger =rougher)	0.05	6.08	5.82	0.54	0.0044
Rind (% rind not ridges etc.)	0.35	84	84.5	0.29	0.1041
Roundness	0.19	92.9	92.1	0.33	<0.0001
Smoothness	0.65	88.4	88.1	0.85	0.0515
Flatness	0.55	11.2	11.3	0.3	<0.0001
Elongation	0.66	4.34	4.33	0.08	<0.0001
Brix (IQS1)	0.14	11.35	11.49	0.23	<0.0001
Granulation (IQS2)	0.61	29.9	30	0.65	0.0081
Granulation (IQS3)	0.25	30.1	30.4	0.66	0.0048

(drought treatment). Irrigation used fan jets (FJ), with normal irrigation set for eight hours, and the frequency of irrigation was adjusted to apply water at 100% of predicted evapotranspiration (ET). Drought treatments on six replications reduced the duration of each irrigation from eight hours to six hours.

Reduced irrigation treatments were applied from early September to harvest in early to mid-December in 2024 and 2025. Fall 2024 flowmeter readings showed that the deficit irrigation treatments received an average of 70% of the water applied to normal irrigation plots, but the amounts per deficit irrigation plot varied greatly. During winter 2025, we attempted to correct the high variation by testing and replacing pressure regulators and flowmeters. However, these efforts were not successful. Fall 2025 flowmeters indicated that three of the deficit irrigation plots received 80% to 84% of the water applied to the paired normal irrigation plots, but the remaining three deficit irrigation plots received 101% to 107%. However, if the flowmeter data is accurate, then some drought treatments received as much or more water than normal treatments, and the variation among supposed replicate plots was very high. Due to the discrepancy between flowmeter and manual deficient projections, all data analysis of the results are not based on flowmeter data. There was no significant correlation between flowmeter readings and yield.

Because clementines can display alternate bearing, we combined single-tree yield and packline data over the two seasons of drought treatment. This analysis (**Table 2**) showed that deficit irrigation produced significantly greener and smoother fruit. Our purpose was to detect significant differences among rootstocks in response to the two irrigation levels. This is called a significant irrigation by rootstock interaction effect. If only a few rootstocks show significant responses, then it is likely that the overall effect of reduced irrigation would not be significant. Most traits did not show a significant irrigation by rootstock interaction, including weight per fruit, fruit density, average fruit size class, percent small size class, rind texture, roundness, smoothness, flatness, Brix (as measured by packline), and granulation. The only trait with a significant irrigation by rootstock interaction was the rind color index (**Table 2** and **Figure 1**), with most rootstocks producing fruit in the orange-yellow (6) to orange (9) range. Most rootstocks differ only slightly between irrigation treatments, with generally lower (less orange) values for fruit from the deficit treatment, but the drought treatment

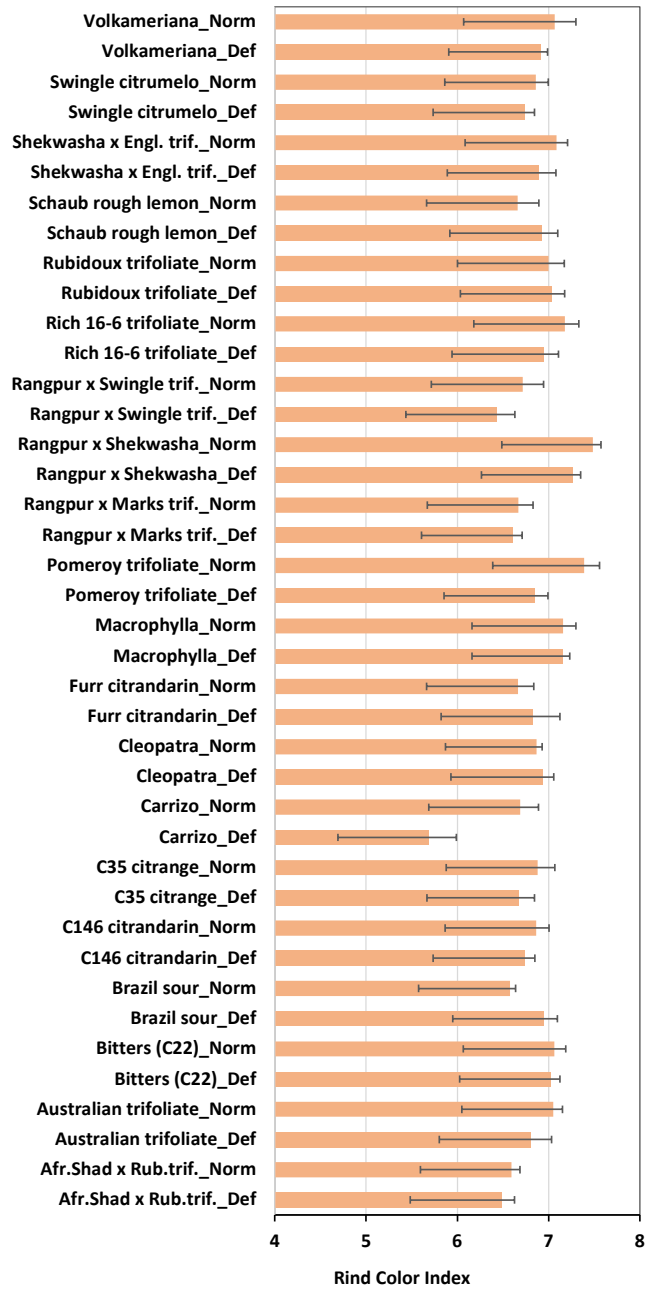


Figure 1. Means and standard errors for Rind Color Index for 20 rootstocks with normal (Norm) or deficit (Def) irrigation in combined data from December 2024 and December 2025 harvests at the Lindcove Research and Extension Center.

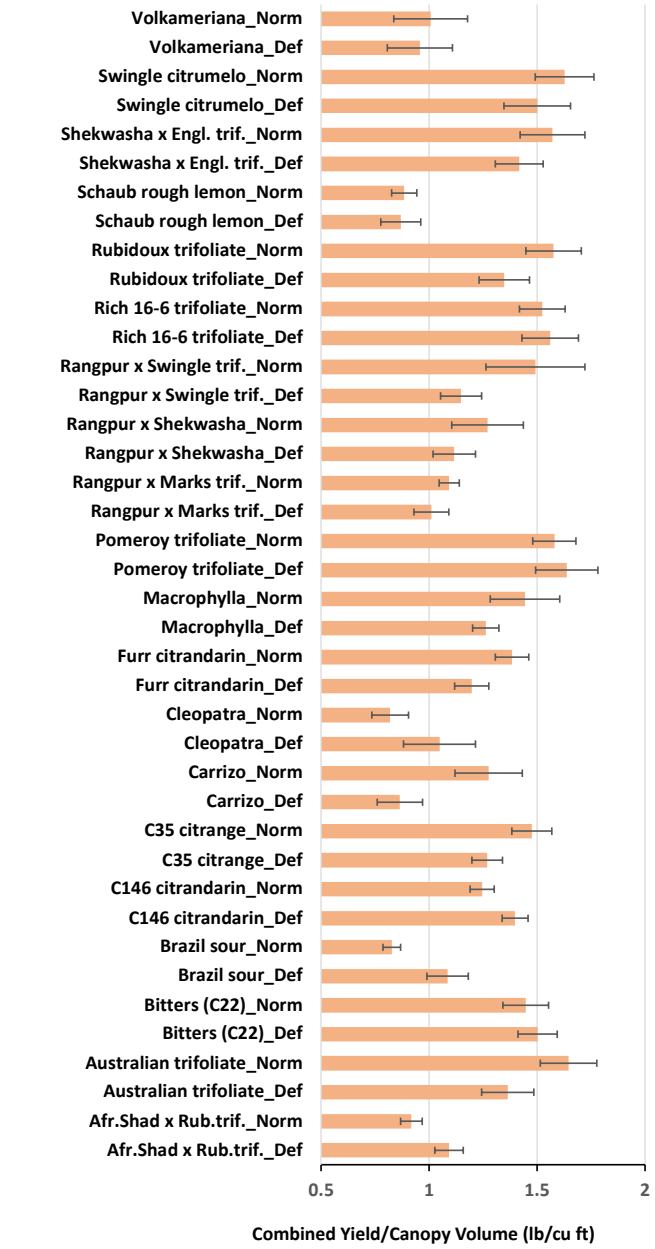


Figure 2. Means and standard errors for combined yield of 'Nules' Clementine in December 2024 and December 2025 divided by May 2025 tree size for 20 rootstocks with normal (Norm) or deficit (Def) irrigation at the Lindcove Research and Extension Center.

substantially reduced color of fruit on Carrizo (**Figure 1**). A few rootstocks, such as Brazil sour orange, showed increases in color but these differences were small relative to the amount of variation among trees.

Overall tree size and health in May 2025 (**Table 2**) was not significantly affected by deficit irrigation. Yields in December 2025 were substantially lower than those in December 2024, but this was true for both irrigation treatments. Fluctuation in yields was sometimes noted for this trial in previous years when no differential irrigation was applied. Irrigation by rootstock interaction was only significant for yield per canopy volume due to most rootstocks having similar or slightly smaller yield per canopy volume ratios in the drought treatments than with normal irrigation (**Table 3**). T-tests comparing the performance of individual rootstocks showed that Brazil sour had significantly more yield relative to tree size in the deficient treatment, while trees on Carrizo had a nearly significant decrease in yield efficiency in the drought treatment (**Figure 2**).

For the December 2024 harvest, the lab fruit quality analysis showed that drought treatments increased Brix slightly (13.48 to 13.89) and increased acid more substantially (0.85

Table 3. Means and statistical analysis of yield and tree size for 2012-planted rootstock trial of 'Nules' Clementine on 20 rootstocks. Irrigation treatments are normal irrigation vs a late-season reduction to 70% of predicted evapotranspiration. A p-value less than 0.05 is considered statistically significant.

TRAIT	IRRIGATION TREATMENT	NORMAL 100% ET	DEFICIT 75% ET	IRRIGATION X ROOTSTOCK	ROOTSTOCK
Statistic	(p value)	Mean	Mean	(p value)	(p value)
Yield Dec 2024 (lb/tree)	0.12	212	203	0.071	<0.0001
Yield Dec 2025 (lb/tree)	0.8	126	122	0.33	<0.0001
Yield Combined	0.53	338	325	0.17	<0.0001
Canopy Volume May 2025 (cu ft)	0.91	263	263	0.29	0.0014
Combined Yield/Canopy Volume	0.36	1.31	1.23	0.02	<0.0001
Tree Health Ratinga (May 2025)	0.22	4.58	4.52	0.45	0.02

[a]Tree health rated on 0 (dead) to 5 (excellent) scale and reflects canopy density, leaf size, and branch dieback.

to 0.93). However, rootstocks did not differ significantly in response to deficit irrigation for any of the traits studied. A fruit quality lab analysis was not completed for the December 2025 harvest.

For the second objective, a range of irrigation strategies (listed in **Table 4**) were evaluated. Trials were conducted over the 2024 and 2025 seasons on 31-year-old Parent Washington navel orange grafted on C35 rootstock, planted at the spacing of 18 x 18 ft and 13-year-old Tango mandarin grafted on Carrizo rootstock, planted at the spacing of 10 x 18 ft at LREC. Irrigation was based on soil moisture content measured by a Teros 10 Volumetric soil moisture sensor, which triggered an automatic valve to turn the water on and off (Verdi Expeditions Inc.). The amount of water supplied to each treatment was measured through a flowmeter installed at the beginning of each treatment's irrigation valve. Each treatment was applied to four rows of 12 trees. Data were collected from the middle 20 trees.

Water Use and Water Savings

Water use varied substantially among irrigation treatments, seasons, and between the two varieties (**Table 5** and **Figure 3**). In Parent Washington navel orange, the alternate root-zone drip (ARZD) treatment reduced water use in 2024 (28.59% less than FJ) and remained among the lower water-use treatments. Deep root irrigation (DRI) also showed water savings in 2024 and maintained an average water use in 2025. In Tango mandarin, ARZD showed water savings in 2024, using 61.8% less water than FJ, while DRI and drip irrigation (DI) also reduced water use by 39.36% and 26.97%, respectively. In 2025, treatments such as drip screw irrigation (DSI) used less water than the FJ system in both varieties (**Table 5** and **Figure 3**). Results show that water savings are possible, but not consistent across seasons or crops, highlighting the need for multi-year evaluation.

Water Use Efficiency

Water use efficiency (WUE) was calculated as pound of fruit per gallon of water. In Parent Washington navel orange, WUE was highest under ARZD and fan jet + shade netting (FJ+SN)

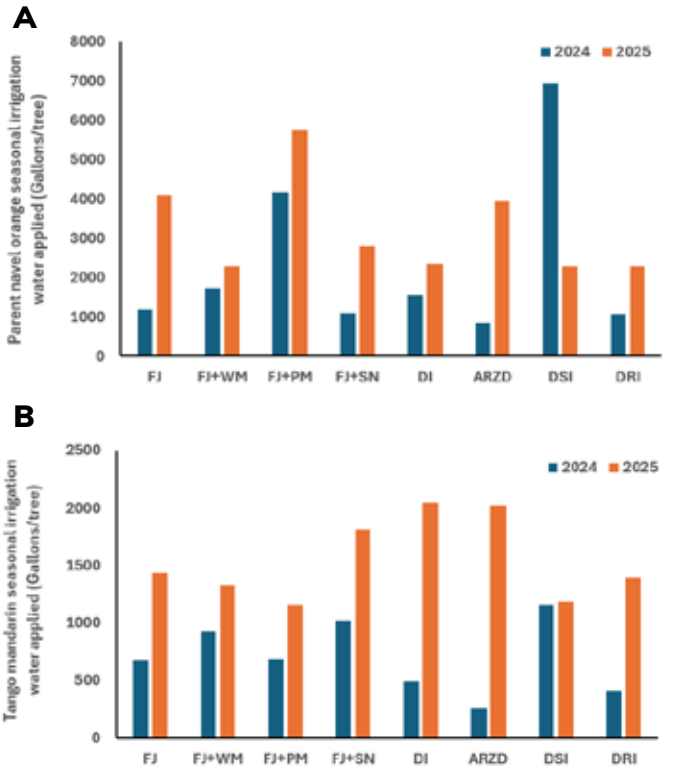


Figure 3. Seasonal irrigation water applied during the 2024 and 2025 seasons from February to October each season, expressed as gallons per tree in orange (A) and mandarin (B). FJ = Fan Jet; FJ+WM = Fan Jet + Wood Chips Mulching; FJ+PM = Fan Jet + Plastic Synthetic Mulching; FJ+SN = Fan Jet + 20% Shade Netting; DI = Drip Irrigation (one line); ARZD = Alternate Root Zone Drying; DRI = Deep Root Irrigation; DSI = DripScrew Irrigation.

in 2024. However, in 2025, WUE declined across most treatments except DRI. In Tango mandarin, in 2024, ARZD showed the highest WUE followed by DI, fan jet + plastic synthetic mulching (FJ+PM), DRI, and fan jet + wood chips mulching (FJ+WM), while other treatments such as FJ+SN and DSI caused a reduction in WUE. In 2025, all treatments were higher than the FJ in WUE with Fan-Jet + Mulching (FJ+WM) being the highest (**Figure 4**). Weather events were not taken into account during trial analysis.

Table 4. Irrigation technologies evaluated under Objective 2 of the project.

TREATMENTS	ABBREVIATION
Fan Jet	FJ
Fan Jet + Wood chips Mulching	FJ+WM
Fan Jet + Plastic synthetic Mulching	FJ+PM
Fan Jet + 20% Shade Netting	FJ+SN
Drip Irrigation	DI
Alternate Root Zone Drying	ARZD
Deep Root Irrigation (2, 12 inches units/tree)	DRI
DripScrew Irrigation (4 units of 9 inch/tree)	DSI

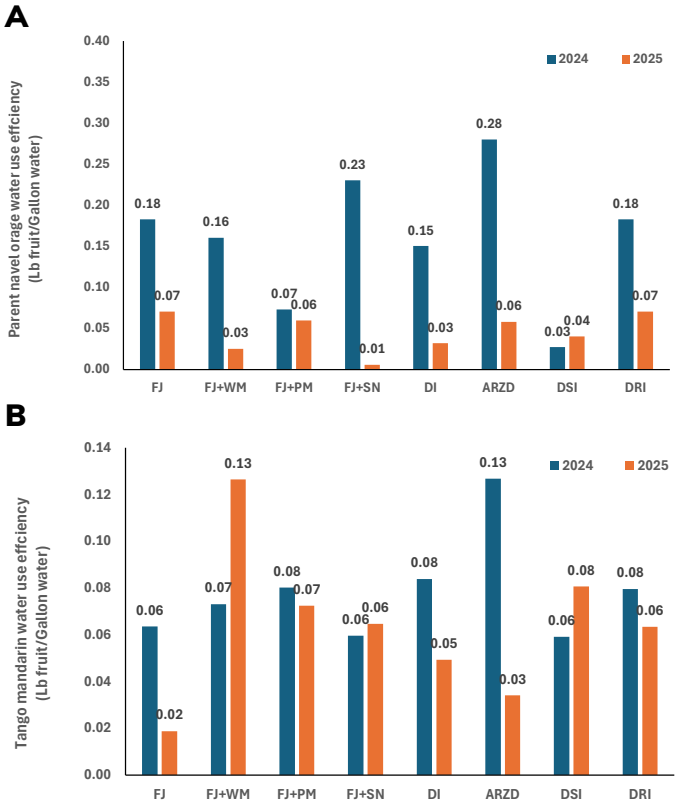


Figure 4. Water use efficiency expressed as pounds of fruit harvested per gallon of water in 'Parent Washington' navel orange and 'Tango' mandarin during the 2024 and 2025 seasons. FJ = Fan Jet; FJ+WM = Fan Jet + Wood Chips Mulching; FJ+PM = Fan Jet + Plastic Synthetic Mulching; FJ+SN = Fan Jet + 20% Shade Netting; DI = Drip Irrigation; ARZD = Alternate Root Zone Drying; DRI = Deep Root Irrigation; DSI = DripScrew Irrigation.

Yield and Yield Components

Yield responses varied significantly between treatments, seasons, and varieties. In Parent Washington navel orange, several treatments increased yield relative to FJ in 2024, particularly plastic mulch (FJ+PM) and wood mulch (FJ+WM) (**Table 6**). However, in 2025, many treatments showed reduced yields compared to FJ, with some treatments experiencing substantial declines due to lower fruit numbers. In Tango mandarin, yield responses were also highly variable.

Table 5. Seasonal irrigation water applied during the 2024 and 2025 seasons, expressed as a percentage relative to the standard fan-jet irrigation system. Red colored cells indicate higher irrigation water applied compared to fan-jet irrigation. Blue colored cells indicate lower irrigation water applied compared to fan-jet. FJ = Fan Jet; FJ+WM = Fan Jet + Wood Chips Mulching; FJ+PM = Fan Jet + Plastic Synthetic Mulching; FJ+SN = Fan Jet + 20% Shade Netting; DI= Drip Irrigation; ARZD = Alternate Root Zone Drying; DRI = Deep Root Irrigation; DSI = DripScrew Irrigation.

	Parent navel orange		Tango mandarin	
	2024	2025	2024	2025
FJ	0.0	0.0	0.0	0.0
FJ+WM	48.0	-43.9	38.9	-7.5
FJ+PM	254.2	41.1	2.7	-19.4
FJ+SN	-7.8	-31.7	52.1	26.2
DI	32.0	-42.3	-27.0	42.5
ARZD	-28.6	-3.4	-61.8	40.7
DSI	490.1	-44.0	72.2	-17.2
DRI	-9.5	-44.1	-39.4	-2.5

Table 6. 'Parent Washington' navel orange and 'Tango' mandarin yield in response to irrigation treatments during the summers of the 2024 and 2025 seasons. FJ = Fan Jet; FJ+WM = Fan Jet + Wood Chips Mulching; FJ+PM = Fan Jet + Plastic Synthetic Mulching; FJ+SN = Fan Jet + 20% Shade Netting; DI = Drip Irrigation ; ARZD = Alternate Root Zone Drying; DRI = Deep Root Irrigation; DSI = DripScrew Irrigation.

	Navel orange		Tango mandarin	
Treatment	2024	2025	2024	2025
FJ	97.6 ± 5.6	130.5 ± 13.3	19.3 ± 13.6	12.2 ± 3.7
FJ+WM	126.7 ± 3.7	26.3 ± 2.6	30.9 ± 5.7	76.2 ± 10.7
FJ+PM	138.4 ± 4.6	156.3 ± 9.9	25.1 ± 1.0	38.0 ± 3.1
FJ+SN	113.3 ± 4.0	7.4 ± 3.2	27.6 ± 6.3	53.1 ± 14.5
DI	105.9 ± 2.9	34.2 ± 8.6	18.6 ± 4.8	45.8 ± 8.8
ARZD	106.6 ± 7.3	103.5 ± 7.7	14.7 ± 3.9	31.2 ± 2.6
DSI	85.2 ± 4.6	41.6 ± 8.4	31.0 ± 2.9	43.6 ± 6.0
DRI	88.2 ± 4.0	72.9 ± 11.1	14.7 ± 5.9	40.3 ± 8.5

In 2024, several treatments, including FJ+WM, FJ+SN, and DSI, increased yield relative to FJ. In 2025, yield increased substantially in several treatments, particularly FJ+WM and FJ+SN, largely due to higher fruit numbers.

Fruit Quality

In Parent Washington navel orange, in 2024, fruit quality differed among irrigation treatments in both years. In 2024, DRI had the highest color index (0.50 ± 0.01); ARZD produced the firmest fruits (758.22 ± 15.58 g/mm); DI had the highest soluble solids (15.40 ± 0.13%); and DSI and DRI had the highest acidity (1.14%). In 2025, FJ had the highest color index (0.39 ± 0.01) and firmness (710.80 ± 30.39 g/mm), while DRI had the highest acidity (1.38 ± 0.03%) and soluble solids (14.10 ± 0.08%). In Tango mandarin, in 2024, FJ+PM had the highest color index (0.61 ± 0.01); FJ+WM had the greatest firmness (385.09 ± 15.95 g/mm); DRI had the highest acidity (1.26 ± 0.05%); and DI had the highest soluble solids (14.15 ± 0.27%). In 2025, DI had the highest color index (0.65 ± 0.01); FJ+WM had the greatest firmness (380.60 g/mm); and DSI had the highest acidity (1.28 ± 0.04%) and soluble solids (11.38 ± 0.50%). Our observation of fruit during harvest analysis showed no insect-related damage that was worth noting.

Table 7. Initial cost of each technology in 'Parent Washington' navel orange (A) and 'Tango' mandarin (B).

A	UNIT /ACRE	$UNITS	$OTHER MATERIALS	TOTAL MATERIALS	LABOR	TOTAL PER ACRE
FJ	134 FanJet	536	0	$0	$0	$0
FJ+WM	400 yard	8000	0	$8,000	$800	$8,800
FJ+PM	32000 sft	9600	0	$9,600	$800	$10,400
FJ+SN	43000 sft	8600	7000	$15,600	$7,853	$23,453
DI	134 Dripper	134	0	$134	$400	$534
ARZD	268 Dripper	268	200	$468	$400	$868
DSI	536	1608	0	$1,608	$400	$2,008
DRI	268	804	0	$804	$400	$1,204

B	UNIT /ACRE	$UNITS	$OTHER MATERIALS	TOTAL MATERIALS	LABOR	TOTAL PER ACRE
FJ	242 FanJet	968	0	$0	$0	$0
FJ+WM	400 yard	8000	0	$8,000	$800	$8,800
FJ+PM	32000 sft	9600	0	$9,600	$800	$10,400
FJ+SN	43000 sft	8600	7000	$15,600	$7,853	$23,453
DI	242 Dripper	242	0	$242	$400	$642
ARZD	484 Dripper	484	200	$684	$400	$1,084
DSI	968	2904	0	$2,904	$400	$3,304
DRI	484	1452	0	$1,452	$400	$1,852



Tree Canopy Size and Photosynthetic activity

Tree canopy size varied among treatments and seasons but was not negatively affected by any irrigation strategy. In Parent Washington navel orange, canopy size increased from 2024 to 2025 across treatments except for the FJ+PM and DSI, reflecting normal tree growth. In Tango mandarin, canopy size was slightly reduced in 2025 compared to 2024, likely due to seasonal variation rather than treatment effects. Photosynthetic activity varied among treatments and between seasons. In both varieties, higher transpiration and assimilation rates were observed in 2025. Treatments such as FJ+WM and FJ+PM promoted higher stomatal activity and gas exchange, indicating improved water availability under these systems.

Costs and Economic Considerations

The economic analysis revealed significant differences in installation costs among the various irrigation systems (**Table 7**). For example, FJ+SN had the highest installation cost at $23,453 per acre for both crops, primarily because the system requires 43,000 square feet of 20% white shade netting, concrete poles, and support wires. In contrast, other options like the DI system were considerably less expensive, costing $534 for oranges and $642 for mandarins. Details regarding the required materials and estimated labor are presented in **Table 7**. Labor costs were associated with replacing the existing fan-jet system and/or installing each new technology. When water costs were estimated using an

Table 8. Calculated irrigation water use per acre based on the number of tree per acre under different irrigation treatments in Parent Washington navel orange and Tango mandarin orchards during the 2024 and 2025 seasons, assuming the FJ treatment receives three acre-feet of water per acre. Red cells indicate higher irrigation water use per acre compared to fan jet treatment. Blue cells indicate lower irrigation water use per acre compared to fan jet treatment. FJ = Fan Jet; FJ+WM = Fan Jet + Wood Chips Mulching; FJ+PM = Fan Jet + Plastic Synthetic Mulching; FJ+SN = Fan Jet + 20% Shade Netting; DI = Drip Irrigation; ARZD = Alternate Root Zone Drying; DRI = Deep Root Irrigation; DSI = DripScrew Irrigation.

	Navel Orange		Tango Mandarin	
Treatment	2024	2025	2024	2025
FJ	3	3	3	3
FJ+WM	4.44	1.68	4.17	2.77
FJ+PM	10.63	4.23	3.08	2.42
FJ+SN	2.77	2.05	4.56	3.79
DI	3.96	1.73	2.19	4.28
ARZD	2.14	2.9	1.15	4.22
DSI	17.7	1.68	5.17	2.48
DRI	2.72	1.68	1.82	2.92

Table 9. Increase or decrease in irrigation water cost ($ per acre) relative to the FJ treatment under different irrigation systems in Parent Washington navel orange and Tango mandarin orchards during the 2024 and 2025 seasons, assuming a water price of $300 per acre-foot. Red cells indicate increase in irrigation water cost per acre compared to fan jet treatment. Blue cells indicate decrease in irrigation water cost per acre compared to fan jet treatment. FJ = Fan Jet; FJ+WM = Fan Jet + Wood Chips Mulching; FJ+PM = Fan Jet + Plastic Synthetic Mulching; FJ+SN = Fan Jet + 20% Shade Netting; DI = Drip Irrigation; ARZD = Alternate Root Zone Drying; DRI = Deep Root Irrigation; DSI = DripScrew Irrigation.

	Navel Orange		Tango Mandarin	
Treatment	2024	2025	2024	2025
FJ	0	0	0	0
FJ+WM	432	-396	351	-69
FJ+PM	2289	369	24	-174
FJ+SN	-69	-285	468	237
DI	288	-381	-243	384
ARZD	-258	-30	-555	366
DSI	4410	-396	651	-156
DRI	-84	-396	-354	-24

average price of $300 per acre-foot, differences in irrigation costs were seen between treatments with no single treatment consistent across years or variety (**Table 8** and **9**).

Conclusions

We attempted to test drought tolerance of mature Nules Clementine on 22 different rootstocks by reducing irrigation starting in early fall. We found only small overall effects and mostly non-significant differences among rootstocks. A major problem appeared to be high variation in water applied among plots which made it difficult to discriminate among rootstocks, and we were unable to solve this problem. Results from both Parent Washinton navel orange and Tango mandarin demonstrate that performance of irrigation systems varied between seasons and varieties. However, longer-term, multi-year trials are needed to confirm the consistency of these trends. Installation costs for each irrigation technology and the water use efficiency of the trees over the two growing seasons of the study were summarized; however, longer-term trials are needed before drawing definitive conclusions about the effectiveness of each technology. No significant differences in disease susceptibility or tree health were observed among the irrigation technologies evaluated in this study.

CRB Project #5400-175

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Experts Name the New Citrus Varieties to Know



Lange Rosy Red Valencia

Pink orange juice? Say no more. This sweet Valencia orange variety, discovered by farmer Nancy Lange in 2009, "is being commercialized on a significant scale in California and the fruit will be sold on supermarkets this year," says Karp.

He adds that there are now about 40 cultivars of pink-fleshed oranges vying for the attention of growers, and ultimately of consumers who appreciate its social media–friendly aesthetic. The demand for the pink orange phenomenon gives the Lange Rosy Red strong potential to become extremely popular, especially because this particular cultivar produces a more concentrated hue than any others on the market, says Karp.

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FIELD RESULTS DRIVE NEXT GENERATION OF NANOVEL'S CITRUS HARVESTER

Isaac Mazor and Yoav Katz

Project Summary

In fall 2025, with funding and support from the Citrus Research Board (CRB), Nanovel conducted a seven-week field trial of its first autonomous citrus harvesting robot in commercial orange groves in Central California. The trial provided a compelling demonstration of autonomous orange picking under real-world commercial conditions. It demonstrated that a robot can identify, reach, and pick fresh-market oranges from deep within dense citrus canopies and revealed the key engineering gaps that must be overcome before commercialization. Based on these results, Nanovel was awarded a European Innovation Council (EIC) grant and follow-on investment in early 2026 and is now developing its next-generation, self-powered, fully autonomous pre-commercial harvester.



Figure 1. Gen-1 robot.

Introduction

The dense, irregular canopies of citrus trees have long hindered autonomous harvesting. Unlike apples or stone fruit, trellis systems have not been widely adopted by commercial citrus producers to date, so any workable robot must navigate a natural, unstructured tree environment, the central unsolved challenge in citrus mechanization for decades. With CRB funding and industry support, Nanovel set out to tackle this challenge directly. This article describes the design and manufacturing of the Gen-1 prototype, the fall 2025 California field trial, and the Gen-2 program that builds on it.

Objective and Timeline

The primary objective of this project was to provide in-field validation of the commercial viability of Nanovel's Robotic Citrus Harvesting system (**Figure 1**), designed and tailored for the California citrus industry. To achieve this goal, Nanovel designed, manufactured, and shipped the Gen-1 prototype from Israel to California, which arrived in early June 2025. Starting in early November 2025, the robot was tested in a seven-week field trial in commercial orange groves in Central California.

Activities and Challenges

The fall 2025 trials were conducted in commercial orange groves in California, in partnership with growers who provided access to operational commercial blocks under real harvest conditions, a shed for storage and maintenance, a towing tractor with a driver, and related support services. The trials evaluated three core capabilities: **fruit detection and characterization, arm navigation through branches in dense canopies**, and **stem length trimming consistency** that complies with fresh-market specifications. The data collected throughout the trial were analyzed, leading to valuable conclusions about the gaps that need to be closed to reach a product that can address the challenge.



Figure 2. Artificial Intelligence model detection and characterization of fruit on the citrus tree.

Fruit Detection and Characterization

The visual detection and characterization of fruit on trees are performed in two phases: the first from outside the foliage and the second performed near the fruit. Detection mapping, the first phase, initially performed poorly, at 10% to 30%, until it became clear that the artificial intelligence (AI) model needed to adjust to handle the early-season fruit color observed during the trial. Updates provided to the model during these trials increased identification of the fruit to 60% to 90% (**Figure 2**).



Figure 3. The telescoping arm of the Gen-1 robot locating fruit with onboard cameras.

Fruit characterization, the second phase in this stage, requires evaluating fruit position and sizing. Positioning accuracy was good for fruits located at the front of the tree but deteriorated significantly for in-foliage fruits. Characterization accuracy varied accordingly, from acceptable (less than 0.5 inches) to several inches, which caused loss of fruit grip and/or corrupted the stored fruit database.

Arm Navigation through Branches within Dense Canopies

Arm navigation typically achieved five feet of canopy penetration and was successful in about 50% to 60% of cases. In the failed cases, it either failed to grasp the fruit due to inaccurate mapping (primarily depth) or the vacuum-grip failed because branches or adjacent fruit within the cluster blocked the gripper (**Figure 3**).

Stem Length Trimming Consistency

Trimming fruit stems to lengths acceptable for post-harvest handling activities was achieved in about 60% of cases. Stem length is controlled by fine-tuning the stem's angle and position relative to the trimming blades within a specified range of blade angles. The current design did not consistently meet the requirement due to loose clamping of the fruit to the blade before clipping, or branch breakage, or stem pull-out (**Figure 4**).

Building Gen-2: The Road to Commercial Harvesting

From these field tests, a number of improvements are being developed for the next generation machine. An upgraded AI system delivers higher real-time performance and improves picking quality and success rates by building a precise, complete map of the fruits on the tree, even through dense, irregular foliage. Fast, high-resolution scanning ensures

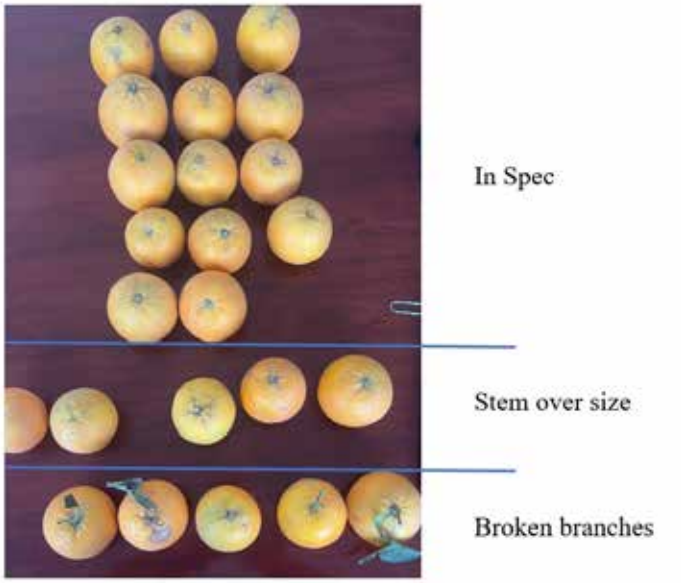


Figure 4. Examples of differences in stem length trimming by the trimmer blades on the telescoping arm of the Gen-1 robot.

every fruit is detected and located multiple times, including fruit hidden deep in the canopy. Once identified, the system guides the arm to vacuum-grip, cradle, and trim each orange cleanly.

Gen-2 replaces the tractor towing with a self-powered, embedded drive system that an operator can easily maneuver along the row and perpendicular to the trees as needed for optimal positioning in front of each tree. For transport between groves, the towing option is retained.

The Gen-2 design and features under development will be validated during 2027 across Europe and Israel, providing early qualification for commercialization.

What California Growers Can Expect Next

Harvest labor is a significant cost for fresh citrus production in California. Nanovel's robot is designed to work alongside existing crews, not replace them, reducing reliance on scarce peak-season labor. Looking ahead, high-resolution data collected from every tree will give growers new insights to improve yields and open the door to precision grove management.

Autonomous citrus harvesting works. The program now underway is focused on perfecting it, giving California's citrus growers the tools to step into a new era of harvesting, grove management, and yield.

CRB Research Project #5400-177

Isaac Mazor is the founder and chief executive officer, and Yoav Katz is chief operating officer and project manager at Nanovel Ltd. For additional information, contact **isaac@nanovel.ag**



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CITRUS GUMMOSIS OF 'STAR RUBY' GRAPEFRUIT CAUSED BY *NEOSCYTALIDIUM DIMIDIATUM*

Yong Luo, Themis J. Michailides, Georgios Makris, Victor Gabri



An entirely dead 'Star Ruby' grapefruit tree, most likely infected twice by the branch gummosis caused by *Neoscytalidium dimidiatum.*

Project Summary

This study focused on citrus gummosis of 'Star Ruby' grapefruit caused by Neoscytalidium dimidiatum. *Using a quantitative real-time PCR (qPCR²) assay developed by our lab, we first investigated the stage of the pathogen when it can be found within host tissue, but it is not causing disease symptoms (latent infection¹). This assay showed 100% incidences of latent infection when symptomatic bark tissues and asymptomatic shoots of a symptomatic tree were surveyed. Variation in incidence of latent infections ranging from 25% to over 90% was observed from asymptomatic shoots among the randomly surveyed grapefruit orchards. We also determined susceptibility of natural wounds such as sunburn, branch breakage and artificially created wounds after inoculation with the pathogen in field experiments in 2025. Various treatments were applied including pruning wounds, wounds by breaking the shoot, inducing sunburn, leaf scar wounds, and nonwounded shoots. Early disease evaluations demonstrated that high incidences were observed for peduncle wounds, pruning wounds, shoot breaking, sunburn, leaf scars, and control (non-wounded sites). The late season treatment of sunburn caused significantly higher incidence of infection compared with the other treatments. We also evaluated natural products and fungicides against branch gummosis caused by* N. dimidiatum. *In lab assays, the fungicides Quadris Top®, Cevya®, Regev®, Priaxor® and Miravis® Duo, showed significant reduction in pathogen growth, while the Surround® product showed no effect. Field assays, using two mature Star Ruby grapefruit trees, found branches treated with the Miravis® Top and Regev® had canker lengths significantly shorter than those treated with Surround®. The average canker length for the shoots treated with Priaxor® and Cevya® after inoculation and those treated with Quadris Top® before inoculation were significantly shorter than the other treatments.*

Table 1. Incidence and molecular severity (MS) of latent infection caused by *Neoscytalidium dimidiatum* for each of the sampled grapefruit or lemon orchards determined with a qPCR assay established in this study. S.D. = standard deviation.

SAMPLE	COUNTY	TREE CROP	NOTE	INCIDENCE (%)	MS	S.D.
A	Kern	Star Ruby grapefruit	Asymptomatic shoots of a severe orchard	90.63	5.57	0.30
B	Kern	Star Ruby grapefruit	Asymptomatic shoots	59.38	5.63	0.24
C	Kern	Lisbon lemon	Asymptomatic shoots	37.50	5.49	0.33
D	Tulare	Melo gold grapefruit	Asymptomatic shoots	31.25	5.39	0.36
E	Tulare	Ray Ruby grapefruit	Asymptomatic shoots	25.00	5.34	0.35
K	Fresno	Star Ruby grapefruit	Asymptomatic shoots	25.00	5.47	0.34
L	Fresno	Star Ruby grapefruit	Asymptomatic shoots	46.88	6.21	0.43
L-2	Fresno	Star Ruby grapefruit	Asymptomatic shoots of a severe tree	100.00	6.23	0.34
M	Fresno	Lisbon lemon	Asymptomatic shoots	37.50	6.08	0.45
S	Tulare	Star Ruby grapefruit	Symptomatic bark tissues	100.00	8.98	0.48

Introduction

Citrus gummosis of 'Star Ruby' grapefruit caused by *Neoscytalidium dimidiatum* has become very severe and widespread in California over the last two years. This disease causes branch wilt and dieback, leading to branch and tree killing. The same pathogen can cause devastating wilts and cankers in various agricultural and forest trees. The fungus *N. dimidiatum*, belonging to the family of Botryosphaeriaceae, was identified as the sole cause of the Star Ruby grapefruit gummosis disease (Michailides et al. 2025). Understanding how the pathogen could infect the trees and initiate such a devastating disease becomes the core issue to design efficient disease control strategies. There are two hypotheses on how gummosis symptoms develop: 1) the initial fungal infection could already be present inside the woody tissues and develop into cankers when field and crop conditions are favorable, or when the fungal level within the branch or tree is high enough for disease to develop; and 2) the fungal spores could cause infection continuously during the season under favorable conditions. For the first hypothesis, we needed to generate a sensitive and efficient approach to quantify the putative latent infection level. For the second hypothesis, we needed to understand the pathogenicity of the pathogen and the various courts of infection. Based on this anticipated knowledge, we then could focus on disease control strategies using natural products and fungicides to reduce infection of grapefruit.

Endophytic[3] (Latent Infection) Stage

To quantify the latent infection level of *N. dimidiatum*, new DNA primers were designed and tested for this project. After confirming their specificity and sensitivity, we used the primers in qPCR assays to test for and quantify the amounts of fungi present in lab and field samples at the molecular level. For this quantification, the number of shoots showing a positive result from qPCR over the total number of samples was calculated as the percent incidence of latent infection. The molecular severity (MS)[4] was calculated to quantify latent infections with a standardized measurement for the level of infection within a branch sample with the measurement considering branch size. It was also used for quantification of latent infection with the MS typically seen in the range of 0 to 15. To confirm the applicability of the qPCR assay, nine orchards (seven grapefruit and two lemons) in Kern, Tulare and Fresno counties showing various levels of canker disease intensity were selected (**Table 1**). From each orchard, 32 asymptomatic shoots were randomly collected, processed to extract DNA, and the qPCR was performed to obtain the corresponding percent incidence and MS values of latent infection.

From field samples, 100% incidence was found in both a sampling of symptomatic bark tissues and asymptomatic shoots from a symptomatic tree, confirming the methodology for latent infection quantification. In samples of asymptomatic trees, variation in incidence was observed, ranging from 25% to over 90% (**Table 1**).

Pathogenicity of the Pathogen on Pruning Wounds

To test the pathogenicity of *N. dimidiatum*, field experiments involving pruning and inoculation were conducted. Two mature Star Ruby grapefruit trees in the field at the University of California Lindcove Research and Extension Center (LREC) in Exeter, California, were used for this work. Shoot wounding with a corkborer and inoculation were performed on May 5, 2025, and May 12, 2025. Various treatments were applied on May 5 and May 12 (**Table 2**). The pathogenicity of *N. dimidiatum* was confirmed with Koch's postulates in our previous study (Michailides et al. 2025). A spore (arthrospore)

Table 2. Treatment list for pathogenicity test experiments.

TREATMENT DESCRIPTION	SAMPLE CODES	
	WITH INOCULATION	WITHOUT INOCULATION
Marked non-wounded sites	F	
Sunburn by wrapping with black plastic	A	L
Wounds by shoot breaking	B	H*
Wounds by pruning shoots	C	K*
Leaf scars by removing leaves	D	I
Peduncle wounds by removing fruit	E	J*
Wounded shoots with a cork borer	G	

**Data of these shoots were not used because they were either broken or attached to the branch that was killed during the season and it was not possible to measure the canker length caused by the inoculation.*

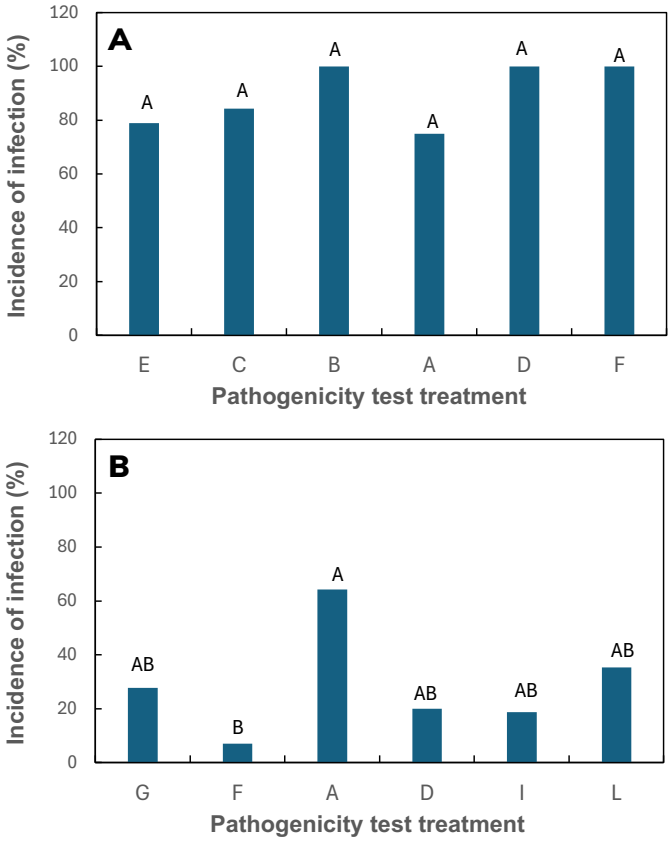


Figure 1. Comparison of incidence of infection of 'Star Ruby' grapefruit shoots caused by *Neoscytalidium dimidiatum* among different wounding and inoculation treatments. Disease evaluation was performed in July 2025 (A) for some treatments and October 2025 (B) for the remaining treatments (Table 2). Destructive sampling method was implemented in this objective with limited sample size; thus, samples could not be collected at both sampling dates, including the treatments B, C, E, G, I, and L. The data on treatments H, K, and J were missing due to branches of corresponding treatments either being broken or dead.

suspension of a *N. dimidiatum* isolate was used for all the inoculations. Twenty shoots were used for each treatment as replicates. To check for early effects of the disease progress, destructive sampling was used. Due to some inoculated shoots not producing symptoms, inoculated shoots from treatments A-F (**Figure 1A**) were collected and evaluated for disease in July, while inoculated shoots of treatment G, I, L and the remaining shoots of treatments A, D, and F were evaluated in October (**Figure 1B**). Shoots were collected, and infection was identified and recorded on each treated site to calculate percent incidence of infection.

No difference in incidence of infection was found among the inoculation treatments (A-F) obtained during disease evaluation in July 2025 (**Figure 1A**). However, at the disease evaluation in October, treatment A (sunburn with black plastic wrapping) showed significantly higher incidence of infection compared with the non-wounded control treatment (**Figure 1B**). The treatment showing the lowest incidence of infection (F) was the inoculation on the non-wounded site (**Table 2**). The results demonstrated that all inoculations resulted in disease development by infecting the shoots, thus confirming the pathogenicity of *N. dimidiatum* on grapefruit shoots. The data on treatments H, K, and J were missing because the branches with the corresponding treatments were either broken or located on a branch that was entirely blighted during the season.

Fungicide Efficacy

Fungicide efficacy for *N. dimidiatum* was determined using an *in vitro* growth inhibition assay. The fungicides used in this experiment included Quadris® Top®, Cevya®, REGEV®, Priaxor®, Miravis® Duo, and Surround® WP. The results of this test demonstrated that Quadris® Top®, Cevya®, REGEV®, Priaxor® and Miravis® Duo were equally effective in inhibiting *N. dimidiatum* growth and could be potential products for canker control in the field. The Surround® product did not inhibit the growth of the pathogen (**Figure 2**). Surround® was included in the field trials with the premise it will protect the shoots from sunburn, and thus may result in less disease.

To further evaluate fungicide efficacy, an experiment was performed in the two Star Ruby grapefruit trees at the LREC. The experiment was conducted in May 2025 with two treatments: (1) A spore suspension was applied to the pruning wound as inoculation and sealed for 24 hours. The wound was then uncovered and sprayed with the assigned treatment fungicide. (2) The pruning wounds were first sprayed with the assigned treatment fungicide, and after 24 hours, the spore suspension was applied on the wound and sealed for 24 hours. The fungicide treatments Miravis®Duo, Regev®, and the compound Surround® WP were used in

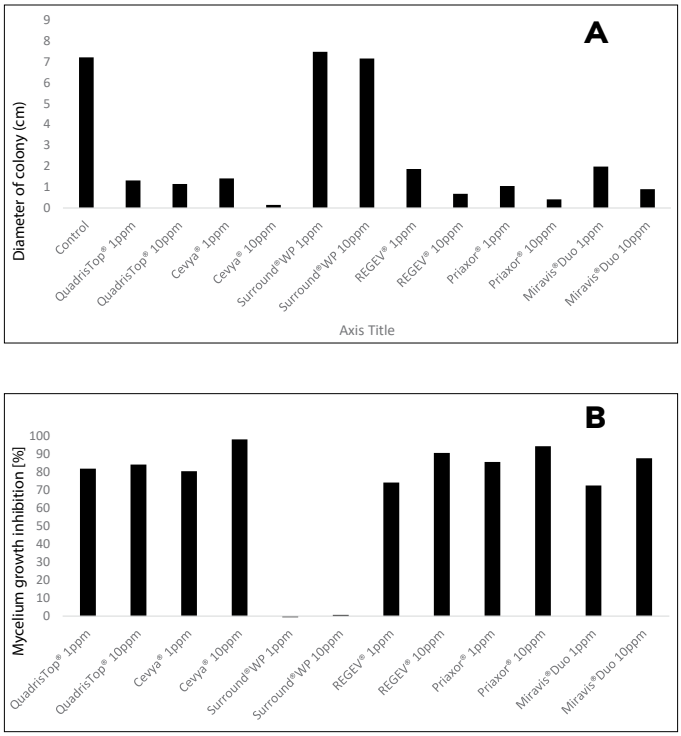


Figure 2. Results of *in vitro* tests on colony diameter (A) and the corresponding inhibition by selected fungicides to mycelium growth on culture plates (B), using a *Neoscytalidium dimidiatum* isolate. The inhibition (%) values were determined based on the growth of *N. dimidiatum* in culture plates without amending fungicide.

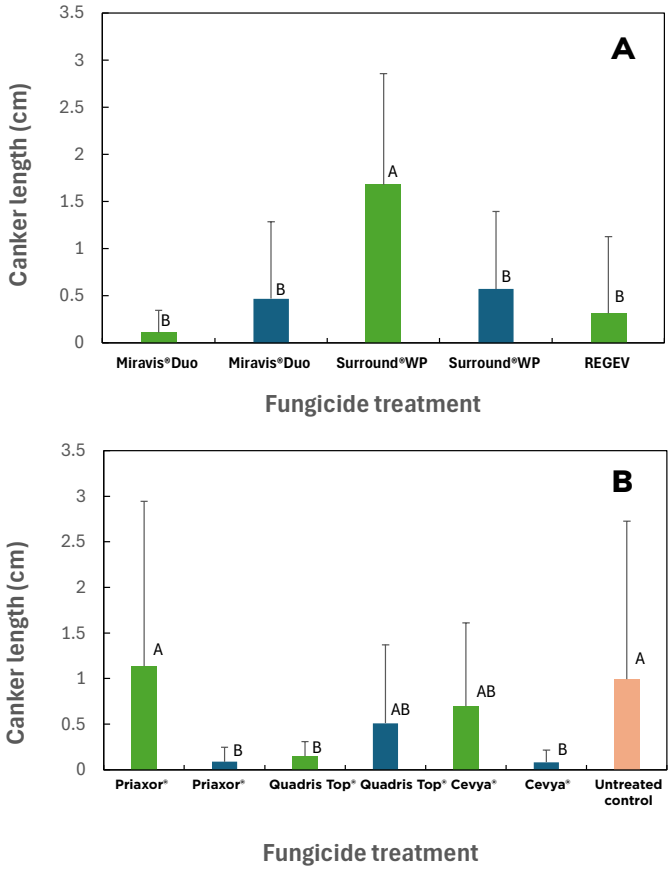


Figure 3. Comparison of canker length on 'Star Ruby' grapefruit shoots among different fungicide treatments. The inoculation and fungicide treatments were completed in early and late May 2025. Disease evaluations were performed in early (A) and late October (B), six months after treatment. Green bars indicate inoculation conducted after fungicide application. Blue bars indicate inoculation conducted before fungicide application. Error bars indicate standard deviation for each treatment. Statistical difference between treatments is signified with different letters within each graph. Untreated control in Graph A is missing due to branches being broken.

early May. The fungicides Priaxor®, Quadris Top® and Sevya® and the untreated control (wounds inoculated with the pathogen's spore suspension) were used in late May. Twenty wounds were used as replicates for each treatment. Six months after inoculation, disease severity was evaluated in early and late October 2025, corresponding to the treatment date, by measuring canker length for each shoot of each treatment.

Results of disease evaluation in early October 2025 showed that the canker lengths treated with fungicide Miravis®Top both before and after inoculation were significantly shorter than those treated with the compound Surround® applied before inoculation, but not when it was applied after inoculation (**Figure 3A**). There is no difference in canker length between the fungicide Surround® applied after inoculation and REGEV® applied before inoculation (**Figure 3A**). Results of evaluation in late October 2025 showed that the average canker length for the shoots treated with Priaxor® after inoculation, Quadris Top® before inoculation, and Cevya® after inoculation were significantly shorter than those of the untreated control and Priaxor® before inoculation (**Figure 3B**). The untreated and inoculated shoots (controls) for **Figure 3A** were not used, due to part of a major branch that was killed, and it was not possible to measure length of cankers. Because of the missing data of the untreated control shoots for the early May treatments, the results are not conclusive, and further work will be needed to make definite conclusions.

Conclusions

This project helped growers understand the mechanisms of citrus gummosis canker disease development and provided growers with information on the causal pathogen.

Further work is ongoing to investigate effective fungicide applications and the best timing of applications. In addition, trials to determine the importance of air-borne spore dynamics of *N. dimidiatum* as a possible source of initial inoculum in causing new infections in the field are ongoing.

CRB Project # 5400-180

Glossary

[1]Latent infection: Persistent infection where a pathogen remains dormant within host cells without causing symptoms or active detectable replication.

[2]qPCR: Quantitative PCR; this PCR method measures the increase in PCR products during the thermal cycling procedure through the use of a fluorescent dye that binds within double-stranded DNA. This allows for an estimation of the initial amount of "template" DNA present in the sample.

[3]Endophytic: Microorganisms that live and grow within the tissues of higher plants without causing harm to the host plant.

[4]Molecular Severity (MS): MS = log10(P/H), where P is the mass of the pathogen DNA in fg calculated from the standard curve, and H is the sample of shoots weight in grams (g).

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ROBOT MAPS SOIL MOISTURE WITH UNPRECEDENTED DETAIL

Elia Scudiero, Francesco Morbidini, Aritra Samanta, Konstantinos Karydis, Peggy A. Mauk, and Todd H. Skaggs



Project Summary

Water management is becoming increasingly important for California citrus growers. Yet soil moisture often varies dramatically within the same orchard, making irrigation decisions difficult. The University of California, Riverside and the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) U.S. Salinity Laboratory developed a robotic system that rapidly maps soil moisture across entire citrus orchards. The system combines mobile soil sensing technology and in-ground soil moisture sensors to reveal soil water patterns that are difficult to detect using traditional monitoring methods. Results show that detailed soil moisture maps can be generated with only a small number of in-ground moisture measurements, providing growers and practitioners with a potential new tool to improve irrigation efficiency, conserve water, and maintain orchard productivity.

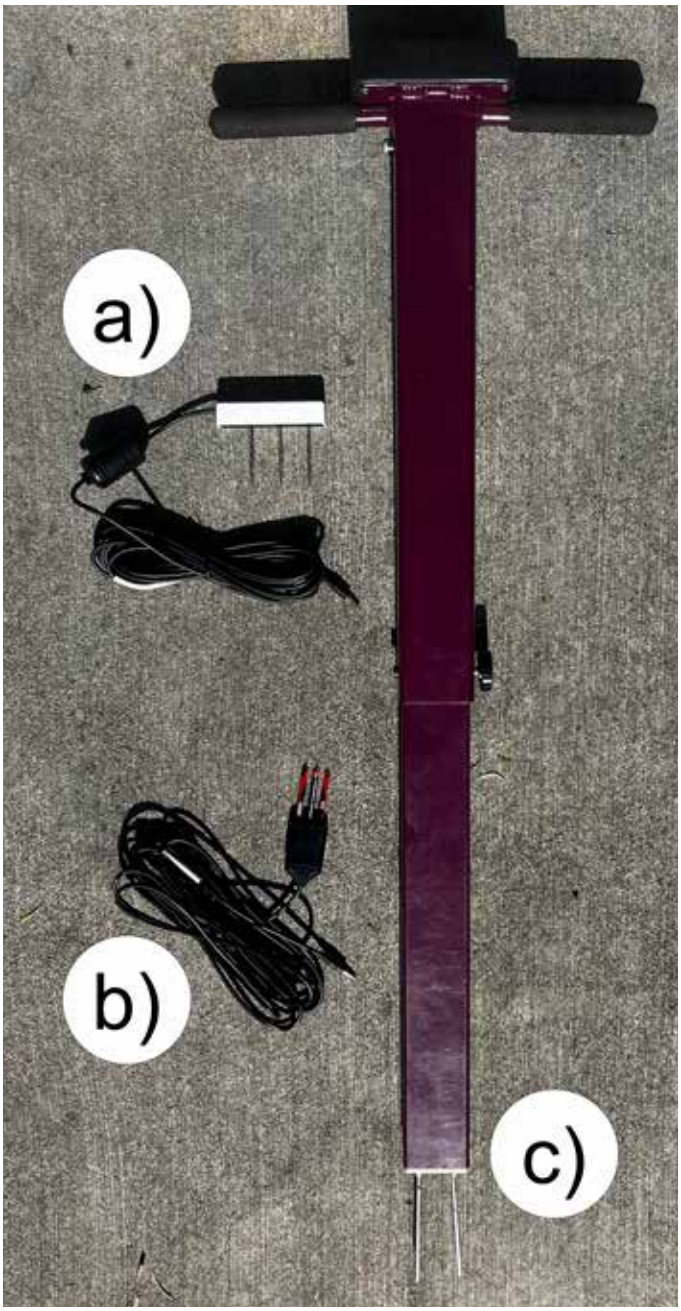


Figure 1. a) The TEROS 11 and b) the 5TE from METER Group (Pullman, WA) as examples of soil moisture sensors for permanent installation. c) The FieldScout TDR 350 handheld soil moisture meter (Spectrum Technologies Inc., Plainfield, IL) used in this research.

Water is Not Distributed Evenly

Soil water is rarely distributed evenly across citrus orchards when underlying soil is heterogeneous. Even orchards irrigated with well-designed micro-sprinkler or drip systems can develop substantial differences in soil moisture because of field-level variations in soil texture, soil depth, topography, root distribution and water movement. These differences can affect tree growth, fruit production, nutrient uptake and disease development. As water becomes increasingly valuable throughout California, understanding spatial heterogeneity of water availability in the soil is becoming just as important as knowing how much water is applied.

The Limits of Traditional Monitoring

Many growers rely on a variety of buried soil water sensors to help schedule irrigation (**Figure 1**). These sensors are based on several technologies, one of which is time domain reflectometry[1] (TDR). These sensors collect soil moisture information over time and can be installed at several depths, with error rates between 2% and 6% (Robinson et al. 2008). TDR sensors are generally considered one of the most accurate sensing technologies, with errors around 2% (Robinson et al. 2008). Buried soil moisture sensors provide valuable information, but they only measure conditions within a relatively small volume of soil. Given the non-uniformity of soil water in orchards, a single sensor may not accurately represent conditions across an entire irrigation block. Installing additional sensors can improve coverage, but doing so increases equipment costs, maintenance requirements and data management challenges. Therefore, we asked whether it might be possible to create detailed soil moisture maps for entire orchards without installing large numbers of permanent sensors.

Bringing Robotics into the Orchard

To address this challenge, we developed an autonomous robotic system consisting of a platform and sensors, capable of rapidly collecting soil information throughout a citrus orchard (**Figure 2**). With artificial intelligence algorithms developed at the University of California, Riverside's (UCR) Autonomous Robots and Control Systems Lab, the robot



Figure 2. The autonomous robot carrying a small portable sensor that can measure soil apparent electrical conductivity (ECa) across an orchard.

platform is able to autonomously travel across the orchard and visit every single tree (Samanta et al. 2026). Unlike larger vehicles commonly used for field work, the compact robotic platform can travel close to trees and irrigation lines where information about root-zone conditions is most valuable. Rather than measuring soil moisture directly, the robot carries a portable electromagnetic sensor (CMD-Tiny, GF Instruments, Czech Republic) that measures soil apparent electrical conductivity (ECa^2), a property influenced by moisture content. As the robot travels through the orchard, it continuously records ECa measurements in the top 40 inches of soil while simultaneously tracking its location (Morbidini et al. 2026). The robotic system surveyed two 'Washington' Navel orange (*Citrus* × *sinensis* Osbeck) orchards (1.3 and 3 acres) at the UCR Citrus Research Center multiple times during spring 2025, collecting thousands of georeferenced ECa measurements across each orchard.

Turning Measurements into Moisture Maps

ECa does not directly quantify soil moisture because other soil properties, such as temperature and sand content, also influence the sensor (Corwin and Scudiero 2020), but ECa measurements provide qualitative information on soil moisture patterns. To convert the ECa measurements into soil moisture values, a data-driven statistical model was developed. The model was calibrated using data from a small number of TDR soil moisture measurements collected at selected locations throughout each orchard. We obtained these soil moisture measurements with a portable FieldScout TDR 350 sensor (Spectrum Technologies Inc., Plainfield, IL; **Figure 1C**). For this study, we measured the soil moisture in the top five inches of soil. Once calibrated, the model converted thousands of robotic ECa measurements into detailed soil moisture maps (**Figure 3**). These ECa-derived soil moisture maps had errors typically lower than 4% and revealed patterns that would have been difficult to identify using traditional monitoring methods alone. Areas that consistently retained more moisture were clearly distinguishable from areas that dried more rapidly, providing a much more complete picture of orchard water distribution.

Less Sampling Than Expected

One of the most encouraging findings was that accurate soil moisture maps could be generated using only a handful of direct soil moisture measurements per orchard. To develop and test the approach, we first collected TDR measurements at 20 calibration locations across each experimental orchard. We then evaluated if only a few measurements (two to 12 per orchard) could calibrate the ECa-soil moisture model accurately. Since installing and managing many permanent soil moisture sensors is costly and requires time and labor, minimizing the number of calibration points is important for practical applications.

Our results showed that when information from at least four monitoring locations per orchard was available, the model was able to generate useful and accurate estimates

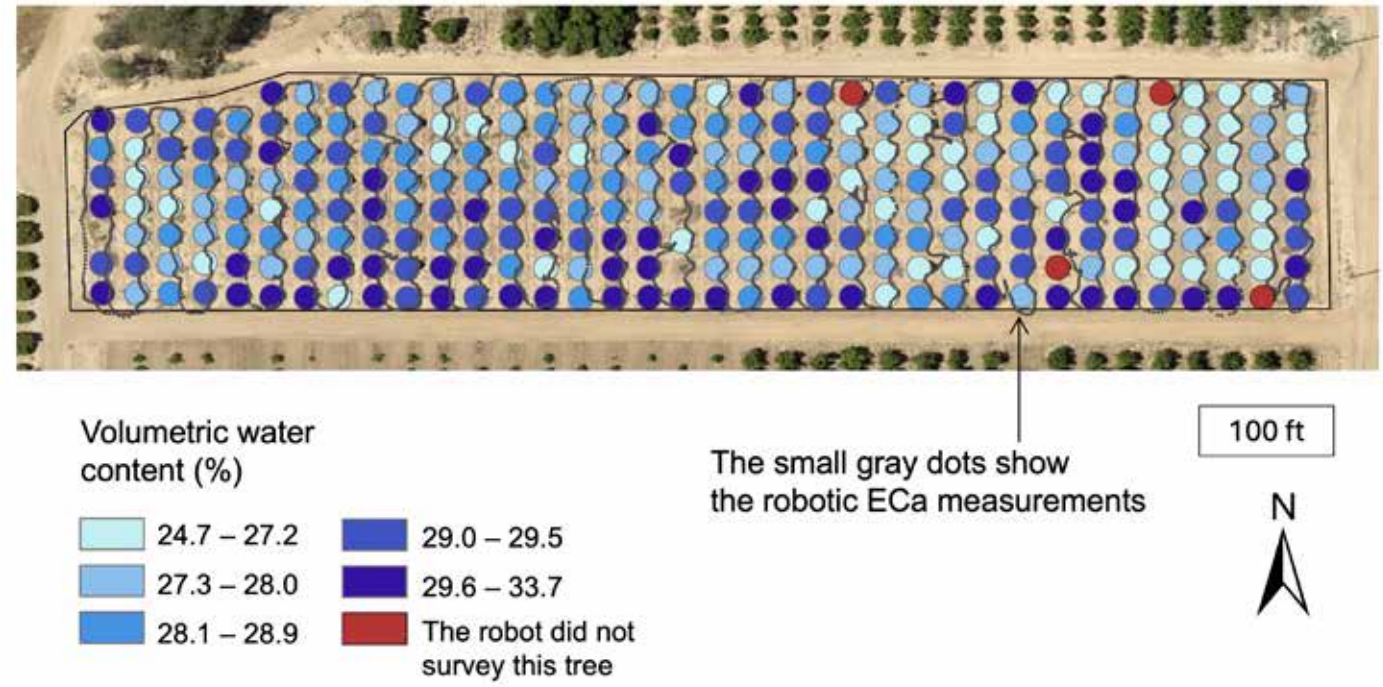


Figure 3. Image of the soil moisture map generated using robotic soil apparent electrical conductivity (ECa) for one of the experimental 'Washington' navel orange orchards at the UCR Citrus Research Center. The orchard was about three acres, with each circle in the figure representing a tree. The robot measured ECa which was then converted to soil moisture under every tree in the orchard, except for four trees (in red) where the robot could not get sufficiently close.

of soil moisture across the fields evaluated. Additional TDR measurements further improved accuracy with little improvement beyond six measurements per orchard. These findings suggest that growers and practitioners may be able to create highly detailed orchard-scale soil moisture maps without deploying large numbers of permanent sensors using robot-assisted ECa mapping together with a small amount of direct soil moisture information from TDR or other sensors used by growers and practitioners.

What This Means for Citrus Growers

The most significant outcome of this research is the new ability to estimate soil moisture at the scale of individual trees, across an entire orchard (**Figure 3**). The method we developed provides accurate orchard-wide soil moisture estimations and detailed maps showing how soil moisture varies from tree to tree and row to row. Remarkable field-scale variability in soil moisture and noteworthy variability in soil moisture between neighboring trees was observed. This level of detail provides an unprecedented way to evaluate irrigation performance. Moisture maps can reveal irrigation non-uniformities, identify areas that consistently remain wetter or drier than expected, and improve understanding of how soil variability influences water distribution. These insights can help growers make more informed irrigation decisions and better manage increasingly limited water resources.

As water availability remains a concern in California agriculture, technologies that allow orchard-wide monitoring of soil moisture may play an important role in the future of precision irrigation. For more information on this specific technology, this research is detailed in a recent open-access peer reviewed article published in the journal, *Computers and Electronics in Agriculture* (Morbidini et al. 2026).

The next step for this project is to evaluate the technology under a wider range of growing conditions, larger orchard sizes, understand criteria for best placement of the in-ground sensors within the orchards, and determine whether orchard-scale moisture maps can help growers improve irrigation scheduling, reduce water use, and enhance nutrient management.

Glossary

[1]Time Domain Reflectometry: Widely used, non-destructive method for measuring soil moisture and electrical conductivity by sending a high-frequency electromagnetic pulse along buried metal rods and measuring the exact time for the signal to reflect back.

[2]Apparent Electrical Conductivity: Field level measurement of a soil's ability to conduct electrical currents. It is referred to as an "apparent" measurement because it reflects the combined influence of multiple soil properties rather than a single chemical or physical property.

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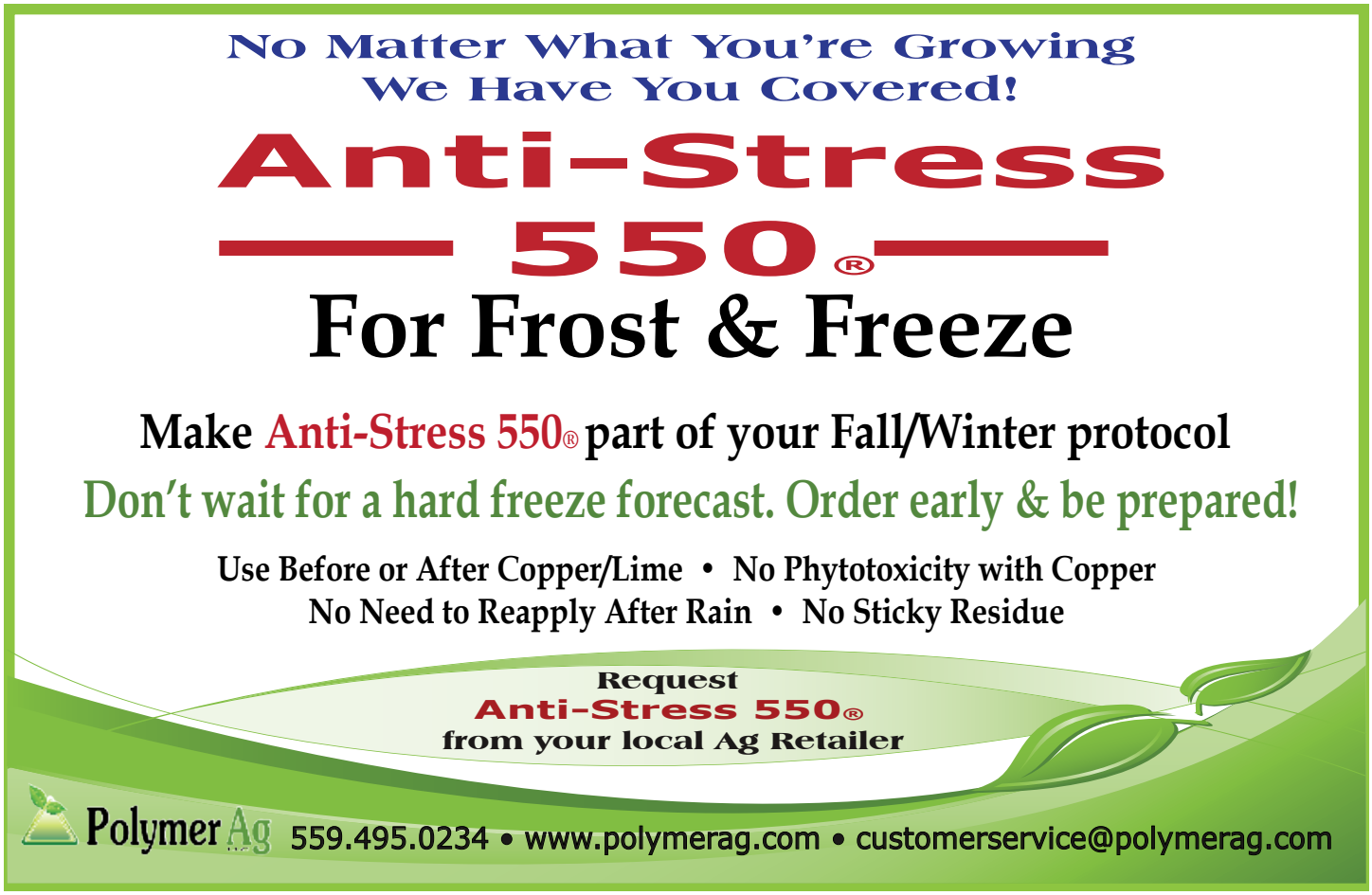
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ADVANCES IN THE PRE- AND POST-HARVEST DISEASE MANAGEMENT CORE PROGRAM

James E. Adaskaveg and Helga Förster

Green mold, blue mold (top left to right), and sour rot and brown rot decays of citrus (bottom left to right).

Project Summary

The Pre- and Post-harvest Citrus Disease Management Core Program was initiated in 2021 to provide the California citrus industry with a comprehensive Integrated Pest Management (IPM) program for diseases caused by fungi (e.g., Septoria citri, Elsinoë australis, Geotrichum citri-aurantii, Colletotrichum *and* Penicillium spp.*), and fungal-like organisms (i.e., Phytophthora* spp.*) occurring in orchards, as well as non-vectored bacteria (e.g.,* Listeria spp.*) and fungi contaminating packinghouses. The broad research components in this program include biological and epidemiological studies, as well as the development of management strategies for pre- and post-harvest diseases using chemical, biopesticide, and biological control treatments and facilitating their registration. Major achievements obtained in the last few years of this core program are highlighted in this article.*

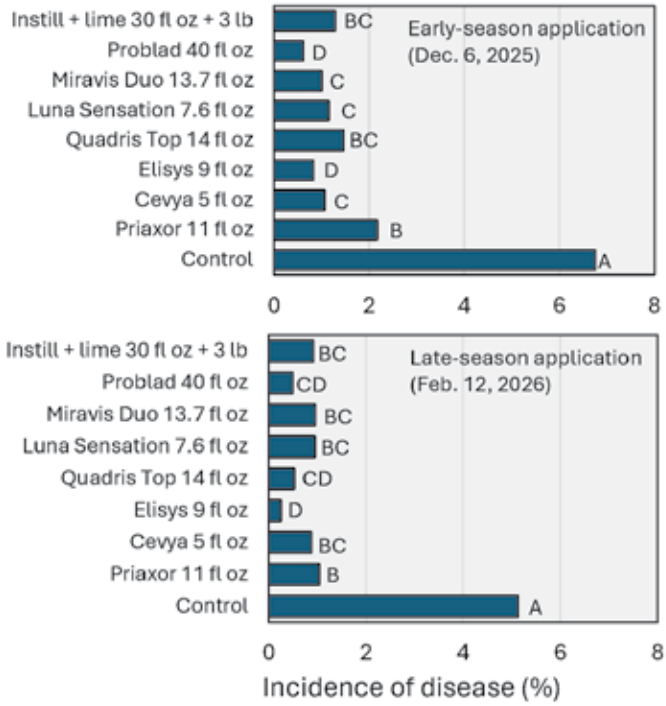


Figure 1. Efficacy of fungicides for managing Septoria spot of Navel oranges. Applications were made using a hand-gun high-volume sprayer (400 gal/A). Disease was evaluated mid-April 2026. Horizontal bars followed by the same letters are not significantly different in comparisons among treatments within each graph.

Septoria spot Management

Since its initiation in 2004, the Navel and Valencia Exports to Korea (NAVEK) program has successfully forecasted Septoria spot caused by *Septoria citri*, a quarantine pathogen in Korea. The program provides guidelines for application timings of traditional and newly registered fungicides based on an environmental risk model and certifies grower fruit lots as disease-free for the United States Department of Agriculture-Animal and Plant Health Inspection Service (USDA-APHIS) trade agreement with Korea. Disease forecasting relies on a risk model that is based on the accumulation of environmental factors during the fall/winter growing season. The program has been highly successful, allowing the lucrative Korean export market to remain open for California growers, packers, and shippers (Adaskaveg 2021). In the 2025-26 season, 144 Navel orange samples and five Valencia orange samples were processed in the NAVEK lab. There were zero detections of Septoria spot, and no detections in Korea.

Over time, the program has evolved from mandatory requirements to voluntary guidelines based on Good Agricultural Practices (GAPs) that are annually revised and posted on industry websites such as the California Citrus Quality Council (CCQC; ccqc.org). To help growers and packers, the program continues to be updated and provides options for the citrus industry to export fruit to Korea. The latest revision of the program for the 2021-22 season (Adaskaveg 2021) has increased NAVEK participation, reduced copper usage, developed alternative fungicides in cooperation with agrochemical companies (BASF, Bayer, Syngenta, and SymAgro), and has allowed exports of fruit from *S. citri*-positive orchards that were treated post-harvest with an anti-sporulation fungicide, provided that no sporulation is present on fruit. Some of the fungicides registered and pending registration for field use for managing Septoria spot are indicated in the studies shown in **Figure 1**.

Phytophthora brown rot and root rot

Minimizing the incidence of brown rot on harvested fruit is imperative because two of the causal organisms, *P. syringae* and *P. hibernalis* (less common), are quarantine pathogens in China, another major export market for California citrus fruit. Our field studies on Navel oranges and Eureka lemons on the management of brown rot with single pre-harvest applications of new fungicides under high-rainfall conditions identified Orondis Ultra® (mandipropamid + oxathiapiprolin) and Revus® (mandipropamid) as viable alternatives to copper with persistence over a two-month period (**Figure 2**). Additionally, our results showed persistence of Revus® and Orondis Ultra® was significantly increased when applied in combination with the sticker adjuvant (e.g., Attach®).

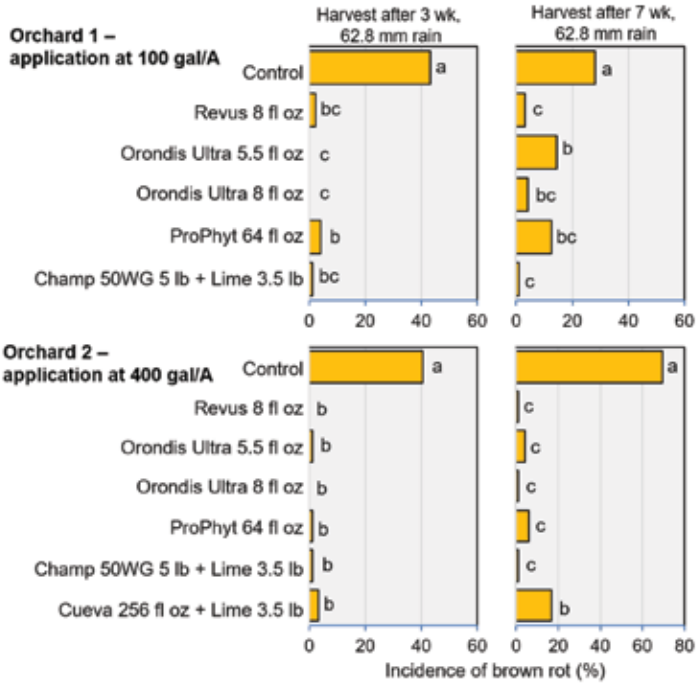


Figure 2. Efficacy of a single pre-harvest application in the winter of 2026 with selected fungicides for management of brown rot of Navel orange after inoculation of harvested fruit. Applications were done on February 10, 2026 at 100 gal/A in combination with 8 fl oz/A of an adjuvant (e.g., Attach®). Fruit were harvested three and seven weeks after application, inoculated with *Phytophthora citrophthora*, and evaluated for the incidence of brown rot. Horizontal bars followed by the same letters are not significantly different in comparisons among treatments within each graph.

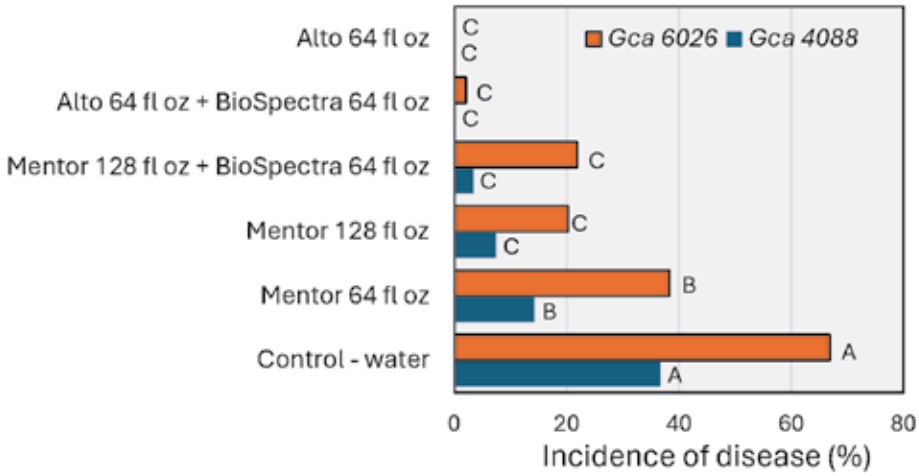


Figure 3. Efficacy of post-harvest applications of propiconazole (Mentor®) and cyproconazole (Alto®) for managing sour rot of 'Tango' mandarins caused by isolates of *Geotrichum citri-aurantii* sensitive (Gca 4088) or resistant (Gca 6026) to propiconazole. Horizontal bars followed by the same letter are not significantly different in comparisons of treatments for each isolate.

Considering the presence of phosphite resistance in *Phytophthora spp*. from citrus and environmental concerns with the overuse of copper, the availability of new alternative treatments with different modes of action allows for sustainable resistance management with fungicide rotations.

Models were developed to predict the regional risk for brown rot infection during the winter season. These were based either on reduction of field-applied copper on fruit by rainfall or on conducive environmental conditions (i.e., accumulated hours with favorable temperatures during rain events) specifically for *P. syringae*. Risk assessments based on data from 29 weather stations in ten counties in the three citrus growing districts in California are posted several times during the winter season on industry websites such as CCQC. Growers who time their fungicide sprays based on these announcements can optimize management of the disease and therefore, minimize the risk for detection of the quarantine brown rot species upon arrival in China.

To manage Phytophthora root rot that can be closely associated with the occurrence of brown rot, we previously were instrumental in evaluating, characterizing, and registering the highly effective Orondis® and Presidio® for field application and Revus® for nursery use. Research was also conducted with another fungicide, ethaboxam (Elumin®), and currently, we are involved in facilitating registration of this compound in California. For this, efficacy data must be generated for different citrus crops (e.g., grapefruit, lemons, and oranges) using a reduced rate of 8 fl oz Elumin® per acre. As for brown rot, having new fungicides provides the opportunity to follow recommended resistance management strategies.

Post-harvest Decay Management

We identified and developed the new post-harvest fungicide cyproconazole (CPZ) in cooperation with Syngenta. This new demethylation inhibitor (DMI) fungicide has high activity against green mold and sour rot and is active against propiconazole (PPZ)-resistant isolates of *Geotrichum citri-aurantii*. Four publications on citrus green mold and sour rot and their management with CPZ were completed in the last year. The first and second publications (Adaskaveg et al. 2025, Nguyen et al. 2025a) reported on baseline sensitivities to CPZ of the two described sour rot species in California, *G. citri-aurantii* (causing decay of mature fruit) and *G. candidum* (causing decay of senescent fruit). In the third publication, we described use rates and application strategies of CPZ alone and in combination with PPZ or natamycin for managing green mold and sour rot (Nguyen et al. 2026). Like PPZ, CPZ is not inactivated by the sanitizers, peroxyacetic acid and sodium hypochlorite. Optimal use is in aqueous applications, but it is compatible with storage and pack waxes with some decrease in performance similar to other post-harvest fungicides (Nguyen et al. 2026).

In a fourth article, populations of *G. citri-aurantii* with moderate (MR) or high (HR) levels of PPZ resistance (average effective concentration to inhibit 50% of growth - EC50 1.88 or 27.44 µg/ml, respectively) were described. The pathogen had two idiomorphs[1], GcaCYP51A and GcaCYP51B, that correlated with the PPZ resistance phenotypes. Isolates sensitive to PPZ that were genetically transformed with the CYP51A-MR and CYP51A-HR alleles[2] exhibited the MR and HR phenotypes, respectively. Those transformed with the CYP51A-sensitive (S) allele, and the CYP51B-S, or CYP51B-HR idiomorphs, however, did not change their PPZ sensitivity (Nguyen et al. 2025b). Therefore, we confirmed that only point mutations in CYP51A are responsible for PPZ resistance in the pathogen. We also demonstrated incomplete cross resistance between CPZ and PPZ where *G. citri-aurantii* isolates moderately resistant to PPZ are sensitive to CPZ. CPZ has gone through the IR-4 program and is pending registration at the Environmental Protection Agency (EPA).

Our evaluations of new sanitation products for citrus fruit washes and equipment are ongoing. We are currently evaluating ultra-pure chlorine dioxide as marketed by the registrant to have less contaminants that could impair

the function of the sterilant or cause phytotoxicity. At 5 ppm, the sanitizer is effective against bacterial and fungal contamination. Like other oxidizers used in fruit sanitation, chlorine dioxide does not kill spores contaminating fruit wounds because it is inactivated by reducing sugars of the fruit. Still, chlorine dioxide leaves no residues because it volatizes after exposure, is non-corrosive to equipment, and there are no odors at rates of 5 to 20 ppm, making it ideal for workers in a packinghouse or other enclosed areas.

This year, we are also addressing the use of PPZ for managing sour rot of lemons and mandarins. The registration for lemons has been under a Special Local Need (FIFRA[3] Section 24c) that will expire in December 2026, and we are looking to renew the registration and expand it to include mandarins. The Section 24c for PPZ use on lemons allows a 2X rate (i.e., 128 fl oz of Mentor/250,000 lb fruit) of the Section 3 full registration label (i.e., 64 fl oz), if only one application is done to a fruit lot before fruit storage instead of two applications (one before and one after storage). We demonstrated that this increased rate results in improved efficacy against sour rot (**Figure 3**) without a need to change the tolerance; residues on mandarins remained below 1.5 ppm. Thus, the tolerance for citrus (EPA Crop Group 10-10) of 8 ppm is not exceeded with this changed pattern of a single post-harvest application to fruit that are subsequently placed into storage.

Sweet Orange Scab (SOS)

We continued to conduct research on *Elsinoë australis*, the pathogen that causes SOS, with an emphasis to develop a more robust detection method. We spent several months contacting, getting approval, and obtaining cultures of *Elsinoë spp*. from the Westerdijk Fungal Biodiversity Institute in Europe. Some requested cultures could not be obtained due to requirements of the Convention of Biological Diversity. Eventually, we did obtain cultures of *E. australis* (three isolates) and the three closely related species, *E. fawcettii* var. *viscosum*, *E. genipae-americanae*, and *E. violae* from the Westerdijk Fungal Biodiversity Institute (Adaskaveg and Förster 2025). Other isolates requested, such as *E. citricola*, *E. anacardii*, and *E. semecarpi* that are also very closely related to *E. australis*, were not provided, although we were put on waiting lists. Dr. Madhurababu Kunta at the Texas A&M University-Kingsville Citrus Center provided 13 additional *E. australis* strains from Texas. Selected cultures will be subjected to whole genome sequencing and assembly using PacBio HiFi[4].

In preliminary screenings, we developed nine new markers from published genomic data for each *E. australis* and *E. fawcettii*. Several of those exhibited a strong, single band of the expected amplicon size in PCR[5] reactions and will be further evaluated. Our research together with Dr. Kunta's efforts to develop a highly specific primer based on the *TEF1α* gene (see page 68 in this *Citrograph* issue) is very promising. New DNA primers that are highly specific to E. *australis* and can detect low concentrations of DNA will allow unambiguous detection of fruit with SOS. This is needed to verify California Department of Food and Agriculture (CDFA) detections that are based on PCR tests using a primer pair that has been demonstrated to be non-specific (Adaskaveg and Förster 2025). We will also continue efforts to culture the pathogen from fruit that CDFA has identified as positive to verify detections that have resulted in expanding quarantine restrictions in California.

CRB Research Project #5400-401

Glossary

[1]Idiomorph: Alternative DNA sequence that, unlike an allele, has no sequence homology and differs in size and gene content but occupies the same location on a chromosome in different strains of the same species.

[2]Allele: Specific variant form of a gene that shares high DNA sequence similarity and common ancestry.

[3]FIFRA: Refers to the Federal Insecticide, Fungicide, and Rodenticide Act. It is the primary United States federal law that governs the distribution, sale, production, and use of all pesticides, including insecticides, herbicides, and antimicrobial products.

[4]PacBio HiFi: A powerful long-read DNA sequencing technology that delivers highly accurate reads averaging 15,000 to 20,000 bases in length with over 99.9% accuracy.

[5]PCR: The acronym for polymerase chain reaction, a widely used molecular biology technique to generate a high number of copies of a specific DNA piece.

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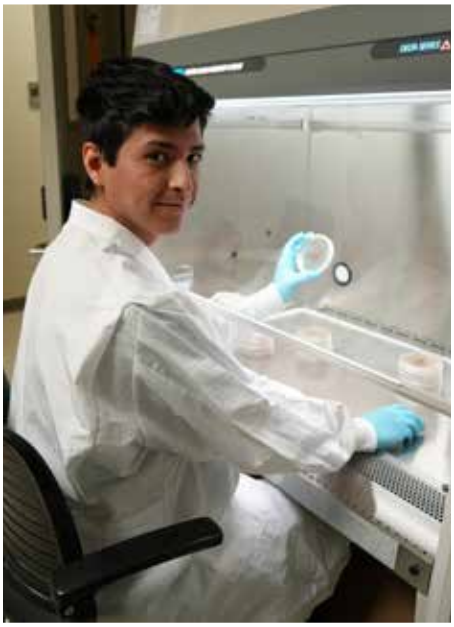
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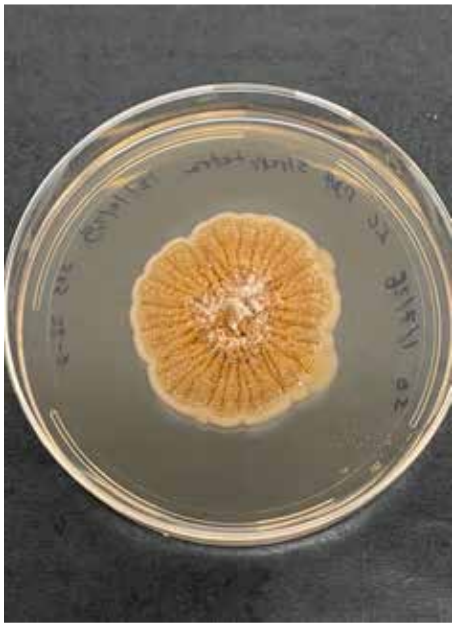
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Rapid High Throughput Diagnostic Method for Sweet Orange Scab Pathogen

Madhurababu Kunta, Jong-Won Park, Marissa Gonzalez, Isaac Cazares, Aditi D. Satpute, Aidan Shands, and James E. Adaskaveg

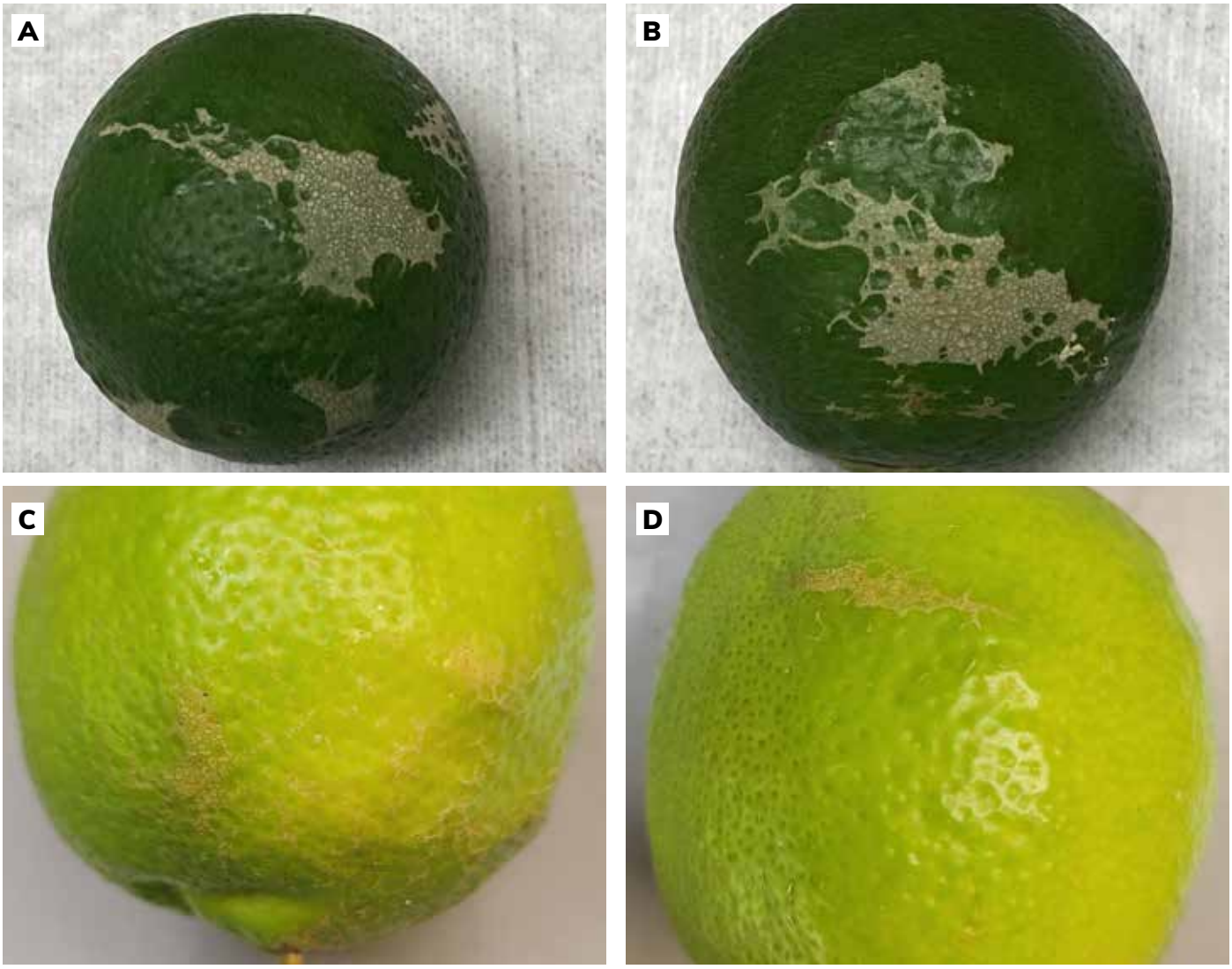


Figure 1. Citrus orange fruit showing sweet orange scab lesions typical for citrus orchards in Texas (Images A and B). California lemon fruit samples determined to be positive for *Elsinoë australis* using molecular methods by the California Department of Food and Agriculture, but isolations to recovered *E. australis* and molecular methods were negative by the Adaskaveg lab (Images C and D).

Sweet orange scab (SOS) is a fungal disease caused by Elsinoë australis *(Kunta et al. 2013, Satpute et al. 2015) that is presently a regulatory issue impacting quality and production efficiency of California citrus. The current United States Department of Agriculture Animal and Plant Health Inspection Service (USDA-APHIS)-approved diagnostic method that is based on a conventional polymerase chain reaction[1] (cPCR) assay is providing inconsistent and confusing results in California (Adaskaveg and Förster 2025). The presence of the pathogen when identified by the California Department of Food and Agriculture (CDFA) could not be confirmed molecularly or culturally in independent work done by university researchers in California. This project's activities address the goal of development of a robust high throughput and validated diagnostic method.*

Symptomatic grapefruit and sweet orange fruit samples were collected in Texas to isolate *Elsinoë australis*. Out of 94 grapefruit and 63 sweet orange fruit samples showing SOS symptoms typical for Texas (**Figure 1**), eight *E. australis* isolates were recovered (**Figure 2**). Five *E. australis* isolates from grapefruit were retrieved from previous collections in Texas. A new qPCR[2] method based on the *E. australis* translational elongation factor 1α (*TEF1α*) gene was developed. *In silico* PCR analysis showed that the qPCR assay is specific to *E. australis* and will not cross-react with *E. fawcettii* and *E. citricola*. The qPCR assay successfully detected all 13 *E. australis* isolates collected in Texas, and the results agree with the cPCR method approved by USDA-APHIS.

For assessment of diagnostic assay specificity, these isolates were shipped to the project co-principal investigator, Dr. James Adaskaveg. His lab has identified five additional candidate markers for *E. australis* with strong single amplicon bands[3] that were not present in closely related *Elsinöe spp.* obtained from the Westerdijk Biodiversity Institute. Whole



Figure 2. *Elsinoë australis* isolates on potato dextrose agar plates obtained from sweet orange fruit in Texas.

genome sequence being obtained for *E. australis* will aid in resolving diagnostic assay specificity issues.

This project will result in a robust multi-locus multiplex diagnostic method for accurate and rapid detection of *E. australis* with no cross-detection of closely related species of the genus such as *E. anacardia*, *E. genipae-americanae*, *E. semecarpi*, or *E. violae* (Elliott et al. 2023) and *E. punicea*, *E. fawcetti*, and *E. citricola*. This will directly benefit growers and marketing sectors that must rely on non-culture-based detection methods leading to SOS quarantines.

CRB Research Project #5400-181

Glossary

[1]Conventional polymerase chain reaction: A widely used molecular biology technique to generate millions to billions of copies of a specific DNA piece which are measured visually to detect the presence or absence of a target DNA sequence.

[2]Quantitative polymerase chain reaction: A widely used molecular biology technique to measure the amount of DNA during the amplification process using fluorescent dyes or probes.

[3]Amplicon Bands: Visible line during gel electrophoresis indicating the presence of a specific simplified segment of DNA.

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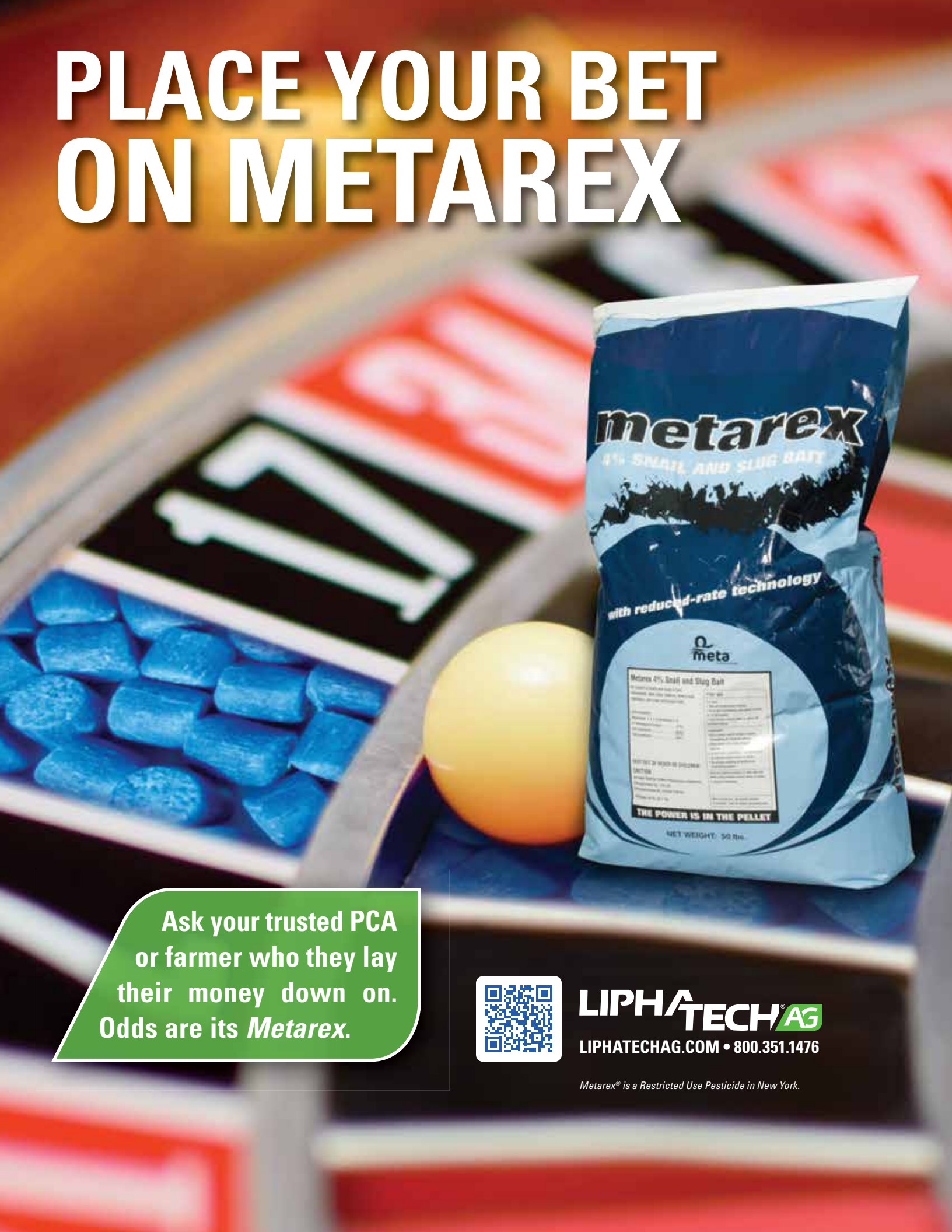




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