Fertilizer Research and Education Program

Final Report

A. Project Information

Project Title: Development of Precision Yield Monitor for Almond and Pistachio
Project leaders: Patrick H. Brown and Stavros Vougioukas
Grant Number: 22-1455
Project Duration: Start Date: 1/1/2023 End Date:12/31/2025
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Final Report
Reporting Period Start Date: 1/1/2023 End Date: 12/31/2025

B. Abstract

Accurate crop yield measurement is critical for determining whether orchard management strategies are beneficial or wasteful. The ability to measure yield at the individual-tree level is an essential research tool for examining yield variability. This project aimed to develop and field-validate a practical system for measuring almond yield at the individual-tree level during commercial harvest operations. Over three years, the research team at UC Davis developed and field-validated a laser-based yield monitoring system mounted on commercial off-ground almond harvesters (TOL Twin-D). The system used a laser line profiler installed above the harvester's conveyor belt to continuously measure almond volume as the nuts moved through the machine. Additional sensors, including GPS, wheel encoders, and vibration sensors mounted on the tree shaker, identified the time and location of each harvested tree. A data-processing pipeline integrated these measurements to assign almond volume to individual trees and generate orchard yield maps at single-tree resolution. Results showed accurate tree-level yield maps that help growers understand yield variability in their orchards.

Field trials from 2023 to 2025 demonstrated that the system can accurately measure almond volume on harvester conveyors, localize each harvested tree using GPS and vibration sensing, and generate single-tree yield maps, with relative errors ranging from approximately 3.44% to 9.09% compared with ground-truth measurements. Seasonal refinements, including improved sensor integration and data processing, reduced yield-assignment uncertainty and enabled consistent mapping of spatial yield variability across orchards, varieties, and harvest years. Repeated measurements in the same orchard across consecutive seasons confirmed the repeatability of tree-level yield estimation, demonstrating the potential to track year-to-year orchard performance.

C. Introduction

Providing uniform water and nutrients to an entire orchard is standard practice, but wasteful. To improve input management efficiency, growers must identify and manage field variability. Noble et al. (2018) measured yields from 4,000 to 7,000 trees over 5 consecutive years. The resulting yield map (Fig. L.1—see section L) illustrates extreme yield variability, with 30% of the orchard yielding more than 6,000 lbs. while 30% yielded <2,500 lbs. In almonds, yield variability is also significant (Fig. L.2—see section L). This project aims to provide the capability for single-tree yield monitoring and tree identification at commercial harvest speed. This precision harvester will immediately provide rationale and context for sub-orchard management and nutrient optimization. The ability to easily measure single-tree yield also represents a revolution for research. It will improve the use of remote soil/plant sensors by providing ground-truth data and linking to field variability. The problems and solutions addressed are as follows:

Efficient N and K Management: Yield is the primary driver of N and K demand in nut crops, and balancing N demand/supply is required under ILRP N guidelines. Currently, most growers make only a single yield estimate per orchard and base N/K applications on that average. Since variability exists across orchards, any decision is a compromise, resulting in undersupplying the highest-performing trees while oversupplying the lower-performing trees. Variability in yield represents lost productivity and prevents maximizing 'crop per drop or lb of N'. Three regulatory programs, ILRP, SGMA, and CVSalts, require growers to increase irrigation efficiency and N use. The 'next' phase of improved nutrient use efficiency will require a change from traditional whole-field management to zonal adaptive management.

Optimizing Orchard Productivity: Maximum profitability and optimal NUE can be achieved by reducing field variability through targeted management of underperforming zones. These decisions cannot be made without the ability to map yield. Precision yield monitoring provides the rationale for targeted management decisions by clearly identifying the sources of yield variability, the first step in determining and ultimately correcting it.

Improving the Utility of In-Field Sensors and Remote Sensing: While soil, water, and plant sensors, along with remote sensing strategies (from drone to satellite), have considerable 'promise,' they have not delivered widespread benefits to growers. The primary constraint facing these technologies has been the inability to link high-resolution sensing with high-resolution yield data. A precision yield monitor will greatly enhance the usefulness of many digital agriculture technologies, improving the ability to interpret data and make local field management decisions.

Improved and Cheaper Research and Testing: A significant constraint on academic, commercial, and grower product testing in almonds and pistachios is yield measurement. A precision yield monitor will greatly improve the ability to test novel management strategies, develop and validate products, and optimize production and NUE.

Solutions and Challenges: Since most growers use a single irrigation/fertigation system, adapting to yield variability is often difficult. There are, however, several easily implemented approaches and solutions that can be implemented immediately. Mapping yield variability immediately improves fertilizer decision-making by providing information on average yield and the yield range. Understanding how outlier zones influence the field-average yield greatly enhances decision-making. Even without modifying fertigation systems, growers can address variability with field-wide N/K fertigation at a rate sufficient to meet the needs of most trees, while supplementing the highest-yielding zones with targeted soil or foliar applications. Current fertilizer prices and N management regulations suggest that even a modest implementation would yield substantial ROI and NUE benefits. Mapping yield variability identifies local yield constraints and enables targeted management and correction, improving overall uniformity. The development of driverless sprayers will dramatically enhance precision by eliminating the need to tank-mix multiple materials and the consequent whole-field applications, thus enabling zonal targeted management.

D. Objectives

Objective #1: Measure yield using optical laser scanning.

Objective #2: Measure yield using optical and gravimetric methods.

Objective #3: Develop and integrate a real-time quality control vision system.

E. Methods

Objective #1: Measure yield using optical laser scanning.

During all three years of the project (2023-2025), two Gocator 2690 Laser Line Profilers and wheel encoders were installed to measure almond flow on the harvester’s conveyor belts. Because each off-ground harvesting system (Tol Twin-D) involves two machines, we used two pairs of scanners and wheel encoders. As almonds moved along the conveyor, the scanners measured the nuts' volume in real time.

To track tree locations, we used GPS to monitor the movements of both machines. A vibration sensor on the shaker head detected when a tree was harvested. By integrating GPS and vibration data, we accurately identified the location of each harvested tree. This approach not only estimated tree positions but also recorded vibration timestamps, which were crucial for assigning yield to individual trees. Using the continuous volume flow data from the yield monitoring system and the exact time each tree was harvested, we formulated an optimization problem to assign yield to individual trees. This method approximated tree-level volume flow using parametric models, or "kernels". The single-tree kernels were fitted to the continuously recorded almond flow, using the vibration sensor timestamp as prior knowledge.

After recording the data, we estimated the volume at the tree level. Then, using the ground-truth trees' weights and volumes, we developed a linear model to describe the relationship between volume and weight. Using this model, the volume obtained at the tree level is converted into weight. The combination of tree localization and tree-level yield was used to create the yield map. These maps show each tree’s fresh weight, with color scales highlighting low- and high-yielding areas.

Figure 1: Almond yield monitoring system: 1. Laser profiler, 2. Wheel Encoder, 3. RTK-GPS, 4. Vibration sensor, 5. Enclosures to protect the laser projections

Objective #2: Measure yield using optical and gravimetric methods.

Load cells were used for gravimetric sensing. Because suitable conventional conveyors with load cells were unavailable for testing the scanners, we designed and built a custom conveyor belt in 2023, completing it one year ahead of schedule. This custom conveyor extended the Tol harvester by approximately 1.3 meters. Because it had to be installed below the Tol machine's final conveyor, it was positioned very close to the ground, which slightly reduced maneuverability in some orchards.

Objective #3: Develop and integrate a real-time quality control vision system.

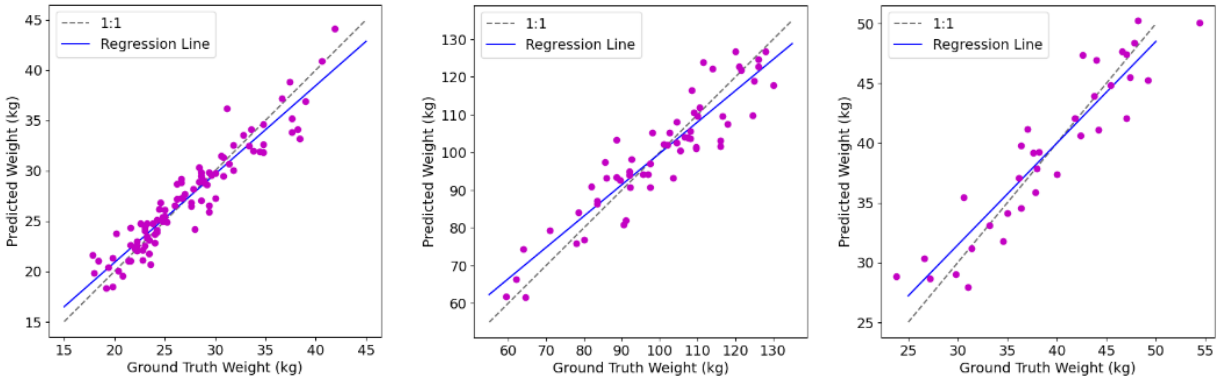
A robust almond segmentation algorithm was developed. This algorithm enabled us to capture images from the almond stream and detect leaves and sticks mixed in with the almonds. By removing these foreign objects from the images, we were able to accurately measure almond yield. A key advantage of this system was that it worked with images generated from the laser profiler's point cloud, eliminating the need for an additional camera and simplifying the setup. Notably, the field error rate was measured at 5.82%, very close to laboratory conditions. This suggested that the current system was already accurate enough for practical use, reducing the need for further adjustments. While the segmentation approach was not used to obtain this result, it could improve accuracy by further refining yield estimation.

F. Data/Results

In the 2023 study, both laser scanners and load cells were integrated into the harvester conveyor system for volume and weight measurement. Laboratory tests using objects of known volume and weight placed on the moving conveyor showed that scanner and load cell measurements were accurate to within 3%. Based on these promising results, both sensing systems were deployed during the 2023 field trials to collect data. During field operation, we found that the machine’s movement between trees and the harvester’s trunk-shaking mechanism transmitted substantial vibrations to the conveyor belt, resulting in noisy load cell signals. In subsequent field trials (2024-2025), laser scanners were used exclusively as the primary data collection sensor. The laser-based system provided millimeter-level measurement accuracy and was robust to vibration and dust commonly encountered during mechanical harvesting. Our yield measurement system was installed on the machines' rear conveyor belts just before the almonds were deposited into the windrows. Experiments were conducted at KG Ranch, Madera, California, in 2023, 2024, and 2025 in orchards growing Nonpareil and Wood Colony varieties. In 2024, the system was also tested at Westwind Farm, Woodland, California, growing the Nonpareil variety. In the 2025 season, the conveyor belt speed was kept the same as in 2024 to maintain system reliability across multiple years. This allowed us to apply and evaluate the generalizability of previously validated model parameters without re-fitting the model to the new dataset.

To determine the accuracy of our yield measurement system, scores of “ground truth” trees were measured as follows: Just prior to reaching a ground truth tree, the conveyors were cleared of all almonds and debris. When the ground truth tree was shaken, all almonds that came off the conveyor were caught on a tarp. Those almonds were placed in a large container and weighed on a portable electronic scale. The height of the almonds in the container was measured, and the volume was calculated.

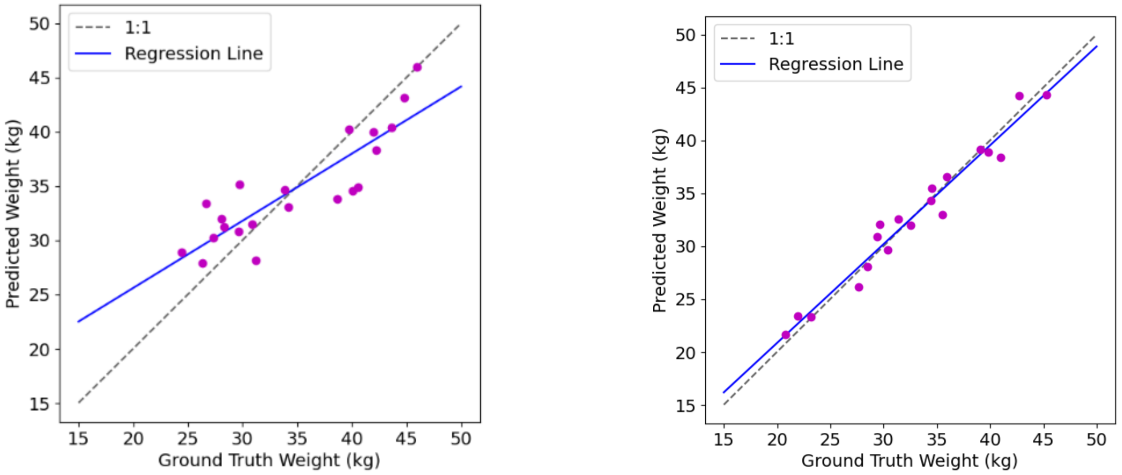
As shown in Figure 2, the relative errors in tree-level yield estimation for ground-truth trees were 5.06%, 5.64%, and 5.82% (Figures 2a, 2b, and 2c), with corresponding coefficients of determination (R^2 values) of 0.90, 0.85, and 0.87. These results confirm the potential of laser-based systems for yield monitoring in mechanically harvested nut orchards.



(a) (b) (c)

Fig. 2. Weight estimation for ground-truth trees based on volume in field conditions, 2024. (a) NonPareil, Westwind Farm, Woodland, CA; (b) NonPareil, KG Ranch, Madera, CA; and (c) Wood Colony, KG Ranch, Madera, CA.

The relative errors in tree-level yield estimates for 2025 (Figure 3) were 9.09% for the Nonpareil variety and 3.44% for the Wood Colony variety (Figures 3a, 3b), with corresponding Pearson's r values of 0.88 and 0.98, respectively. These results demonstrate the potential of laser-based systems for real-time yield monitoring in mechanically harvested almond orchards. They also indicate that, provided the data collection system remains unchanged, previously validated models perform consistently across multiple years and can be directly applied to future volume estimation without additional parameter estimation.



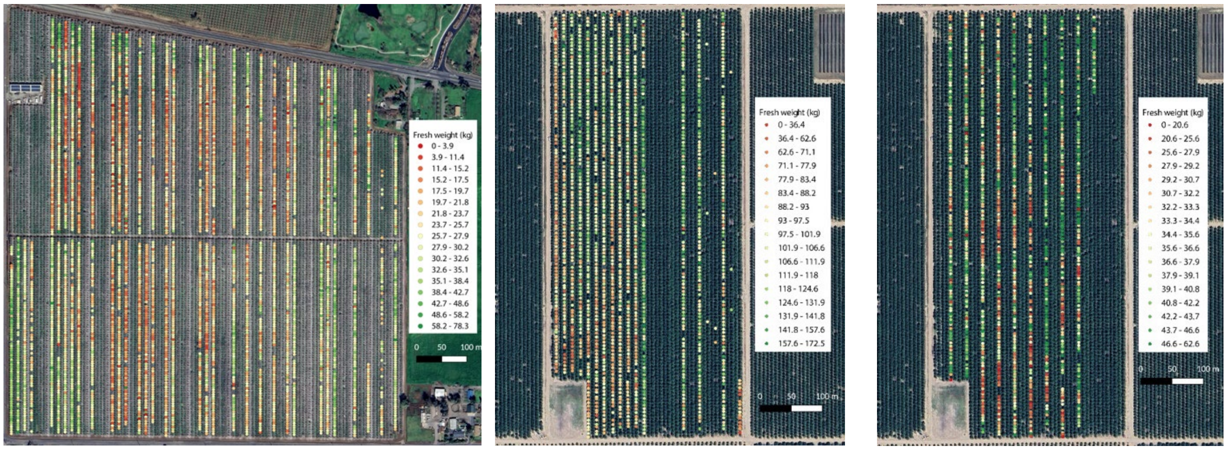
(a) (b)

Fig. 3. Weight estimation for ground-truth trees based on volume in field conditions, 2025. (a) Nonpareil, KG Ranch, Madera, CA (b) Wood Colony, KG Ranch, Madera, CA.

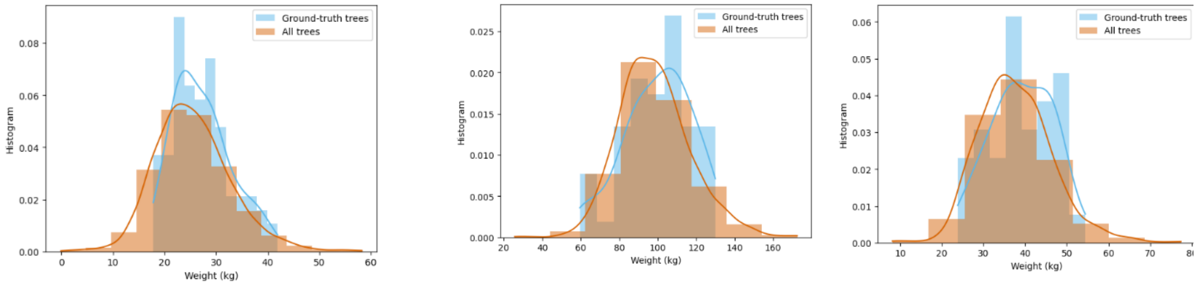
The higher error in Nonpareil compared with Wood Colony is attributed to *branches and debris* in the harvested almonds during data collection. This highlights the challenges faced by sensing systems operating under high field uncertainty and unstructured harvesting conditions. Nevertheless, even in these demanding field environments, the results are promising and demonstrate the practicality of laser-based yield monitoring for commercial almond harvesting operations. Increased debris removal by fine-tuning the blower system and integrating automated identification and removal of branch and debris signals into the processing pipeline is expected to further improve estimation accuracy.

Figure 4 presents the yield maps for the three fields. Figures 4a, 4b, and 4c show fresh weight per tree (in kilograms), with low-yield zones in red. Spatial variability is more apparent in Figure 4a because of the greater number of rows and trees, leading to a smoother transition in yield values. In contrast, Figure 4c, with tree rows more widely spaced, shows sharper yield distinctions.

We also included histograms of the tree-level yield density function in Figures 4d, 4e, and 4f, allowing a direct comparison between ground-truth yield data and the estimated values for all trees in the field using our system. This comparison demonstrates that our method effectively captures the true yield distribution, even in orchards with varying layouts and spatial characteristics.



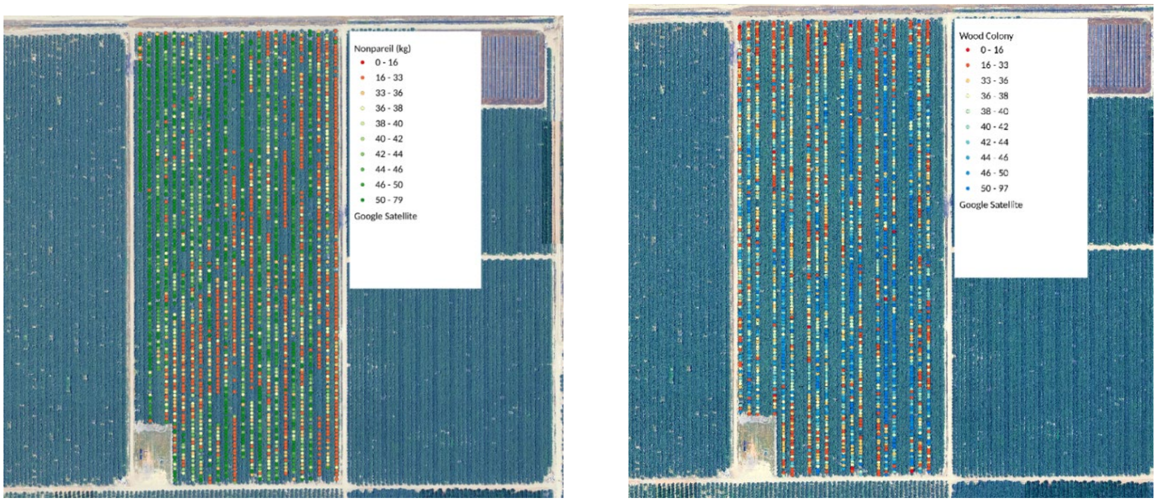
(a) (b) (c)



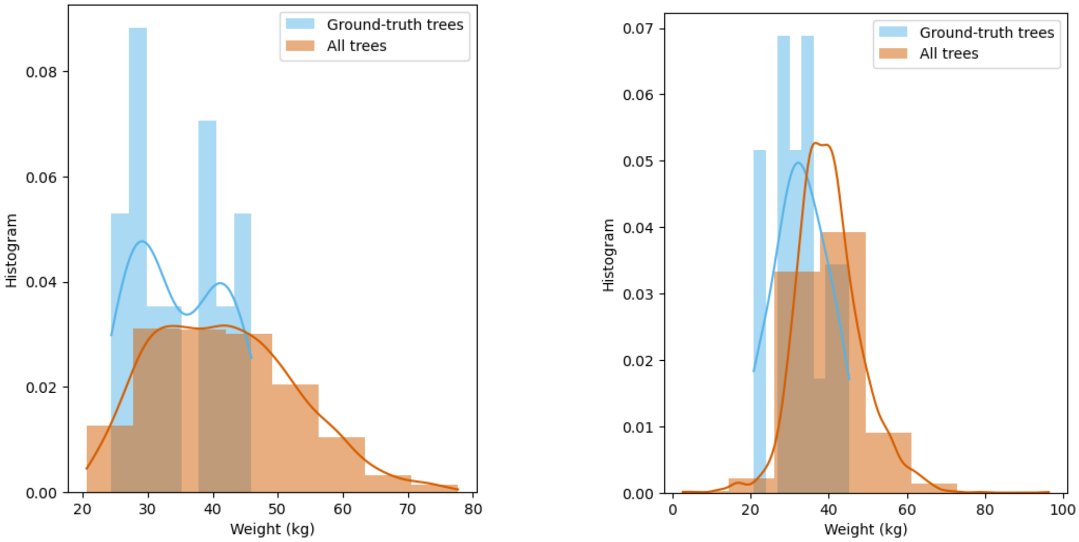
(d) (e) (f)

Figure 4: Yield maps at tree level (a-c) and their data distribution for ground-truth and estimated (all trees) trees in (d-f). The fields are (a) NonPareil, Woodland, CA, (b) NonPareil, Madera, CA, and (c) Wood Colony, Madera, CA.

Figure 5 presents yield maps for the two varieties harvested at KG Ranch, Madera, CA. Figures 5a and 5b show yield maps of fresh weight per tree (kg). Low-yield zones appear in red, while high-yield zones appear in dark green and blue. This visualization allows growers to readily identify spatial yield variability, locate underperforming areas, and make informed management decisions for targeted interventions. We also included histograms of the tree-level yield density function in Figures 5c and 5d, enabling a direct comparison of ground-truth yield data with the estimated values from our system. This comparison shows that our method captures the true yield distribution, even across varying orchard layouts and multiple varieties and years of experimentation.



(a) *(b)*



(c) *(d)*

Figure 5: Yield maps at tree-level (a,b) and their data distribution for ground-truth and estimated (all trees) trees in (c,d). The fields are (a) NonPareil, Madera, CA, and (b) Wood Colony, Madera, CA.

We used a Monte Carlo simulation to estimate the uncertainty. This approach used ground-truth almond flow profiles and generated artificial mixing of almonds between neighboring trees. By repeating this procedure multiple times, we quantified the uncertainty as the standard deviation of the error.

For instance, the average time needed to harvest a tree under commercial harvesting conditions was 12.77 seconds. However, our simulations indicated that, due to almond overlap on the conveyor belt from neighboring trees, the uncertainty in the estimate was approximately 50%. To address this, we slowed the tree-to-tree harvesting time to around 20 seconds, which, according to our simulations, would reduce the uncertainty to 15%.

G. Discussion and Conclusions

This project demonstrated a practical system for measuring almond yield at individual-tree resolution during commercial mechanical harvesting without disrupting normal operations. A key outcome was the development of a repeatable framework for generating high-resolution yield maps at the orchard scale. The data acquisition hardware and software performed effectively under real-world commercial harvesting conditions. The improved system could accurately localize trees even during GPS outages by using vibration data from the shaker. The errors observed in field experiments ranged from 3.44% to 9.09%. The presence of debris, leaves, or branches can lead to overestimating volume, affecting the accuracy of weight estimation. However, based on our optimization approach, the data distribution of randomly sampled ground-truth trees aligned well with the tree-level yield estimates generated in this study.

Multi-year field trials showed that the system can support year-to-year tracking of orchard performance. Another outcome was the validation of laser-based volume sensing as a reliable solution under commercial harvesting conditions. Field trials revealed that load-cell-based weight sensing with custom-made belts installed at the end of the machine's belts was highly sensitive to harvester vibrations, prompting the adoption of laser scanning for robust volume measurement.

For growers, tree-level yield maps provide a clear view of spatial yield variability and support data-driven decisions for targeted orchard management, including irrigation, replanting, and varietal performance evaluation. With continued refinement and industry collaboration, this technology has strong potential to become a practical tool for orchard performance assessment and precision management in almond production.

H. Challenges

Challenge	Corrective Action and/or Project Change/lessons learned
Loss of matching funding from the California Pistachio Research Board.	This project initially intended to develop the yield monitor for almonds and pistachios, contingent upon matching funds from the almond board and pistachio research committee. Unfortunately, the Pistachio Board did not provide funding. The project re-focused entirely on almond.
Unpruned branches hit the monitoring system and recalibration of the laser mounting point was needed, which would delay the harvesting process.	The yield monitoring enclosure was redesigned to be more robust against environmental impacts and easier to mount on the harvester than previous versions. This improvement enhanced system durability and reduced downtime for recalibration.
The laser scanners used in this project were designed for indoor use, making them sensitive to sunlight, which affected measurement performance.	The monitoring system was enhanced with improved sun shielding. By blocking all external light sources, the sensors could function as effectively as they would indoors, ensuring reliable data collection.
Dense canopies and the distance between the main computer (which records laser-encoder data) and the vibration sensor caused delays that affected tree identification	A low-cost computer was installed closer to the sensor, eliminating the delay and ensuring accurate tree identification.

I. Project Impacts

Prior FREP-funded projects by this research group established the principle that accurate crop yield measurement is critical for defining orchard fertilizer management strategies and have led to the widespread adoption of crop yield-based fertilizer decision-making. Field-based yield estimation is now the widely adopted standard for fertilizer decision-making and the foundation of mandatory regulatory requirements. Achieving the next level of nutrient use efficiency will require the development of technologies that enable sub-field and ultimately single-tree yield mapping. The ability to measure yield at the individual-tree level is essential to this advancement.

This project has demonstrated that single-tree yield monitoring is possible and provides the foundational technology growers and commercial partners need to achieve the next level of productivity and efficiency. Several immediate impacts can be highlighted: 1) Through numerous high-visibility presentations, growers and commercial service providers have, for the first time, recognized that within-field variability is significant and that it compromises the efficiency of field operations and the profitability of growers (Figs. 4 and 5 above). 2) Our demonstration of the feasibility and value of single-tree and sub-field yield management has encouraged numerous commercial vendors to bring this technology to growers. 3) This project has also spurred development of commercial technologies to enable sub-field precision fertilization strategies. 4) This project has provided researchers with foundational information to enable the development of high-resolution yield technologies (Jin et al., FREP and Almond Board funded) and to improve understanding of nutrient monitoring and management (Brown et al., FREP; Brown et al., Almond Board; Geissler et al., Almond Board; Jin et al., FREP).

Overall, this project has provided the foundational information and demonstrated the commercial viability and agronomic relevance of sub-field yield monitoring. The near- and long-term outcomes will be increased efficiency in fertilizer use, improved efficiency of production practices, greater productivity and profitability through the identification and ultimate remediation of within-field variability.

J. Outreach Activities Summary

Event Name (1): White House Office of Science and Technology
Presentation title: Biostimulants, including the development of product testing strategies and the need for precision yield monitoring.
Location and date: Webinar 1/12/2023
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.), consultants, researchers, government officials, and policy makers
CCA/Grower Continuing Education Units (CEUs) offered: N/A
Number of participants: 35

Event Name (2): Almond Board Project Update
Presentation title: Yield prediction and Yield Monitoring Projects
Location and date: 3/10/23, Davis, CA
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.)
Growers, consultants, Farm Advisors, Almond Industry Representatives
CCA/Grower Continuing Education Units (CEUs) offered: N/A
Number of participants: 30

Event Name (3): The 2023 Almond Conference
Presentation title: Five posters related to nutrient management, yield monitoring and precision agriculture
Location and date: 12/4/23-12/7/23, Sacramento, CA
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.)
Growers, agronomists, researchers, consultants, industry representatives, students
CCA/Grower Continuing Education Units (CEUs) offered: N/A
Number of participants: Estimated 500 viewers

Event Name (4): The Agronomy Society of America Annual Meeting
Presentation title: Biostimulants and Precision Agriculture for Tree Crops
Location and date: 10/31/23, St. Louis, MO
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.)
Students, faculty, researchers
CCA/Grower Continuing Education Units (CEUs) offered: N/A
Number of participants: 122

Event Name (5): Fruit Growers Lab Annual Customer Day
Presentation title: Update on the management of nutrition in tree crops.
Location and date: 2/1/23, Lodi, CA
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.)
Growers, consultants
CCA/Grower Continuing Education Units (CEUs) offered: N/A
Number of participants: 125

Event Name (6): The 2024 Almond Conference
Presentation title: Poster related to nutrient management, yield monitoring, and precision agriculture
Location and date: 12/10/24-12/12/24, Sacramento, CA
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.)
Growers, agronomists, researchers, consultants, industry representatives, students

CCA/Grower Continuing Education Units (CEUs) offered: N/A
Number of participants: Estimated 500 viewers

Event Name (7): The 2024 Almond Conference
Presentation title: Nutrient Management Workshop- Nutrient Management in Tough Times
Location and date: 12/10/24-12/12/24, Sacramento, CA
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.) Growers, agronomists, researchers, consultants, industry representatives, students
CCA/Grower Continuing Education Units (CEUs) offered: N/A
Number of participants: 1000

Event Name (8): Almond Nutrient Management
Presentation title: Managing Nutrients in Almond: Role of yield monitoring
Location and date: U. Merced, Jan 10th, 2024
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.) Growers, agronomists, researchers, consultants, industry representatives, students

CCA/Grower Continuing Education Units (CEUs) offered: 3
Number of participants: 400

Event Name (9): XX International Plant Nutrition Colloquium
Presentation title: Understanding and Characterizing Potassium Soil Variability in the Almond System to Improve Potassium Management
Location and date: Porto, Portugal July 22-25, 2025
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.) Scholars, researchers
CCA/Grower Continuing Education Units (CEUs) offered:0
Number of participants: 200

Event Name (10): 2025 UCCE Yolo-Solano-Sacramento Almond Meeting
Presentation title: Potassium
Location and date: Woodland, CA, March 27 2025
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.) Growers, consultants
CCA/Grower Continuing Education Units (CEUs) offered: 0
Number of participants: 40

Event Name (11): Almond Board of California Conference
Presentation title: "Optimizing Potassium in Almond: Plant and Soil K variability" poster presentation.
Location and date: Sacramento, December 10-12 2025

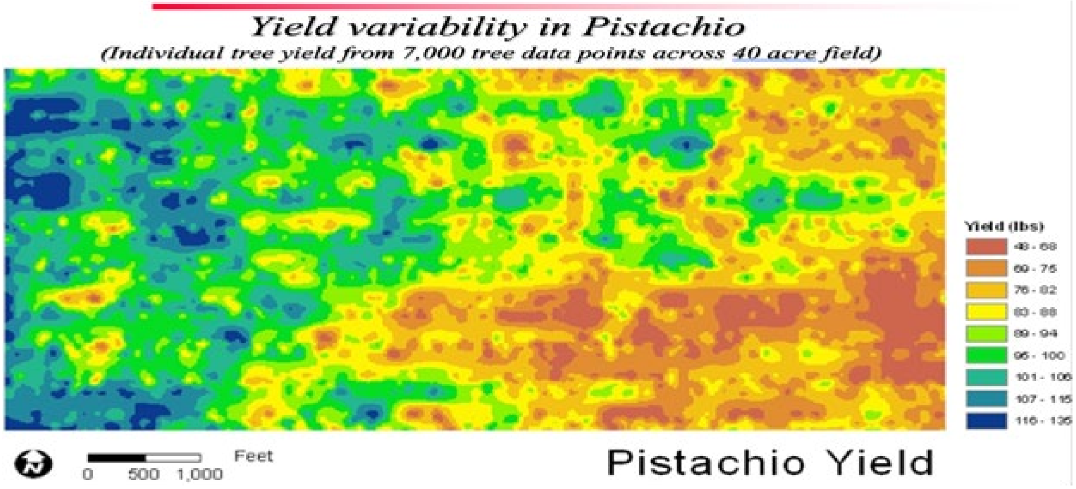
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.)
Growers, researchers, consultants
CCA/Grower Continuing Education Units (CEUs) offered: **3**
Number of participants: 500+

Event Name (12): Almond Board of California Conference
Presentation title: "Single-tree yield mapping in off-ground almond harvesting" poster presentation.
Location and date: Sacramento, December 10-12 2025
Attendee demographics (CCAs, PCAs, growers, consultants, researchers, etc.)
Growers, researchers, consultants
CCA/Grower Continuing Education Units (CEUs) offered: **3**
Number of participants: 50+

K. References

Noble, AE., TS Rosenstock, PH Brown, J Machta, A Hastings 2018 Spatial patterns of tree yield explained by endogenous forces through a correspondence between the Ising model and ecology. Proceedings of the National Academy of Sciences 115 (8), 1825-1830 https://www.pnas.org/content/115/8/1825

L. Appendix



Figures from Section 3, Project Background

Fig. L.1: Single tree yield measurement in 55 acres, 15-year-old pistachio orchard (Lost Hills, CA). Yield is expressed as fresh fruit weight per tree (125 trees per acre).

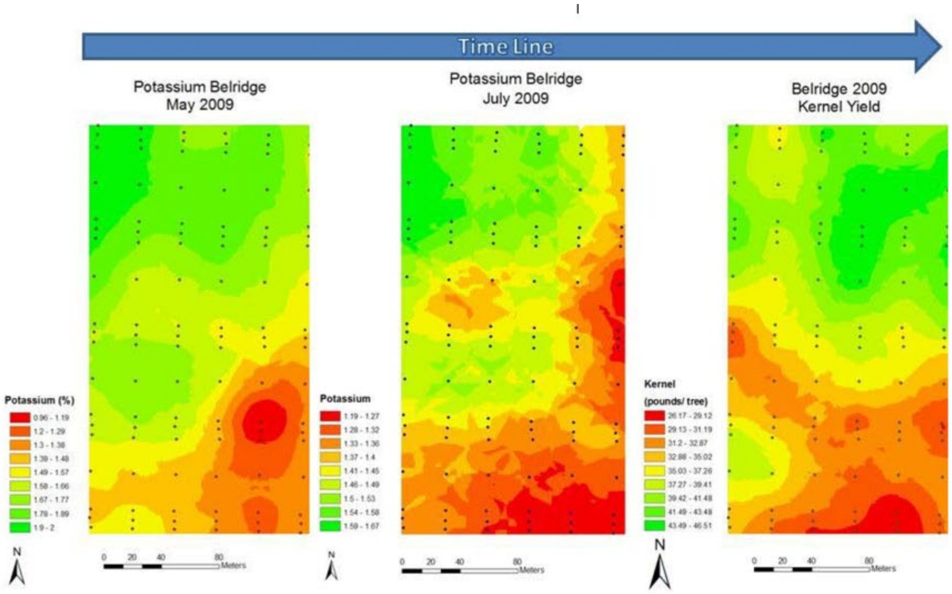


Fig L.2: Individual tree yield (kernel lbs per tree) and leaf K values (%) were determined for 125 almond trees spaced across 30 acres (125 trees per acre). Interpolated yield and leaf K % at 20 tree pixel size are shown.

M. Factsheet

1. **Project Title**: Development of Precision Yield Monitor for Almond and Pistachio

2. **Grant Agreement Number:** 22-1455

3. **Project Leaders:** Patrick H. Brown and Stavros Vougioukas

4. **Start Year/End Year:** 2023/2025

5. **Location:** Davis, CA; Woodland, CA; Madera, CA

6. **County:** Yolo, CA; Madera, CA

7. **Highlights:**
    1. Developed and field-validated a laser-based system to measure almond yield at the individual-tree level during commercial harvest
    2. Integrated laser scanning, GPS, vibration sensing, modeling, and optimization to generate single-tree orchard yield maps
    3. When trees were harvested independently, without mixing from previous trees, yield errors in the range of 3.44–9.09% were achieved
    4. Single-tree yield estimates become more accurate as harvest speed decreases

8. Introduction:

Providing uniform water and nutrients across an entire orchard is common, but it can be inefficient and wasteful. To improve input management, growers need to identify and address field variability. This project aimed to develop and validate a practical system for measuring almond yield at the individual-tree level during commercial harvests, enabling growers to make more informed, data-driven decisions. Researchers at UC Davis designed and tested a laser-based yield monitoring system mounted on commercial off-ground almond harvesters (TOL Twin-D). A laser line profiler, installed above the harvester’s conveyor belt, continuously measured almond volume as the nuts passed through the machine. Additional sensors, including GPS, wheel encoders, and vibration sensors mounted on the tree shaker, recorded the time and location of each harvested tree. A data-processing pipeline integrated these measurements to assign almond volume to individual trees and generate yield maps at single-tree resolution. The results showed that the system produced accurate tree-level yield maps, with relative yield estimation error ranging from 3.44% to 9.09% compared with ground-truth measurements. This technology can help growers better understand yield variability within their orchards and make more precise management decisions.

9. Methods

Two Gocator 2690 Laser Line Profilers and wheel encoders were installed to measure almond flow on the Tol Twin-D harvester’s conveyor belts. As almonds moved along the conveyor, the scanners measured the nuts' volume in real time. GPS units tracked both machines' movements to determine tree locations. A vibration sensor on the shaker head detected when a tree was harvested. By integrating GPS and vibration data, the location of each harvested tree was identified. Tree positions and vibration timestamps, which were crucial for yield assignment to individual trees, were estimated. Continuous volume flow data from the yield monitoring system and the exact time each tree was harvested were used to formulate an optimization problem to assign yield to individual trees. Tree-level volume flow was approximated using parametric models or "kernels." Single-tree kernels were fitted to continuously recorded almond flow using vibration sensor timestamps as prior knowledge. After the data were recorded, the tree-level volume was estimated. Using the ground-truth trees' weights and volumes, a linear model was developed to describe the relationship between volume and weight. The volume obtained at the tree level was then converted into weight using this model. The combination of tree localization and tree-level yield was used to create the yield map. Yield maps were generated to show each tree’s fresh weight, with color scales used to highlight low- and high-yielding areas.

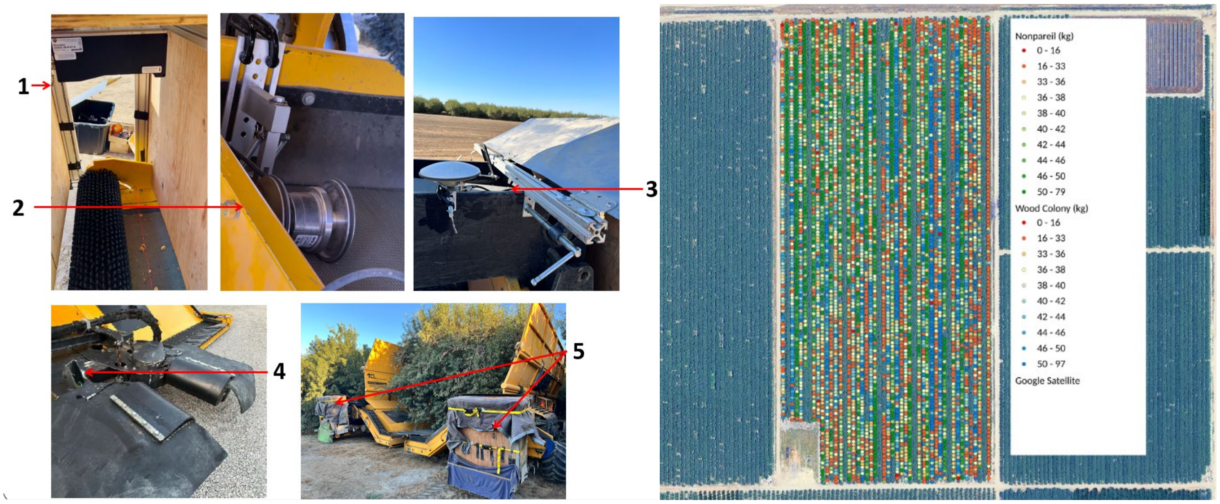


Figure 1: (Left) Almond yield monitoring system: 1. Laser profiler, 2. Wheel Encoder, 3. RTK-GPS, 4. Vibration sensor, 5. Enclosures to protect the laser projections. (Right) Generated yield map, Nonpareil and Wood Colony, Madera, CA

10. Findings

Laser-based sensing reliably measured almond yield under commercial harvesting conditions. GPS and vibration fusion accurately localized each harvested tree, enabling consistent multi-year yield mapping. Field validation showed 3.44–9.09% tree-level yield error when ground-truth trees were harvested independently, i.e., when the conveyor belt was empty before shaking, thus avoiding any nut mixing from previously harvested trees. The system can generate yield maps at any desired resolution, from single-tree to row. However, to generate single-tree maps with low uncertainty, the harvest speed must be reduced to reduce or eliminate almond mixing from previously harvested trees. The tree-level yield maps revealed spatial variability, supporting targeted nutrient management and orchard optimization.