## Title

Evaluation of the use of almond hulls and shells as organic matter amendments

## Author

Andrews, Helen

## Publication Date

2022

# Evaluation of the Use of Almond Hulls and Shells as Organic Matter Amendments

By

HELEN ANDREWS
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Horticulture and Agronomy

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Patrick H. Brown, Chair

Amélie Gaudin

Daniel Geisseler

Committee in Charge
2022

**Contents**

## List of Tables

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Supplementary

**List of Figures**

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Supplementary

## List of Equations

## Abstract

Returning almond hulls and shells to the orchard soil as organic matter amendments can provide numerous soil, water, and plant benefits. Billions of pounds of almond hulls and shells accumulate at California almond processors annually and need a convenient and sustainable outlet. As hulls and shells contain substantial potassium (K) concentrations, surface-applying these materials as organic matter amendments onto nearby almond orchard soil could reduce K fertilizer costs for growers by around 80% by retaining plant K in the orchard. Prior studies have found many crop residues including nutshells release K readily under water application, can improve soil-plant water dynamics, and support higher levels of soil microbiology. However, field trials characterizing the effects of nutshell amendments on K cycling, soil-water dynamics, and soil microbial responses are scarce. Research is needed to evaluate K release from nutshells and impacts on soil K availability and tree K status in commercial orchards. The effects of surface-applied nutshell amendments on soil-plant water dynamics and impacts on soil microbial community composition over time merit further research to assess potential benefits to soil and plant function. Three field trials were conducted to evaluate the effects of this practice on: hull/shell K solubilization, soil K availability, plant nutrient status, yield, soil-plant water dynamics, decomposition rates, and soil microbial functional community composition. Research questions were investigated in field trials established in 2020 in mature commercial California almond orchards. All field trials are randomized complete block designs with each treatment applied to the entire row (at least 40 trees per experimental unit). Each site was approached as a case study with distinct research questions and treatments tailored to grower priorities and current research gaps. This research was funded through a Western SARE grant. Results indicate surface-applied almond hull and shell organic matter amendments can increase K cycling and plant K status, reduce soil surface evaporation, maintain higher moisture in the upper soil layer, moderate plant water stress during dry periods, and increase microbial biomass of many beneficial functional groups in the soil and the amendment layer including arbuscular mycorrhizal fungi. Off ground harvest machinery can be used to maintain the microbially-rich amendment organic layer on the soil surface in the tree row and release a more complete percentage of total amendment K. Findings can be used to support grower decision-making, practice implementation, and future research across different orchard contexts and management approaches.

**Acknowledgements**

I would like to thank grower collaborators for their interest and consistent support of these research field trials: Amanjit Sandu at Crown Nut Company, Kristen Jacobs and Nick Edsall at Bullseye Farms, and Kirk Pumphery at Westwind Farms. Thank you to the many undergraduate students, graduate students, and staff who provided critical field and lab work assistance, including Teena Armstrong, Erini Galatis, Raymond Barsch, Lauryn Armstrong, Lais Teles de Souza, Dante Leventini, Maila Silva, Gustavo Ferreira, Sydney Cho, Evie Smith, Ricardo Camargo, Muhtarima Tabassum, Fray Traganza, Rosa Julius, Dawn Ren, and Ciera Kelly. Thank you, Rad Schmidt for guidance creating CCA plots in R, Erika Yao for your expertise on soil ecology and Biolog EcoPlates protocols, and Srini Peddinti for guidance with TDR Acclima installation and data collection. Thank you, Sam Metcalf and Dan Rivers, for guidance on many practical aspects of fieldwork, equipment recommendations, and sample collection. I appreciate the many skilled farm worker collaborators who I worked with briefly but who made annual amendment applications and yield data collection possible; thank you Andreas, Miguel, Jose, and Bob Gordon and company. I am grateful for the support and guidance of UC Cooperative Extension specialists and advisors including Katherine Jarvis-Shean, Anthony Fulford, Brent Holtz, and Mallika Nocco. I appreciate the following professors for sharing their knowledge and guidance on their areas of expertise: Dr. Amelie Gaudin for microbial methods and agroecology; Dr. Daniel Geisseler for soil fertility and potassium cycling; Dr. Tom Buckley, Dr. Ken Shackel, and Dr. Matthew Gilbert for plant physiology; Dr. Isaya Kisekka for soil water monitoring; Dr. Cristina Lazcano for EcoPlate

guidance, and Dr. Emilio Laca for modeling and statistics. Thank you, Dr. Patrick H. Brown and Dr. Sat Darshan S. Khalsa, for guidance related to nutrient dynamics, project creation, field trial design, and grant writing.

I would like to thank my peer mentor Leah Renwick and all participants in the Graduate Group of Horticulture and Agronomy's peer mentor program who have helped open doors and lower barriers for me and many others. I am grateful to my soil ecology faculty mentor, Dr. Becky Ball, and everyone organizing and supporting the Women in Soil Ecology network. Thank you, Astrid Volder and Lisa Brown, for your commitment to supporting me and our Graduate Group of Horticulture and Agronomy. Dr. Troy Magney and Dr. Matthew Gilbert, I enjoyed working with you in the Plant Sciences Diversity, Equity, and Inclusion Committee and appreciated your mentorship and support immensely; I know many other students feel the same. Erini Galatis, I am so grateful you chose to work with me as an undergraduate research assistant—your work was central to supporting my research, I enjoyed our shared appreciation for fungi, and I am excited to see where you go in science. Evie Smith, Sire Kassama, Jane Fudyma, Clarissa Reyes, Paige Kouba, Sam Hilborn, Sequoia Williams, Katie Simpson-Johnson, Katie Lauck, Jessie Kanter, thank you for your encouragement, excellent scientific advice, thoughtful perspective, and camaraderie. Finally, I would like to thank my family, Jean, Jim, and Peter Andrews for always supporting me. Thank you for raising me in an environment where I was encouraged to ask questions about the natural world and our role in it. Thank you, Chris Chen, my fiancé, for believing in me.

# Chapter 1 Introduction: A review of potassium-rich crop residues used as organic matter amendments in tree crop agroecosystems

This paper was published in *Agriculture's* 2021 Special Issue: Organic Management and Productivity of Tree Crops, 11, 580 https://www.mdpi.com/2077-0472/11/7/580 Minor edits have been made to this version since publication based on dissertation committee feedback.

**Abstract:** Ecosystem-based approaches to nutrient management are needed to satisfy crop nutrient requirements while minimizing environmental impacts of fertilizer use. Applying crop residues as soil amendments can provide essential crop nutrient inputs from organic sources while improving nutrient retention, soil health, water conservation, and crop performance. Tree crop hulls, husks, and shells have been found to contain high concentrations of potassium across species including almond, cacao, coffee, pecan, and hazelnut. The objective of this review is to characterize organic sources of potassium focusing on lignocellulosic pericarps and discuss reported effects of surface application on potassium cycling, water dynamics, soil functionality, and crop yield. Research indicates potassium ions solubilize readily from plant material into soil solution due to potassium's high mobility as a predominately unbound monatomic cation in plant tissues. Studies evaluating tree crop nutshells, field crop residues, and forest ecosystem litter layers indicate this process of potassium release is driven primarily by water and is not strongly limited by decomposition. Research suggests orchard soil management practices can be tailored to maximize the soil and plant benefits provided by this practice. Contextual factors influencing practice adoption and areas for future study are discussed.

**Keywords:** potassium; soil fertility; water; nutrients; organic matter amendments; yield; tree crops; soil health; agroecosystem management

## 1.1 Introduction

Sustainable nutrient management is critical if we are to satisfy crop nutrient requirements while minimizing impacts on human and environmental health (Drinkwater & Snapp, 2007; Harter & Lund, 2012). As agricultural wastes increase worldwide, regional crop residues used as soil amendments can provide crop nutrient inputs while supporting nutrient cycling and retention, soil and water conservation, and soil biology (Lal, 2008). Recycling crop residues provides an efficient strategy for reusing co-products which otherwise may pose financial and ecological waste management hurdles (Panak Balentić et al., 2018; Thiyageshwari et al., 2018; Thomas et al., 2019). This practice has the potential to reduce residue burning and offsite disposal thereby lessening air pollution and groundwater contamination (Esmaeili et al., 2020; Madar et al., 2020; Karimi et al., 2013). Increased interest in agricultural resource use efficiency at the local scale has directed attention toward recycling crop residues and mulches as soil amendments due to relative availability, economic accessibility, and the potential to lower carbon (C) footprints of crop production chains (Hannam et al., 2016; Holtz et al., 2015; Jahanzad et al., 2020; López et al., 2014). At the crop system level, residues can be strategically used as surface amendments to improve soil health (Jahanzad et al., 2020; Kallenbach et al., 2019), water and nutrient use efficiency (Qin et al., 2015), and yields particularly under water or nutrient limited conditions (Iqbal et al., 2011; Jafari et al., 2012; Qin et al., 2015). This practice offers critical ecosystem services that can protect agricultural soils and enhance regional water and air quality (Moore et al., 2019). In contrast, relying solely on inorganic fertilizer can be associated with soil organic matter (SOM) loss, erosion, poor drainage, nutrient leaching, and regional water contamination issues (Harter & Lund, 2012; Lal, 2020; Moore et al., 2019). Nutrient management practices that harness agricultural ecosystem processes can strategically integrate mineral and organic nutrient sources while enhancing biogeochemical processes that build nutrient reservoirs (Drinkwater & Snapp, 2007). Provisioning ecological services through optimized soil management is a central component of sustainable nutrient management in tree crop systems (Montanaro et al., 2017).

While nitrogen (N) and phosphorus (P) cycling in agricultural and forest ecosystems have been extensively investigated, studies focused on potassium (K) cycling and retention are relatively scarce despite the central role of K in plant function (Sardans & Peñuelas, 2015; Tripler et al., 2006). Many tree crops have high K demand particularly when fruits and nuts are ripening as sufficient K helps ensure fruit production and high quality (Alva et al., 2006; Muhammad et al., 2018; Zeng et al., 2001). For instance, Muhammad et al. 2015 determined that 75 kg of K is removed in fruit (kernel, shell, and hull) per 1,000 kg of kernel almond yield, exceeding N removal of 68 kg per metric ton (Muhammad et al., 2015). Potassium fertilizer used to fulfill this demand can be prohibitively expensive in some regions which can impose limitations on crop productivity (Sardans & Peñuelas, 2015). Closing on-farm K cycles and reducing reliance on conventional K fertilizers can provide a strategy to improve crop system sustainability. Studies indicate that K from crop residues can substitute a portion of K fertilizer to fulfill crop requirements, reduce fertilizer expenses, and promote soil and crop benefits (Dong et al., 2019; Jiang et al., 2019; Kasongo et al., 2011; Sui et al., 2015; Zipori et al., 2020). This practice can enhance crop system K cycling, reduce nutrient export, and moderate chronic depletion of soil K in agricultural systems where access to conventional K fertilizer may be limited (Madar et al., 2020; Rafique et al., 2012; Singh et al., 2018; Yadav et al., 2019; Yan et al., 2020). Organic-sourced K from recycled crop residues is a critical component of sustainable K management (Öborn et al., 2005). Across different crop systems, around 70-80% of K in harvested crop biomass could be retained on site if crop residues such as nutshells and straw remain in the field (Madar et al., 2020; Nagao et al., 1992; Singh et al., 2018). In combination with crop residue retention, nutrient cycling from tree crop leaf fall and alleyway biomass can be harnessed as valuable nutrient resources already present in orchard ecosystems (Tagliavini et al., 2007). Plant residue retention offers a strategy to limit K losses from agroecosystems while improving soil health and plant functioning.

For instance, in regions where nut crops are common, nutshells can be highly available and inexpensive nutrient-rich residues typically sold as mulches, feed or bedding for livestock, or otherwise burned or discarded (Wartelle & Marshall, 2001). A growing body of research suggests applying nutshells as amendments can help retain valuable nutrients on site, improve agroecosystem functioning, and create favorable plant growth conditions to improve crop performance. Nutshells are lignocellulosic materials that contain around 1 to 7% K

(Table 1) and often have relatively high C to N ratios (C:N >30:1). Amendments with high C content can increase SOM, soil quality, and yield over time (Holtz et al., 2015; Madar et al., 2020; Neilsen et al., 2014). Further research is needed to characterize potential cycles of N bioavailability under high C:N ratio amendments which often depends on a variety of contextual factors. However, N and K cycles are driven by different processes and microbial communities do not substantially immobilize K (Krishna & Mohan, 2017). Nutshells are a source of plant-derived K that solubilizes easily under water application as a plant-available monovalent cation ($K^+$). Prior research demonstrates residue K solubilization is driven primarily by water, occurs rapidly, and is not strongly limited by C:N ratio or residue decomposition rate (Brito et al., 2014; Dong et al., 2019; Hougni et al., 2021; Kaushal et al., 2012; Li et al., 2014; Rodríguez-Lizana et al., 2010; Tagliavini et al., 2007). While N is a reactive element found in many forms and oxidation states in crop systems, the dynamics controlling organic-sourced K availability appear to be substantially more simplistic and potentially predictable. A better understanding of amendment nutrient release rates and timing will assist researchers and growers in utilizing recycled organic matter to help meet crop nutrient demands (Hannam et al., 2016).

This review examines current knowledge of the utilization of crop residues as organic matter amendments to supply K and enhance crop system function, with a focus on nutshells applied in orchards. Since relatively few studies have been conducted on this topic, prior research was reviewed from orchards across different climates, irrigation and nutrient management approaches, and nutshell application rates in order to best summarize existing knowledge. Processes of K solubilization, soil availability, plant uptake, crop responses and productivity are explored from a whole-system perspective. This review aims to survey current understanding of these dynamics and provide a springboard for future research investigating this practice. While K provided through crop residues is the central focus, this review additionally describes associated improvements in soil health and crop functioning and potential areas for future research.

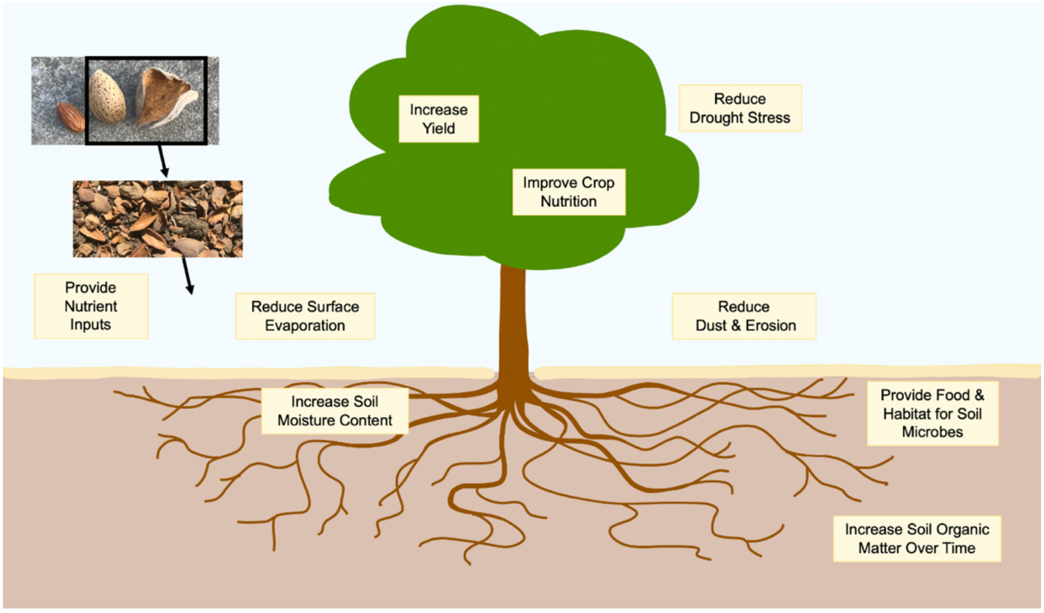


Figure 1.1. Conceptual diagram of potential plant and soil benefits provided by tree crop nutshells applied as organic matter amendments, using almond hulls and shells as an example.

## 1.2 Residue Decomposition and Potassium Solubilization

High C:N ratio (>30:1) residues provide C inputs that can slowly build SOM over time. Decomposition processes are controlled by biological activity and contextual variables such as rainfall, irrigation, temperature, soil management, existing SOM levels, and microbial community composition (Camiré et al., 2002; Kaushal et al., 2012; Krishna & Mohan, 2017; Li et al., 2014). Carbon transformation processes and products are a function of a specific soil ecosystem and are influenced by these environmental factors across spatial and temporal scales (Lehmann & Kleber, 2015; Schmidt et al., 2011). Decomposition occurs along a continuum as soil microbial, chemical, and physical processes produce a variety of organic and inorganic compounds from plant residues (Gross & Harrison, 2019; Lehmann & Kleber, 2015). These processes are driven by cycles of soil microbial communities and associated physiology and enzymes (Gross & Harrison, 2019). For instance, the degradation of almond shell lignin produced a progressive release of C compounds, increasing the variety of C sources that could be further metabolized by soil microbes (Vida et al., 2016). In general, lower temperatures, lower moisture levels, and higher C:N ratios tend to be linked with slower decomposition rates (Dong et al., 2019; Li et al., 2014). While initial decomposition rates may correlate with chemical components indices such as N or lignin content (Schmidt et al., 2011), biological and physical controls of nutrient flows between pools strongly influence soil organic carbon (SOC) dynamics and persistence (Daly et al., 2021). These drivers and controls of decomposition should be considered when designing residue management approaches. For instance, in dry environments high C:N ratio amendments such as almond shells tend to decompose slowly on the soil surface and thus have been recommended for tree crops in water-limited regions to provide a stable soil surface barrier layer and to slow nutrient leaching (Jafari et al., 2012; López et al., 2014; Singh et al., 2018). On the other hand, pericarps with lower C:N ratios such as cacao husks in tropical environments tend to decompose more quickly and have been recommended as an organic nutrient source in depleted soils (Iremiren & Ipinmoroti, 2014; Molina-Murguía et al., 2009). This highlights the importance of considering the effects of a site's climate, soil characteristics, management history, and residue composition on decomposition when designing residue management approaches to meet specific agroecosystem goals.

Soil organic carbon plays a critical role in sustaining agricultural systems by enhancing soil fertility and maintaining productivity (Yan et al., 2020). As a critical functional component of soil health, SOC improves soil structure and water holding capacity while providing substrates for soil biota (Bonanomi et al., 2014). While conventional agricultural practices are known to deplete SOC, organic matter management strategies such as residue retention can reduce the severity of C losses. For instance, increased SOC has been found under surface-applied pecan husks (Idowu et al., 2017), husks and pulp from coffee (Kasongo et al., 2011), and rice straw residues (Yan et al., 2020). A three-year study using wood mulch applications found that SOC increased 23% on one site and 87% at a second site, the difference being attributed to differences in initial SOC between locations, and SOC was the soil component most positively correlated with increased yield (Bonanomi et al., 2014). Coupling residue retention with reduced surface disturbance can provide further SOC building benefits. For instance, zero tillage with residue retention can reduce rapid oxidation of organic matter since residues are not mixed with soil, thus slowing decomposition and building residue-stored C (Madar et al., 2020). Under organic management practices, composted olive pomace application can improve soil quality in olive groves and long-term benefits such as C storage and reduced erosion (Aranda et al., 2015). While residue transformations can contribute a fraction of dissolved organic C to building SOM in agricultural systems (Ma & Rivero, 2010;

Moore et al., 2019), a substantial amount of total SOC is typically derived from microorganisms and rhizodeposition (Gross & Harrison, 2019). Further research is needed to evaluate potential interacting drivers of increased SOC under different residues, including contributions from increased plant root growth, rhizosphere C processes, microbial dynamics, and organic C from plant residues (Gross & Harrison, 2019).

Potassium is the most abundant cation in plant cells (Hawkesford et al., 2012; Sardans & Peñuelas, 2015). Typically, nutrient content in crop residues is influenced by nutrient and water management, soil characteristics, crop-specific nutrient demands, and phenological stage at harvest (Hartemink, 2005; Öborn et al., 2005; Zipori et al., 2020). Plant developmental stage can influence K contents in crop residues as plant K dynamics change over the season (Franchini et al., 2003). A substantial fraction of annual K uptake can be accumulated in tree fruits during development; for instance around 91% of whole plant K accumulation in almonds is allocated to fruit tissues (Muhammad et al., 2015). Additionally, nutrient concentrations can vary substantially across regions as shown in cacao husk (Singh et al., 2019; Hartemink, 2005). Post-harvest processing can influence residue K concentrations; for instance, composting can substantially increase K content (Zoca et al., 2014). Table 1 shows ranges of K values in nutshells across crop species. Based on available literature, Table 1 demonstrates that cacao, almond, coffee, hazelnut, pecan pericarps often contain substantial K levels. Supplementary Diagram 1 illustrates examples of tree crop pericarp materials. Post-processing residues from olive and grape contain notable amounts of K, as do a wide variety of row crop residues. Studies have found nutshell biochar can supply K (Adu-Dapaah et al., 1994;

Munongo et al., 2017), however this review focuses on residue use without pyrolysis to evaluate practices that minimize environmental pollution.

Table 1.1. Estimated percent potassium (%K) in residues from a variety of tree crops, other permanent crops, and row crops. Most sources did not report standard deviations.

| Source Crop | Material | Estimated %K | Region and Reference |
|---|---|---|---|
| **Residues and biomass from tree crops and other permanent crops** | | | |
| Almond | hull | 3.2 | Murcia, Spain; Valverde et al. 2013 Table 2 |
| Almond | shell | 0.5 | Murcia, Spain; Valverde et al. 2013 Table 2 |
| Almond | hull | 3.3 | California, U.S.A.; Atkas et al. 2015 Table 6 |
| Almond | shell | 1.7 | California, U.S.A.; Atkas et al. 2015 Table 6 |
| Bhimal (Grewia) | leaf litter | 2.55 | Himachal Pradesh, India; Verma et al. 2012 Table 3 |
| Cacao | husk | 2.89 | Cote d'Ivoire and the Netherlands; Hougni et al. 2021 Table 1 |
| Cacao | husk | 3.18 | Review; Campos-Vega et al. 2018 Table 2 |
| Cacao | husk | 3.73 | Pingtung, Taiwan; Tsai and Huang et al. 2018 Table 2 |
| Cacao | husk | 2.8-3.8 | Review; Lu et al. 2018 Table 1 |
| Cacao | husk | 3.78 | Akure, Nigeria; Agele et al. 2008 Table 1 |
| Cacao | husk | 1.6 | Cote d'Ivoire; Kone et al. 2021 Discussion |
| Cacao | husk | 3.77-7.69 | Review; Hartemink et al. 2005 Table III |
| Coffee | husk | 4.57 | Brazil; Carmo et al. 2016 Table 2 |
| Coffee | pulp husk mixture | 2.49 | Kinshasha, Congo; Kasongo et al. 2011 Table 2 |
| Coffee | pulp | 3.89 | Sao Paulo, Brazil; Zoca et al. 2014 Table 2 |
| Coffee | husk | 3.47 | Sao Paulo, Brazil; Zoca et al. 2014 Table 2 |
| Gliricidia | leaves | 2.65 | Malaysia; Zahara et al. 1999 Results |
| Grape | stalk | 3.0 | Spain; Bustamante et al. 2008 Table 1 |
| Grape | pomace | 2.42 | Spain; Bustamante et al. 2008 Table 1 |
| Grape | wine lee | 7.28 | Spain; Bustamante et al. 2008 Table 1 |
| Hazelnut | husk | 4.29 | Turkey; Kizilkaya et al. 2008 Results |
| Olive | pruned material | 0.56 | Review; Zipori et al. 2020 Table 1 |
| Olive | leaf | 0.69-1.19 | Review; Zipori et al. 2020 Table 2 |
| Olive | olive mill waste | 2.10 | Italy; Altieri et al. 2008 Table 1 |
| Olive | olive mill waste | 2.6 | Spain; Cayuela et al. 2004 Table 1 |
| Pecan | husk | 3.47 | New Mexico, U.S.A.; Idowu et al. 2017 Table 2 |
| Pecan | shell | 0.15 | New Mexico, U.S.A.; Idowu et al. 2017 Table 2 |
| Poplar | leaf litter | 1.24 | Himachal Pradesh; Verma et al. 2012 Table 3 |
| **Residues from row crops** | | | |
| Alfalfa | mulch | 2.2 | B.C., Canada; Neilsen et al. 2003 Table 1 |
| Black oat | green manure | 2.86 | Brazil; Franchini et al. 2003 Table 1 elongation stage |
| Black oat | residue | 4.22 | Brazil; Miyazawa et al. 2002 Table 1 |
| Maize | straw | 1.48 | Heilongjiang, China; Dong et al. 2019 Materials & Methods |
| Maize | residue | 1.53-1.69 | New Delhi, India; Madar et al. 2020 Table 1 |
| Radish | green manure | 3.85 | Brazil; Franchini et al. 2003 Table 1 vegetative stage |
| Rice | straw | 2.7 | Punjab, India; Yadav et al. 2019 Materials and Methods |
| Rice | residue | 2.1 | Punjab, India; Yadvinder-Singh et al. 2010 Methods and Materials |
| Rice | straw | 2.19 | Wuhan, China; Li et al. 2014 Materials and Methods |
| Rye | residue | 2.76 | Brazil; Miyazawa et al. 2002 Table 1 |
| Ryegrass cover crop | residue | 5.15 | Italy; Tagliavini et al. 2007 Table 1 |
| Soybean | straw | 1.05 | Heilongjiang, China; Dong et al. 2019 Materials & Methods |
| Sunflower | residue | 2.77 | Spain; Rodriguez-Lizana et al. 2010 Results |
| Wheat | straw | 1.22-1.91 | Jiangsu, China; Sui et al. 2014 Table 2 |
| Wheat | straw | 2.26-2.60 | New Delhi, India; Madar et al. 2020 Table 1 |
| Wheat | straw | 3.78 | Shaanxi, China; Wei et al. 2015 Table 1 |

In plant cells, potassium ions ($K^+$) function as highly mobile osmolytes that form weak complexes and remain readily exchangeable (Hawkesford et al., 2012). Plant residue K is predominantly present in the soluble form of $K^+$ in cell cytosol (Brito et al., 2014; Li et al., 2014; Rosolem et al., 2005; Sardans & Peñuelas, 2015). Numerous studies demonstrate that K is rapidly released from plant residues through water extraction (Dong et al., 2019; Hougni et al., 2021; Li et al., 2014; Rosolem et al., 2005). This process is typically characterized by extremely high release rates after initial water application followed by a slower release stage (Cobo et al., 2002; Dong et al., 2019; Li et al., 2014; Rahman, 1999; Rodríguez-Lizana et al., 2010; Tagliavini et al., 2007). The small size and high mobility of K in plant cell solution enables solubilization from plant residues at rapid release rates largely independent of decomposition rates (Brito et al., 2014; Kaushal et al., 2012; Li et al., 2014; Rodríguez-Lizana et al., 2010). As a result, $K^+$ release rates from plant residues tend to be dramatically faster than mass decomposition rates (Li et al., 2014; Rosolem et al., 2005), although decomposition rate may influence $K^+$ release in later release stages to a lesser degree. Compared to other macronutrients, K often demonstrates the most rapid release rates across a variety of crop residues (Cobo et al., 2002; Dong et al., 2019; Hougni et al., 2021; Rahman, 1999; Wu et al., 2011), composts (Khalsa et al., 2021), and leaf litter (Dhanya et al., 2013; Kaushal et al., 2012; Mubarak et al., 2008; Tagliavini et al., 2007).

The quantity and frequency of water application (as both rainfall and irrigation) determines the rate and total amount of K solubilization from plant material. For instance, Hougni et al. (2021) found that K released rapidly from cacao pod husks at rates that varied as a function of rainfall frequency and quantity. A study comparing straw residues found that 10-20mm of precipitation led to the greatest $K^+$ release while less than 5mm of precipitation did not release significant amounts of K (Rosolem et al., 2005). Maize and soybean residues released around 95% of K contents under 275mm precipitation over 2 months (Dong et al., 2019). When inundated with water, rice straw residues have been shown to release 90% total

K after three days (Li et al., 2014). Zahara et al. (1999) found that green manures released 95% of total K during the rapid initial release phase and 99.99% was released after 70 days under 689 mm of total rainfall (Rahman, 1999). Considering that K solubilization is driven by water and tree K uptake occurs through water uptake, strategically timed water applications during periods of crop demand could be used to supply K from residues in a similar fashion as inorganic fertilizers. As many prior studies on K release have been conducted in row crop residues, there is a need for further research to evaluate K release dynamics from tree crop residues across climates and levels of rainfall and irrigation.

Many residue studies emphasize the strong relationship between initial K release and water application and that the C:N ratio does not strongly regulate K solubilization (Dong et al., 2019; Li et al., 2014; Rodríguez-Lizana et al., 2010). However, some studies additionally suggest that K release rates in later stages may be influenced to a minor degree by plant structural components such as cellulose and lignin concentrations (Rosolem et al., 2005). For instance, while legume green manures with very low C:N ratios (around 9:1) may not show links between C content and K release (Rahman, 1999), other green manures with higher C:N ratios ranging from 10:1 to 30:1 showed a correlation between K release and hemicellulose and C content (Cobo et al., 2002). At higher (>30:1) C:N ratios, different types of nutshells contain varying concentrations of cellulose, hemicellulose, and lignin (Wartelle & Marshall, 2001). Rosolem et al. (2013) note that the lignification of cells in plant residue tissue may reduce the ability for water to enter plant tissues and solubilize K and that biological degradation can help break cell barriers enabling further K diffusion (Rosolem et al., 2005). Other plant compounds may influence K release; for instance, Hougni et al. (2021) suggest the waxy epicarp of cacao pod may require initial decomposition to enable K solubilization (Hougni et al., 2021). In that study, water saturation for 48 hours resulted in only 11% K release from fresh cacao husks compared to 92% K release from partially decomposed husks. Future research focused on K supply from high C:N ratio residues could assess and model all potential drivers of K solubilization including water application rate and frequency, climate variables, C content and forms, decomposition rate, and microbial activity and community composition.

### 1.3 Potassium Availability

The bioavailability of solubilized K in the soil depends on several factors. Soil K can be found in four functional pools: solution K, exchangeable K, non-exchangeable interlayer ("fixed") K, and structural lattice K in primary minerals (Bell et al., 2021; Öborn et al., 2005; Yadav et al., 2019). Figure 2 below provides a conceptual illustration of K dynamics in tree crop systems. Solution and exchangeable K are considered plant available, while fixed and structural K are considered unavailable or only gradually available. These pools exist in dynamic equilibrium and determine plant K availability (Yadav et al., 2019). Water application increases K availability in soil solution as $K^+$ ions desorb from cation exchange sites and K solubilization occurs from organic, fertilizer, and mineral sources. While K can enter and exit mass flow streams, diffusion is the main mechanism of K movement in soil solution to roots (Havlin et al., 2016). Soils high in vermiculite, hydrous mica, or other K-fixing minerals can trap or fix K in interlayers (Havlin et al., 2016; Murashkina et al., 2007; Pettygrove et al., 2011). This fixation can make large quantities of applied K unavailable and may be worsened by K-depletion from a history of intensive agriculture (Singh et al., 2018). However, increased SOM content has been associated with reduced K fixation and improved K availability attributed to interlayer exchange and organic molecule adsorption sites (Cassman et al., 1990; Olk & Cassman, 1995). Appropriate application of K-rich residues may assist in saturating K-fixing soils (Singh et al., 2018; Yadav et al., 2019).

While organic sources of K can increase all four pools of soil K, increases in soil exchangeable K (XK) are the most reported due to the relevance of XK for changes in plant availability. Soil XK has been shown to increase in tree crop systems under cacao husk amendments (Doungous et al., 2018; Samuel & Agbona, 2008), coffee husks (Carmo et al., 2016), a mixture of coffee husks and pulp (Kasongo et al., 2011), pecan husk mulch (Idowu et al., 2017), macadamia nutshells (Bittenbender et al., 1998; Lobel et al., 1994), bark mulch and alfalfa residues (Neilsen et al., 2014). Composted olive pomace and olive mill wastewater are applied to supply K, increase orchard soil XK, CEC, SOM, nitrogen and other nutrients (Altieri & Esposito, 2008; Aranda et al., 2015; Cayuela et al., 2004; Chartzoulakis et al., 2010; Zipori et al., 2020). Citrus pulp residues have been shown to increase soil XK, other cations, and SOM content (Belligno et al., 2005; Guerrero et al., 1995; Meli et al., 2007) and can be used as an alternative to expensive fertilizers (Altieri & Esposito, 2008; Aranda et al., 2015). In other crop systems, increased soil XK has been found under rice straw (Yadav et al., 2019), green manures (Franchini et al., 2003), cereal residues (Miyazawa et al., 2002), cover crops (Amaral et al., 2004), wheat straw (Iqbal et al., 2011), and a mixture of compost and wood scraps (Bonanomi et al., 2014). In one study, rice straw application significantly increased solution K, XK, and lattice K within the upper 60 cm in a sandy loam soil (Yadav et al., 2019). This study proposed that increased solution K could be explained by direct K inputs, reduction in K fixation, solubilization and release of K due to interactions of SOM with clay.

However, the movement and fate of solubilized K depends on many factors such as minerology, CEC, pH, SOM, soil nutrient concentrations, water dynamics, environmental conditions, and soil management (Brito et al., 2014; Öborn et al., 2005; Zeng et al., 2001). For instance, green manure residues led to higher and more immediate plant K uptake in coarse loamy soil compared to fine silty soil (Rafique et al., 2012). A soil trial evaluating pecan husk mulch found water extractable K was higher in sandy soil than finely textured soils after four weeks (Idowu et al., 2017). While K leaching through the soil profile can occur in sandy soils under high water application (Öborn et al., 2005), surface applied K is not commonly prone to leaching below the rootzone due to the inherent CEC of most clay minerals. Several studies indicate that K movement from surface crop residues is concentrated in the top 15 cm of soil (Brito et al., 2014; V. K. Singh et al., 2018). The depth of K movement in the soil profile can be influenced by application rates and residue K content (Brito et al., 2014; Rosolem et al., 2005). Supplementary Diagram 2 provides a template for calculating amendment application rate to achieve a given K input rate. As K movement relies on water availability, drought can restrict K diffusion rates while simultaneously limiting root growth (Hasanuzzaman et al., 2018). Examining the movement of K across pools and evaluating processes of K fixation, release, and leaching beyond the root zone would greatly benefit K balance models (Singh et al., 2018). A better understanding of the spatial and temporal fate of applied K across different types of agricultural soils would improve prediction methods for K availability to guide K management strategies (Tagliavini et al., 2007).

The Potassium Cycle in Tree Crops

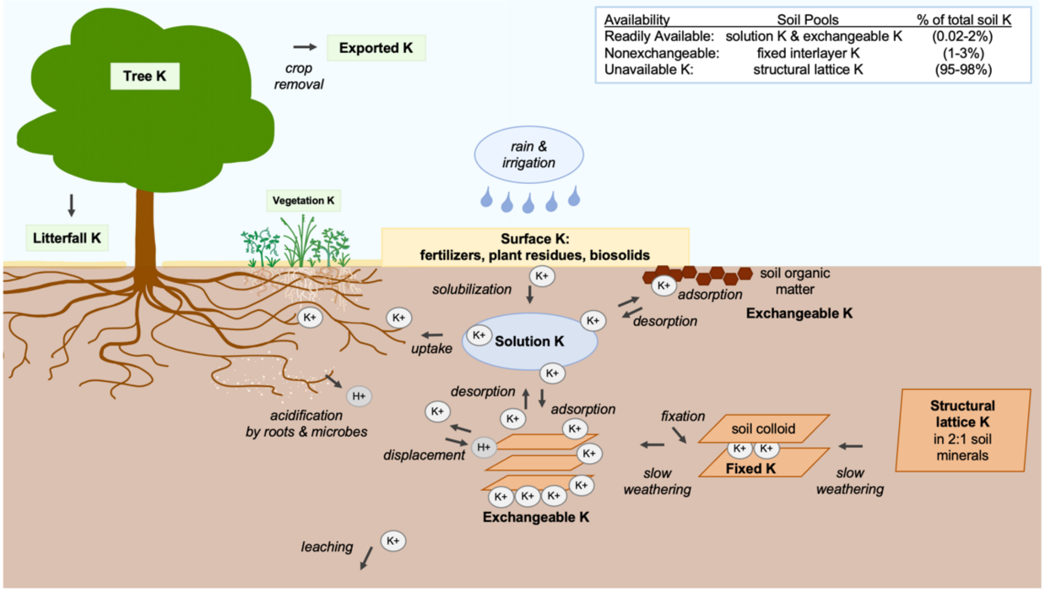

| Availability | Soil Pools | % of total soil K |
|---|---|---|
| Readily Available: | solution K & exchangeable K | (0.02-2%) |
| Nonexchangeable: | fixed interlayer K | (1-3%) |
| Unavailable K: | structural lattice K | (95-98%) |

Figure 1.2. Conceptual diagram of the potassium cycle in tree crop systems. Processes are in italics and pools are bolded. In tree crop agroecosystems, K pools and processes overlap and interact more than pictured here. Potassium primarily moves through the soil by diffusion and can diffuse in and out of mass flow streams. The mechanism and rate of K movement depends on location in the soil and water dynamics. Potassium losses from leaching tend to be minimal unless in sandy soil (Havlin et al., 2016). Plant K can be stored in perennial organs, exported during crop removal, and recycled during litterfall and residue return.

## 1.4 Impacts of increased soil health on potassium availability and nutrient cycling

Crop residue amendments can improve soil structure while providing a surface mulch which can enhance soil water availability and therefore solution K. For instance, soil bulk density has been reduced under almond shell amendments (López et al., 2014), hazelnut husks (Özenç & Özenç, 2008), cacao husks (Molina-Murguía et al., 2009; Moyin-Jesu, 2007), olive mill waste (Regni et al., 2017), and alfalfa mulch (Neilsen et al., 2014). Residue cover may alleviate negative effects of soil compaction (Ma & Rivero, 2010; Shao et al., 2016). Additionally, soil aggregate stability has been improved by the application of pecan hulls and shells (Idowu et al., 2017), pecan wood chips (Tahboub et al., 2008), coffee husks (Moreno-Ramón et al., 2014), and alfalfa mulch (Neilsen et al., 2014). As a barrier on the soil surface, coffee husk application can protect against erosion, reduce runoff rates, and produce cleaner water flows (Moreno-Ramón et al., 2014). Retaining crop residues and mulches is a soil conservation strategy that can help build SOM while reducing erosion (Laird & Chang, 2013; Montanaro et al., 2017; Moore et al., 2019; Moreno-Ramón et al., 2014). In semi-arid regions, studies found reduced surface evaporation under almond shell amendments (Jafari et al., 2012), pistachio shells, pistachio hull-based compost, and olive pomace (Farzi et al., 2017; Karagoktas et al., 2014). Crop residue mulches can reduce evaporation (Moore et al., 2019, 2019; Singh et al., 2018) and improve water use efficiency to produce more crop per drop (Farzi et al., 2017; Morison et al., 2008). Increased available water content has been found under pecan husk mulch (Idowu et al., 2017), hazelnut husk compost (Özenç & Özenç, 2008), almond shells (Jafari et al., 2012), and macadamia husks (Cox et al., 2004). Residue applications can increase soil available water, water storage, and irrigation use efficiency (Moore et al., 2019; Shao et al., 2016). Water infiltration can be improved under coffee husks (Moreno-Ramón et al., 2014), maize and soybean residues (Moore et al., 2019), and alfalfa mulch (Neilsen et al., 2014). Crop residues can moderate effects of salt buildup by enabling salts to leach out of the top surface layer due to enhanced water infiltration, reduced evaporation, and increased soil moisture content (Madar et al., 2020; Moore et al., 2019). The potential gains in water conservation are particularly high in semi-arid regions given that water availability is expected to become increasingly unreliable in the future (Farzi et al., 2017; Hannam et al., 2016). An immediate soil surface barrier coupled with long-term improvements in soil physical properties have the potential to substantially improve water use efficiency, nutrient uptake, and tree water and nutrient status.

Tree crop residue application can increase SOM over time and improve soil chemical properties that govern the availability and retention of K and other nutrients. Improved SOM levels can generate new exchange sites, chelate and solubilize ions, and increase nutrient availability (Karagoktas et al., 2014). For instance, increased soil CEC under coffee husk amendments has been attributed to changes in SOC, pH, and decomposition byproducts (Carmo et al., 2016; Kasongo et al., 2011). A seven-year trial in apple orchards found that annual applications of alfalfa residues significantly increased CEC, soil C, N, K, and slightly increased pH ( Neilsen et al., 2014). In forest ecosystems, litterfall can contribute to replenishing cations and buffering soil acidity (Zimmermann et al., 2002). In addition to SOM exchange sites, plant residues themselves can absorb and adsorb K during decomposition enabling K release and plant uptake later in the season (Li et al., 2014). Nutshells such as pecan, cacao, and almond have been characterized by high lignin content and high phenolic and carboxylic functional groups which favor cation adsorption (Fernandez-Bayo et al., 2020; Hernández-Montoya et al., 2011; Panak Balentić et al., 2018). Further research is needed to investigate the dynamics of high C:N ratio residue cation release and adsorption under different water regimes. In addition, decomposition processes release organic acids that can generate negative charges and preferentially adsorb divalent and trivalent cations, freeing up negatively charged sites on soil colloids that help retain K within the root zone (Brito et al., 2014; Miyazawa et al., 2002; Singh et al., 2018). This complexation has been shown to moderate high $Al^{3+}$ levels under residues (Amaral et al., 2004). While long-term, repeated residue applications at appropriate rates can build SOM and nutrient reserves (Madar et al., 2020), further research is needed to evaluate changes in SOM and CEC across orchard soils in tree crop agroecosystems.

Over time, improved SOM under tree crop residues can moderate soil pH toward neutral, promoting nutrient availability. Several studies recommended residues as liming materials to increase pH (Diehl et al., 2008; Kasongo et al., 2011). For example, cacao husk compost may help raise pH and alleviate Al toxicity in soils where extended cacao production reduced pH (Doungous et al., 2018). In another study, cacao husk amendments increased pH to 6.9 compared to the pH of 5.4 in control plots, which was accompanied by increases in available P, K, Ca, and Mg (Moyin-Jesu, 2007). A lab incubation trial found higher soil pH under coffee husk amendments compared to the control after 330 days across three soil types (Carmo et al., 2016). Within 3 months, Kasongo et al. (2011) found coffee pulp and husk application increased soil pH, XK, Ca, and Mg while reducing Al toxicity (Kasongo et al., 2011). In this study, maximum CEC occurred after 1 year under the highest application rate. Residues from certain species such as black oats can accelerate the mobility of surface-applied lime through topsoil layers likely due to complexation between organic ligands and divalent cations (Amaral et al., 2004; Miyazawa et al., 2002). Conversely, other studies indicate crop residues can ameliorate basic soils by reducing pH. For instance, almond shells in avocado orchards reduced high soil pH which increased available P after ten years (López et al., 2014). Since the almond shells contained minimal amounts of P, researchers concluded that pH reduction likely mobilized otherwise unavailable soil P. In another study, pistachio hull-based compost increased available P and Zn by lowering the pH of calcareous soils likely due to the formation of acids which supply hydrogen ions (Karagoktas et al., 2014). Future studies are needed to investigate the potential for crop residues to moderate pH levels from both acidic and basic extremes and associated effects on nutrient availability in agricultural soils.

High C residue application can increase soil microbial biomass and activity while shifting functional community composition. For instance, studies have found increased microbial biomass under macadamia husk mulch (Cox et al., 2004), rice straw residue (Yan et al., 2020), and bark mulch (Forge et al., 2015; Neilsen et al., 2014). Similarly, soil microbial respiration has been found to increase under maize and soybean residues (Laird & Chang, 2013), leaf litter (Khalsa et al., 2016), and mixtures of compost and wood chips (Bonanomi et al., 2014). Residue C:N ratio strongly impacts microbial growth and respiration as certain microbial groups are capable of utilizing high-C substrates more successfully than others (Manzoni et al., 2008). As a result, high C:N ratio amendments tend to promote more C efficient microbes such as fungi (Forge et al., 2015; G. Neilsen et al., 2014). As materials degrade, distinctive shifts in community composition occur due to changes in available substrates, a phenomenon observed under almond shell amendments for example (Bonilla et al., 2012; Vida et al., 2016). However, some studies show conflicting results about whether low vs. high C:N ratio amendments improve microbial community C use efficiency (CUE, proportion of $C_{assimilated} : C_{respired}$) likely due to site-specific environmental trait filtering (Kallenbach et al., 2019). However, a variety of C inputs with different C and N availabilities, including retained residues, could help maintain resources that support microbial CUE and avoid a shift to an overabundance of inefficient microbes (Kallenbach et al., 2019). In these ways, the integration of crop residues into soil management offers a strategy to diversify soil C inputs, maintain more functionally diverse soil microbial communities, and maintain microbial CUE in agroecosystems.

More broadly, it is well-established that microbial biodiversity is essential for maintaining agricultural soil productivity and quality (Wall et al., 2015; Yan et al., 2020). High amounts of taxa can impart functional redundancy and a 'portfolio effect' that buffer microbial processes against environmental stressors (Allison & Martiny, 2008). Improved soil microbial diversity provides a greater variety of nutrient cycling functions. For instance, diverse species of ubiquitous soil fungi and bacteria are capable of solubilizing K from mineral sources, making K available for plant uptake and microbial use as the most common osmolyte in living cells (Benito et al., 2011; Haro & Benito, 2019; Meena et al., 2014; Rashid et al., 2016). While the response of microbial biodiversity to agricultural management is complex, conventionally managed soils often contain lower microbial species richness than organically managed or undisturbed soils (Bruggen et al., 2019; Diepeningen et al., 2006; Hartmann et al., 2015). Specific management approaches in organically managed systems can cause distinct shifts in microbial community guilds (Diepeningen et al., 2006; Hartmann et al., 2015). However, the direction of shifts in microbial species richness and biodiversity in response to management remains challenging to predict in the field due to variables such as climate, litter quality, SOC, N supply, vegetation, crop rotations, root exudates, soil pH, and impacts of climate change (Bonilla et al., 2012; Jansson & Hofmockel, 2020; Urra et al., 2018; Yan et al., 2020). Nonetheless, agronomic strategies are needed to mediate biotic homogenization in agroecosystems and improve functional trait diversity and associated ecosystem services, such as nutrient retention (Gámez-Virués et al., 2015; van der Heijden & Wagg, 2013; Wood et al., 2015). Residue retention is a soil health building strategy that can be used to provide C and nutrient inputs that support microbial community functioning and biodiversity.

### 1.5 Effects of potassium-rich organic matter amendments on crop performance

Potassium uptake and transport are closely linked to water dynamics and fruit sink demands in tree crops (Kuzin et al., 2020; Sardans & Peñuelas, 2015; Zeng et al., 2001). As plants rely on available water for transport of K across membrane barriers, K uptake is strongly related to soil water content (Hawkesford et al., 2012; Sardans & Peñuelas, 2015). Mulches provide a physical barrier on the soil surface that improves temperature and soil moisture conditions for fine root growth which can enhance nutrient uptake. Tree crop fine root growth has been shown to increase under almond shell mulch (Jafari et al., 2012), macadamia husk mulch (Lobel et al., 1994), and bark mulch (Forge et al., 2015). Surface residues can increase available K in the upper soil layer where roots proliferate, and higher plant K uptake can facilitate root growth (Madar et al., 2020; Singh et al., 2018). Root exudates assist in making K and other cations plant-available in soil solution through acidification and chemical reactions which can mobilize cations, promoting a positive feedback loop between roots and available nutrients (Diehl et al., 2008). In addition, root exudates and decomposing residues can contribute labile C compounds that stimulate microbial activity and nutrient cycling (Hoagland et al., 2008). Since plants take up solubilized K, tree crops do not discriminate between different K sources to fulfill K demand (Muhammad et al., 2015). Transpiration rates under amendments have been shown to increase compared to unamended controls (Farzi et al., 2017), suggesting improved uptake rates of both water and nutrients in solution. Potassium is highly mobile throughout plant cells and tissues with primary functions as an osmolyte and counter-ion, and roles in enzyme activation and protein synthesis (Hawkesford et al., 2012). The timing of K demand is strongest during fruit development or nut fill (Kuzin et al., 2020; Muhammad et al., 2020; Zeng et al., 2001). It plays a central role in carbohydrate transport in developing fruit and has been linked to fruit and nut quality (Alva et al., 2006; Kuzin et al., 2020; Zeng et al., 2001). Potassium plays an essential role in plant water dynamics contributing directly to osmotic potential (Hawkesford et al., 2012). Sufficient K uptake is critical for growth, yield, and long-term plant health.

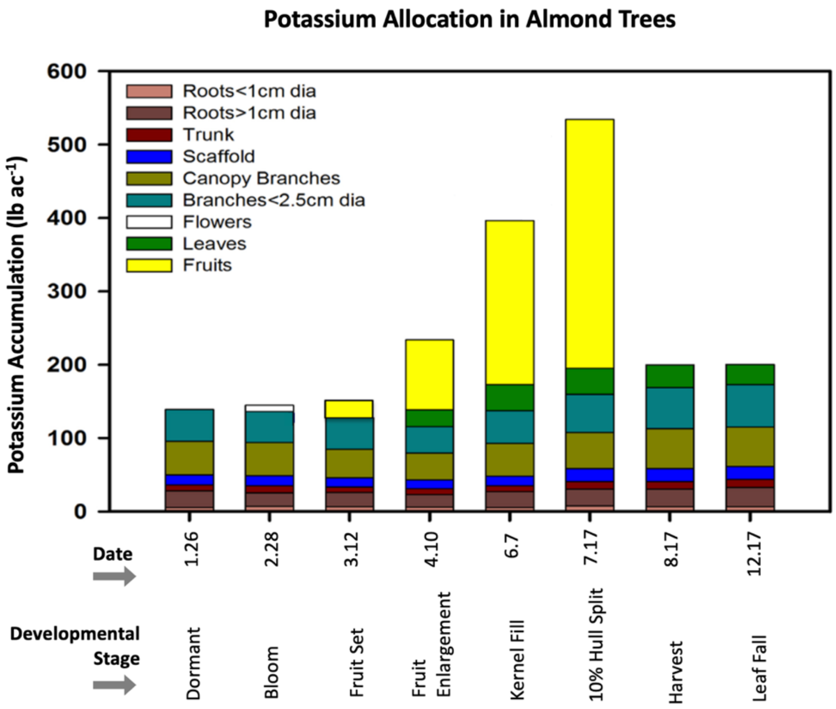


Figure 1.3. Potassium allocation in almond tree tissues, California 2012. 83% of total K accumulated during a season was allocated to fruit tissues in almond trees. Adapted from Muhammad et al. 2020 (Muhammad et al., 2020).

Potassium application is an agronomic practice used to increase plant tolerance to temporary water shortages as it assists plants in responding to short-term water deficits (Grzebisz et al., 2013; Hasanuzzaman et al., 2018). Potassium is utilized in nearly all physiological plant processes that involve water including stomatal regulation, assimilate translocation, and water transport. Optimizing K uptake can mitigate water stress through improved water use efficiency (Elsa et al., 2016; Hasanuzzaman et al., 2018). The roles of K in physiological and molecular mechanisms of drought stress resistance include contributions to cell elongation, cell membrane stability, aquaporins and water uptake, osmotic adjustment, stomatal regulation, and detoxification of reactive oxygen species (Wang et al., 2013). Potassium fertilization can increase hydraulic conductance of xylem and solute sap content (Hasanuzzaman et al., 2018). Leaf K levels modulate the severity of effects of water stress on photosynthesis through osmotic adjustment (Gupta et al., 1989; Hawkesford et al., 2012). One study indicated K fertilization can induce isohydric stomatal behavior which increased responsive stomatal closure during water stress while increasing evapotranspiration in maize (Elsa et al., 2016). Across numerous crop types, studies have recommended ensuring sufficient K supply to alleviate detrimental impacts of mild water deficit on plant growth, crop development, and yield during critical periods of crop K sensitivity (Elsa et al., 2016; Grzebisz et al., 2013). Given projected global climate changes and the central role of K in water use efficiency, providing adequate K supply from an organic residue layer that simultaneously maintains soil water content could provide a critical strategy for maintaining crop productivity particularly in arid and semi-arid agroecosystems.

Potassium deficiency impedes plant water dynamics, growth, metabolism, photosynthesis, carbohydrate transport, and resistance to stress. Stomata do not operate as efficiently under K deficiency, assimilate transport to roots is greatly reduced, and root growth slows (Hawkesford et al., 2012). Potassium's role in stomatal conductance makes K-deficient plants more susceptible to drought, thus maintaining adequate crop K is critical for plant drought resistance (Öborn et al., 2005; Wang et al., 2013). Reduced K uptake can lower water uptake by reducing activity of aquaporins (Sardans & Peñuelas, 2015). Potassium deficiency can lead to reduced turgor, lower enzyme activation, metabolic disorders, and strong limitations on photosynthesis (Hawkesford et al., 2012). Insufficient K can accelerate premature leaf senescence and reduce numbers of flowers and fruits in subsequent years (Brown et al., 2000;

Muhammad et al., 2018). Increased susceptibility to both biotic and abiotic stressors occurs during K deficiency; this reduced stress resistance is attributed to increased ROS production (Hawkesford et al., 2012). At the crop system level, long-term soil fertility depletion from intensive agriculture can create nutrient imbalances as high quantities of nutrients are exported annually in harvested crops and crop residues (Rao, 2017). When residues are not returned, a more severe net-negative K balance can develop in productive regions (Li et al., 2014; Yadav et al., 2019). For instance, nutrient export in cacao beans and husks over time can remove substantial quantities of K and deplete soil K reserves unless replenished (Munongo et al., 2017; Singh et al., 2019). Cacao husks and composted processing waste amendments can reduce this net nutrient export and address K losses (Hougni et al., 2021; Singh et al., 2019). Potassium deficiency can develop due to insufficient K fertilizer use and increased yield demands, as well as innate soil K fixation and excessive N fertilizer use (Zeng et al., 2001). Nutrient retention tends to be low in soils that have been farmed for many decades. In addition, degraded soil structure and compaction can reduce K availability and uptake by reducing soil solution mobility (Öborn et al., 2005),(Iqbal et al., 2011). The utilization of crop biomass wastes as amendment sources could be particularly useful in tropical regions with nutrient depleted soils (Moyin-Jesu, 2007; Nduka et al., 2015; Rao, 2017) and arid regions where water conservation is needed (Farzi et al., 2017; Idowu et al., 2017; Jafari et al., 2012). In regions where K fertilizer is less financially accessible, tree crops may be K-limited (Koné et al., 2020). Tree crop growers may opt to supply nutrients from organic residues as a cost-effective alternative to ensure sufficient supply (Koné et al., 2020; Oyewole et al., 2012).

Many studies that found increased yields under nutshell amendments most often attributed yield effects to increased soil water content and uptake of K and other nutrients. Residue mulches provide a physical barrier over the soil surface which can reduce soil evaporation, improve soil water storage, and lower tree water stress. This can enable higher transpiration, nutrient uptake and translocation, and C assimilation which can directly increase biomass production. These improved water and nutrient dynamics have been linked with yield increases. For instance, a study in a water-limited region of Iran found that fig trees under almond shell mulch produced higher quality fruit and higher yields while increasing leaf width, leaf number, shoot growth, and shoot diameter (Jafari et al., 2012). A trial in avocado found that yield was maintained and occasionally increased under almond shell mulch which mitigated drought conditions in Spain's Mediterranean climate (López et al., 2014). In a study with young olive trees, pistachio shell mulch maintained less negative stem water status, increased stomatal conductance and chlorophyll fluorescence ratio (Farzi et al., 2017). Another study found that composted pistachio hull and rice husk significantly increased shoot and root K concentrations as well as shoot fresh weight (Karimi et al., 2013). Macadamia husk mulch can increase macadamia yield and foliar K (Lobel et al., 1994; Nagao et al., 1992). Cacao pod husk amendments can enhance cacao seedling stem girth and height (Oyewole et al., 2012), as well as leaf K levels and growth parameters of cashew seedlings (Samuel & Agbona, 2008). Similarly, coffee husks have been shown to improve cashew seedling development, increasing seedling leaf count, plant height, leaf area, biomass, and leaf K, N, P, K, Ca, and Mg (Nduka et al., 2015). Cacao pod husk used as an organic fertilizer can improve maize yields (Iremiren & Ipinmoroti, 2014) and okra yields, root length, leaf Ca, pod weight and nutrients (Moyin-Jesu, 2007). Solid olive mill waste application can increase olive fruit productive efficiency, dry weight, and yield over time (Nasini et al., 2013; Regni et al., 2017).

Similarly, increased tree crop yields under wood mulch have also been attributed to improved water and nutrient dynamics. A study with wood chip mulch led to a 20-30% savings in irrigation water while improving apple tree growth (despite its high C:N ratio) and prompting extensive fine root growth near the soil surface, indicating mulch likely improved conditions for tree roots (Granatstein & Mullinix, 2008). Similarly, wood chip mulch led to exceptional tree growth in a study in sweet cherry which researchers attributed to greater water availability (Hoagland et al., 2008). In another study, apple trees under bark mulch had larger average trunk cross-sectional area three years after application (Neilsen et al., 2014). Grinding and incorporating woody tree crop biomass into the soil led to higher yields, a 20% increase in irrigation WUE during drought stress, and improved soil water retention and soil nutrients (Jahanzad et al., 2020). Neilsen et al. (2014) note the tradition of using mulches to address K deficiency in particular in apple production systems. A study in a semi-arid region found K-rich alfalfa mulch in coarse-textured orchard soils helped address K fertilization issues under drip irrigation in apple orchards (Neilsen et al., 2003b). Mulches have been shown to improve soil physical properties, moderate water stress, increase trunk circumferences, tree size, leaf K concentrations, and yields in apple orchards in semi-arid regions (Neilsen et al., 2003a, 2003b).

Studies in row crop systems support these findings and suggest increased yields under residues likely result from improved soil physical conditions that promote water and nutrient availability and uptake (Singh et al., 2018). Singh et al. (2018) found that residue retention increased rice and maize K content, kept 75-80% of total K on site, and increased yields which were attributed to improved soil physical conditions. Mulching can significantly enhance yields and water and nutrient use efficiencies of maize and wheat (Lu, 2020; Qin et al., 2015). Iqbal et al. (2010) found that wheat mulch and no-till increased soil K availability, delayed the onset of crop water stress in a semi-arid region, and improved root development, soil water utilization, and grain yield (Iqbal et al., 2011). Authors suggested that mulch application may facilitate nutrient uptake by maintaining greater soil water content for longer time periods. Residue retention in a maize-wheat rotation has been shown to increase total chlorophyll, leaf area index, carotenoids, seedling establishment, nutrient uptake, root growth, grain yield, and protein content (Madar et al., 2020). These improvements were attributed to enhanced aspects of soil nutrient cycling such as physical characteristics, nutrient availability, SOC, soil microbial biomass, and enzymatic activity.

Research from diverse crop systems indicates that recycling crop residues as mulches can contribute to closing the yield gap between attainable and actual yields particularly in arid climates and low nutrient input systems (Qin et al., 2015). However, delineating causal factors of yield differences is often complex due to numerous interactions between the residue, soil, crop, climate, microbial communities, fertilizer inputs, and other site-specific factors (Laird & Chang, 2013; G. H. Neilsen et al., 2003a; Rodríguez-Lizana et al., 2010). In some cases, no clear relationship can be found between yield and effects of residues (Bittenbender et al., 1998). Additionally, while many studies have found increased soil XK under nutshell amendments and other crop residues, fewer studies have measured and reported leaf K status over time. For instance, a study with nutshell amendments found increases soil XK but no differences in foliar K in macadamia (Bittenbender et al., 1998). A ‘dilution effect’ of increased growth may be partially responsible for less frequent observations of increased leaf K levels (Zeng et al., 2001). Researchers suggest that long-term field trials are needed to investigate effects of residues on yield and crop physiology (Laird & Chang, 2013; G. H. Neilsen et al., 2003a).

### 1.6 Future research directions: nitrogen cycling and bioavailability

The availability of N inputs from crop residues integrated with N fertilizer can be challenging to predict considering variables such as C:N ratios, N fertilizer rates, microbial dynamics, existing SOM levels, temporal scales, and decomposition and mineralization rates across temporal scales. Nitrogen immobilization by microorganisms may prompt the need for short-term increased N fertilizer rates to ensure sufficient crop N. This was found to be true in a trial with compost-wood mixtures (30 and 60 Mg $ha^{-1}$) (Bonanomi et al., 2014) and a study with bark mulch (10 cm depth) (Neilsen et al., 2014). However, other studies indicate N immobilization may not necessarily impact crop N status, or in other cases may improve crop N. For instance, Granatstein et al. (2014) did not find significant changes in leaf N under 10 cm thick wood chip mulch in apple orchards (Granatstein et al., 2014). TerAvest et al. (2011) found wood chip mulch resulted in slight N immobilization but led to high yield and tree growth. Similarly, two other studies found no effects of soil N immobilization on crop N status with applications of macadamia nutshell (5 cm depth) (Galanti et al., 2019) and pecan wood chip amendments (18000 kg $ha^{-1}$) (Tahboub et al., 2007). Some sources advise against high C:N ratio amendments in young orchards without supplemental N fertilizer, while other studies indicate high C:N ratio amendments can lead to vigorous young tree growth and high yields (Hoagland et al., 2008; TerAvest et al., 2011). Increased leaf N has been found under coffee husk residues in cashew seedlings (Nduka et al., 2015) and wood chip mulch in apple trees (TerAvest et al., 2011). Although short-term N immobilization occurred during the first year of a study utilizing 74 tons $ha^{-1}$ incorporated woody biomass, Jahanazad et al. (2020) found higher almond tree leaf N content and yield nine years after establishment. While potential N deficiency due to reduced plant fertilizer use is a major concern associated with amendments in organic tree crop production, organic management practices are needed to reduce synthetic N inputs and N losses while synchronizing N availability with crop demand (Hoagland et al., 2008; Neilsen et al., 2014). A holistic framework is needed to assess the processes driving plant-microbe-mineral regulation N bioavailability cycles which can be influenced by substrate accessibility, N fertilizer management, microbial physiological traits, and climatic factors (Daly et al., 2021; Idowu et al., 2017; Manzoni et al., 2008). Further research is needed to resolve these discrepancies and develop more nuanced organic matter management strategies to recouple C and N cycles across diverse agroecosystems, soils, and climates.

## 1.7 Future research directions: harvest practices that build the organic layer

Nutrient cycling processes in forest and orchard agroecosystems often support plant nutrient availability. Decomposition and nutrient release processes from plant residues play major roles in global C and nutrient cycles (Manzoni et al., 2008). In forests, undisturbed litter layers comprised of leaves, woody biomass, and nutshells supply notable amounts of nutrients such as N, Ca, and K (Zimmermann et al., 2002). In regions with low soil nutrients, forest ecosystem productivity is strongly influenced by nutrient cycling efficiency (Zimmermann et al., 2002). For instance, in a study in chestnut forests annual return of Ca, Mg, and K through litterfall corresponded to 35% of the available soil pool of these cations which buffered soil acidity from atmospheric deposition (Zimmermann et al., 2002). In this study, leaves were richest in N and Ca while husks contained high N, K, and Ca. Similarly, leaf litter in tree crop systems can build an active N pool capable of net N mineralization (Khalsa et al., 2016; Tagliavini et al., 2007). Leaf litter decomposition is a fundamental ecosystem process closely linked to nutrient supply for agroforestry tree species (Kaushal et al., 2012). Mulching plays an important role in avocado production in California and creates a visible series of litter layers at different stages of decomposition (Valenzuela-Solano et al., 2005). While fresh litter layers with high C:N ratios may immobilize soil N, lower more decomposed litter layers typically have reduced C:N ratios and release more N compared to less decomposed layers (Valenzuela-Solano et al., 2005). Humified forest organic layers often display higher N mineralization rates than soil layers (Valenzuela-Solano et al., 2005). Understory tree crops such as cacao and coffee are typically grown under shade trees which provide substantial organic matter and nutrient inputs from leaf litter (Singh et al., 2019; Van Der Vossen, 2005). In coffee agroecosystems, nutrient losses can occur due to crop removal and long-term monocropping, while leaf fall, pruning, organic matter application, and intercropping can enhance soil nutrients (Pham et al., 2020; Van Der Vossen, 2005). These studies indicate that tree crop systems can be managed to optimize the inherent litter layer and integrate recycled nutrients into nutrient management strategies.

Orchard soil management plays an important role in organic tree crop production systems given the central focus on managing SOM and more limited options for fertilizers and herbicides (Granatstein et al., 2014; G. H. Neilsen et al., 2003b). Some tree crop systems such as apple, macadamia, walnut, and almond utilize on-ground harvest practices which typically require bare orchard soil to enable crop pickup. This is accomplished through removal of organic litter and intensive herbicide use in conventional systems. For instance, standard on-ground harvest in California almonds involves shaking trees, drying the crop on the bare orchard soil, and windrowing and sweeping up the crop (Chen et al., 2021). On-ground harvest can lead to soil degradation, erosion, air pollution due to dust production, and a longer time period of opportunity for pest contamination (Chen et al., 2021; Cox et al., 2004; Galanti et al., 2019). In apple orchards, bare orchard soils are maintained by herbicides in conventional production systems and cultivation in organic systems, both of which have detrimental impacts on soil quality, SOC, N cycling, beneficial biota, and nutrient availability (TerAvest et al., 2011). For instance, glyphosate applications reduced recycling of orchard vegetation and resulted in lower apple tree leaf K approaching deficiency compared to mulch amendments

(Neilsen et al., 2014). Prolonged herbicide reliance in the tree row reduces plant biomass return, depletes SOM, and increases susceptibility to erosion (Sanchez et al., 2003). In addition, recurring machinery passes and orchard soil disturbances can damage feeder roots responsible for nutrient and water uptake (Granatstein et al., 2014) and offset benefits of organic matter amendments (Glover et al., 2000). Alternative practices to on-ground harvesting and drying are urgently needed to address these issues and improve nutrient management (Chen et al., 2021).

These challenges highlight the need to further evaluate benefits of residue retention and reduced orchard soil disturbances on nutrient cycling, water dynamics, pest management, crop performance, and economic savings (Chen et al., 2021; Granatstein et al., 2014; Ter-Avest et al., 2011). Alternative orchard soil and nutrient management strategies offer high potential for improving soil, water, and air quality while maintaining or increasing yields ( Chen et al., 2021; Sanchez et al., 2003). Organic matter retention and reduced disturbance can be integrated with and allow wider adoption of other soil health building practices. For instance, cover vegetation such as legumes can reduce nutrient losses and increase N stored in tree biomass (Hoagland et al., 2008; Sanchez et al., 2003; TerAvest et al., 2011). In deciduous tree crops, substantial amounts of nutrients and C are returned to the soil annually through leaf abscission, mowing of vegetation, rhizodeposition, and tree pruning, which are processes that can be deliberately managed to enhance nutrient cycling (Tagliavini et al., 2007). Orchard leaf litter N can contribute to the balance of N mineralization and immobilization which is influenced by N management history and orchard soil practices (Khalsa et al., 2020). At a site with a history of mulch applications, one study found that net N release from eucalyptus mulch (C:N ratio of 51:1) doubled after 3 years (Valenzuela-Solano et al., 2005). Nutshell applications can contribute to the formation of new organic layers in avocado orchards over time (López et al., 2014). Returning higher rates of plant litter while reducing soil aggregate disruption can mitigate soil C depletion in agricultural systems (Janzen, 2006). Building SOC content over time can provide long-term nutrient cycling benefits such as fertilizer N retention and supply to tree crops (Khalsa et al., 2020). High C:N ratio amendments may help build long-term soil N reserves (TerAvest et al., 2011). Some research points to the process of microbial N immobilization under high C:N ratio amendments as a potential tool to mitigate nitrate leaching potential, reduce denitrification, and improve N cycling without limiting crop-available N (Hannam et al., 2016; Jahanzad et al., 2020; Jahanzad et al. 2022). Evaluating nutrient release dynamics from high C:N ratio residues will improve predictions of nutrient availability for tree crop uptake to guide management (Kaushal et al., 2012; Tagliavini et al., 2007). Site-specific orchard soil management strategies can be modified to improve nutrient and water cycling and tailored to optimize crop health as trees mature over time (Hoagland et al., 2008; TerAvest et al., 2011). This body of research highlights great potential to develop our understanding of nutrient cycling and availability across trophic levels under reduced orchard soil disturbance and organic residue retention.

### 1.8 Future research directions: implementation considerations, constraints, and benefits

Tree crop growers may face a variety of practical constraints potentially limiting the use of nutshells and other high C:N ratio residues as organic matter amendments. Contextual factors such as access to residues, application equipment, labor, and pest and disease considerations may present different implementation challenges across crop systems and regions. Evaluating factors that promote implementation and potential barriers to adoption is essential for future applied research and communications focused on organic matter amendment use (Khalsa & Brown, n.d.; Lubell et al., 2014). Further investigation of social, economic, and regional constraints will enable more effective and holistic agricultural recommendations that serve tree crop growers and the public (Singh et al., 2019). Multidisciplinary research examining these questions will assist growers of diverse scales and management approaches in adjusting tactics to support system efficiency and profitability. Current literature suggests that the application of composted cacao and coffee pericarps could provide key agroecosystem services such as K cycling and pathogen suppression. Management considerations in these two tree crop systems provide examples of specific benefits and constraints for further evaluation.

Composted cacao pod husks amendments can be used to provide K, enhance tree nutrition, and suppress plant pathogens (Doungous et al., 2018; Hougni et al., 2021). These ecosystem services could provide meaningful benefits given that cacao productivity is often limited by soil fertility, pest pressures, and postharvest practices (Singh et al., 2019; Walton et al., 2020). While cacao husks are well-known to be nutrient-rich, piles of husks scattered on cacao farms can cause sanitation issues and amplify pest pressures (Fidelis & Rao, 2017;

Oyewole et al., 2012). Effective composting practices can kill certain pests such as cacao pod borer larvae and black pod disease (*Phythophthora palmivora*) (Fidelis & Rao, 2017; Munongo et al., 2017) and suppress mycelial growth of *Phytophthora megakarya* pod rot (Doungous et al., 2018) although it may not eliminate viral diseases (Koné et al., 2020). Additionally, compost applications may induce systemic plant defenses against diseases by enhancing the growth of beneficial soil microbial consortium (Doungous et al., 2018). Simultaneously, composting can improve cacao husk amendment pH and increase nutrient concentrations (Fidelis & Rao, 2017). However, further research is needed to evaluate implementation considerations, constraints, and which specific insect pests and plant pathogens could be addressed through composting (Samuel & Agbona, 2008). Cacao management tends to be labor-intensive, and logistics of husk transportation and application may pose barriers to implementation (Samuel & Agbona, 2008). Labor shortages and fluctuating market values may limit the adoption of best management practices in cacao (Singh et al., 2019; Walton et al., 2020). However, a study in Nigeria found that farmers using cacao pod husk as fertilizer gained triple the profit per hectare than farmers not using this amendment (Agbeniyi et al., 2011; Lu et al., 2018). To optimize labor efficiency in resource-constrained smallholdings, rotating pod breaking stations and sequential mulching in small field areas could lower labor requirements. Considering that cacao yields are often limited by fertility and disease in many regions (Munongo et al., 2017), improved husk management could offer an avenue for lifting yield limits if logistical constraints are adequately addressed.

Similarly, composting coffee residues can be used to improve amendment pH, increase K content, suppress certain pathogens, and benefit crop performance. While initial coffee wastes can be acidic, composting husks together with plant and animal wastes can dramatically improve pH while increasing nutrient concentrations and building beneficial microbial communities (Nduka et al., 2015; Nogueira et al., 1999; Shemekite et al., 2013). For instance, composting coffee husk with manure and beneficial microbial inoculants has been shown to enhance pathogen suppression of *Rhizoctonia solani* while increasing pH and nutrient content (Sathianarayanan & Khan, 2008). Coffee husk amendments have been shown to improve soil K, N, and C, fertility, yield while reducing pollution and erosion due to runoff (Carmo et al., 2016; Kasongo et al., 2011; Moreno-Ramón et al., 2014; Nduka et al., 2015). While different types of post-harvest processing methods affect K content, high K release across many coffee residue types indicates residues can substitute for mineral K sources (Zoca et al., 2014). However, the implementation of sustainable practices in coffee varies widely across regions depending on factors such as farm size, external input use, mechanization, economic stability (Le et al., 2020; Winter et al., 2020). Regular access to substantial amounts of organic matter as nutrient inputs in organic coffee production can be challenging for smallholders (Van Der Vossen, 2005). Typically, coffee is often processed offsite and residues might not be easily transported back to coffee farms, which are often located on steep slopes at high altitudes (Van Der Vossen, 2005). Access, labor, transportation, and farm financing are likely limitations for coffee producers interested in applying coffee husk amendments. Further studies are needed to evaluate the practical constraints potentially limiting the adoption of this practice in addition to nutrient supply dynamics and the potential to enhance disease suppression.

### 1.9 Conclusion

In summary, a growing body of research points to the substantial potential of regional crop residues to be recycled as soil amendments in tree crop agroecosystems. Relatively high C:N ratio amendments can supply K and other nutrients, promote many components of soil health, and enhance crop water use and crop performance. Current literature has established that water application is the central driver of the solubilization of K ions from plant residues into soil solution. Evidence from tree crops, other permanent crops, field crops, and forest ecosystem studies indicate that residue retention can be integrated with soil management practices to provide plant and soil benefits. Further research is needed to assess all potential factors influencing K release, K solubilization rates, K fate, crop K and water uptake, impacts on plant function and yield across crop types, management approaches, and regions. Findings indicate great potential for recycled residue K to supplement or substitute fertilizer K in tree crop systems. Impacts could be particularly meaningful in areas where agriculture has depleted soil K and soil organic matter and where water may be a limiting factor. Additionally, future studies could evaluate nitrogen dynamics, effects of harvest practices, and composting and potential use within integrated pest management approaches. Integrating contextual constraints to practice adoption are essential, including access to residues, transportation, labor, and local socio-economic considerations. Interdisciplinary research is needed in order to fully understand likelihood of grower adoption and to support management recommendations that are deliberately tailored to unique agroecosystem contexts.

**1.10 Author Contributions**: Conceptualization, P.H.B, S.D.S.K., E.M.A., S.K.; Methodology, E.MA.; Investigation, E.M.A., S.K., E.S.; Resources, E.M.A., S.K., E.S.; content curation, E.M.A.; writing—original draft preparation, E.MA.; writing—review and editing, E.M.A., S.K., E.S., P.H.B., S.D.S.K.; visualization, E.M.A., S.K.; supervision, S.D.S.K., P.H.B.; project administration, S.DSK., P.H.B; funding acquisition, E.M.A., S.D.S.K., P.H.B. All authors have read and agreed to the published version of the manuscript.

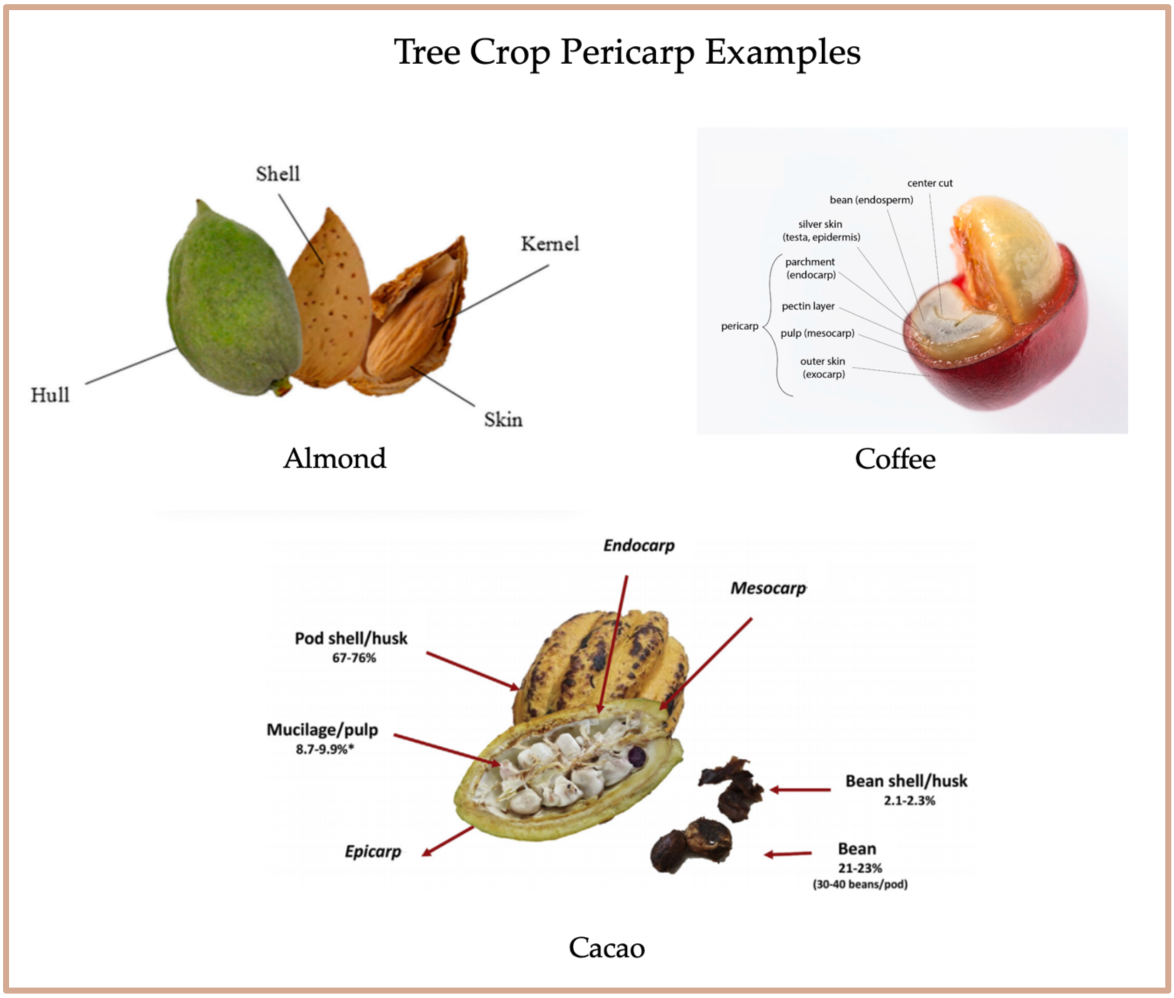
**Funding**: This research was funded by the Western Sustainable Agriculture Research and Education Grant, grant number SW20-912, and the Foundation for Food & Agriculture Research.

WESTERN
SARE
Sustainable Agriculture
Research & Education

**Acknowledgements**: Authors would like to thank Dr. W.R. Horwath and Dr. D. Geisseler for feedback on Figure 2.

**Conflicts of Interest**: The authors declare no conflict of interest.

**1.11 Supplementary Materials**: Supplementary Diagram 1: Tree Crop Pericarp Examples: almond, cacao, coffee. Supplementary Diagram 2: Example Application Rate Calculation – Almond Hulls and Shells.



Supplementary Diagram 1.1. Tree Crop Pericarp Examples: almond, cacao, coffee. Crop hulls, husks, shells, and outer skin are materials that can be used as K-rich organic matter amendments. Diagram was adapted using imagery of almond from (Prgomet et al. (2017), coffee from Klingel et al. (2020), cacao from Campos-Vega et al. (2018).

## Supplementary Diagram 1.2. Example Application Rate Calculation – Almond Hulls and Shells.

**1. Find crop yield dry weight tons/ac.** For example, an almond orchard produces 2500 lb/ac kernel yield and 7500 lb/ac hulls and shells. Kernels are around 25% of the crop weight leaving the orchard at harvest, and hulls and shells are around 75% (fresh weight). Hulls alone are 50% fresh weight in this example.

**2. Find corresponding residue dry weight tons/ac.** Weigh samples of fresh samples of hulls, shells, and kernels dehydrate, and weigh again dry.

Percent dry weight of hulls = dry weight / fresh weight = 60 grams / 70 grams = 85%
5000 lb/ac hulls x 0.85 = 4250 dry weight lb/ac hulls
Percent dry weight of shells = 65 grams / 70 grams = 93%
2500 lb/ac shells x 0.93 = 2325 dry weight lb/ac shells
Percent dry weight of shells = 68 grams / 70 grams = 97%
2500 lb/ac kernels x 0.97 = 2425 dry weight lb/ac kernels

**3. Find or estimate %K in residue materials and kernel separately.** Send in samples of hulls, shells, and kernel to a lab for analysis for K content or estimate. In this example, lab results show hulls are 3% K by dry weight, shells are 1.5% K, and kernels are 1.1% K.

**4. Calculate total lb/ac K removed at harvest in hulls, shells, kernel.** Multiply K fraction (percent x 0.01) in hulls/shells and kernel by respective dry weight.

0.03 K in hulls x 4250 lb/ac dry hulls = 127.5 lb/ac K in hulls
0.015 K in shells x 2325 lb/ac dry shells = 34.8 lb/ac K in shells
0.011 K in kernels x 2425 lb/ac dry kernels = 26.7 lb/ac K in kernels

**5. Calculate tons/ac material needed to supply K removed.**

Sum of total K removed lb/ac = 127.5 in hulls + 34.8 in shells+ 26.7 in kernels = 189 lb/ac K removed

In this example, 189 lb/ac K is needed to replace removal rate. If hulls & shells are returned as an amendment on a per acre basis, only 26.7 lb/ac K needs to be applied. Or, hulls & shells could be returned as an amendment at a higher rate to supply the full required 189 lb/ac K.

**6. Find % moisture of material right before application if needed.**

If moisture has likely changed since %K was obtained, consider adjusting application rate based on current % moisture.

**7. Calculate rate required to supply full K demand.** In this example, only hulls will be applied.

189 lb K / *[how many?]* lb hulls = 3 / 100 189 x 100 / 3 = 6300 lb hulls/ac dry weight

Assuming hulls are 93% moisture still from step 2,

6300 lb hulls dry / ? lb hulls fresh = 85 / 100 6300 x 100 / 85 = 7412 lb hulls fresh weight

To completely fulfill K demand, ~7410 lbs/ac fresh hulls could be applied over tree roots. Application strategy should consider factors such as water inputs, timing, and soil type. Alternately, a portion of total K demand could be integrated with inorganic fertilizer K.

**8. Compare K fertilizer and hull/shell application costs and benefits.** For inorganic and organic sources of K, compare costs of acquisition, transportation, application, labor, etc. Consider crop system benefits related to yield, tree health, nutrition, water, soil health, agroecosystem, and regional sustainability. This practice can be adjusted to serve unique goals and contexts.

## 1.12 Literature Cited

Adu-Dapaah, H. K., Cobbina, J., & Asare, E. O. (1994). Effect of cocoa pod ash on the growth of maize. Journal of Agricultural Science, Cambridge, 122, 31–33.

Agbeniyi, S. O., Oluyole, K. A., & Ogunlade, M. O. (2011). Impact of cocoa pod husk fertilizer on cocoa production in Nigeria. World Journal of Agricultural Sciences, 7(2), 113–116.

Aguilar, A. A., Smith, N. E., & Baldwin, R. L. (1984). Nutritional Value of Almond Hulls for Dairy Cows1. Journal of Dairy Science, 67(1), 97–103.

Allison, S. D., & Martiny, J. B. H. (2008). Resistance, resilience, and redundancy in microbial communities. Proceedings of the National Academy of Sciences, 105 (Supplement 1), 11512–11519.

Altieri, R., & Esposito, A. (2008). Olive orchard amended with two experimental olive mill wastes mixtures: Effects on soil organic carbon, plant growth and yield. Bioresource Technology, 99, 8390–8393.

Alva, A. K., Jr, D. M., Paramasivam, S., Patil, B., Dou, H., & Sajwan, K. S. (2006). Potassium Management for Optimizing Citrus Production and Quality. International Journal of Fruit Science, 6(1), 3–43.

Amaral, A. S., Anghinoni, I., & Deschamps, F. C. (2004). Residues of cover plants and mobility of the products of lime dissolution applied to the soil surface. Brazilian Journal of Soil Science, 28(1), 115–123.

Aranda, V., Macci, C., Peruzzi, E., & Masciandaro, G. (2015). Biochemical activity and chemical-structural properties of soil organic matter after 17 years of amendments with olive-mill pomace co-compost. Journal of Environmental Management, 147, 278–285.

Bell, M. J., Ransom, M. D., Thompson, M. L., Hinsinger, P., Florence, A. M., Moody, P. W., & Guppy, C. N. (2021). Considering Soil Potassium Pools with Dissimilar Plant Availability. In T. S. Murrell, R. L. Mikkelsen, G. Sulewski, R. Norton, & M. L. Thompson (Eds.), Improving Potassium Recommendations for Agricultural Crops (pp. 163–190). Springer International Publishing.

Belligno, A., Di Leo, M. G., Marchese, M., & Tuttobene, R. (2005). Effects of industrial orange wastes on soil characteristics and on growth and production of durum wheat. Agron. Sustain. Dev., 25, 129–135.

Benito, B., Garciadeblás, B., Fraile-Escanciano, A., & Rodríguez-Navarro, A. (2011). Potassium and sodium uptake systems in fungi. The transporter diversity of Magnaporthe oryzae. Fungal Genetics and Biology, 48(8), 812–822.

Binkley, D. (2002). Ten-year decomposition in a loblolly pine forest. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere - Can J Forest Res. 32, 2231–2235.

Bittenbender, H. C., Hue, N. V., Fleming, K., & Brown, H. (1998). Sustainability of organic fertilization of macadamia with macadamia husk-manure compost. Communications in Soil Science and Plant Analysis, *29*(3–4), 409–419.

Bonanomi, G., D'Ascoli, R., Scotti, R., Gaglione, S. A., Caceres, M. G., Sultana, S., Scelza, R., Rao, M. A., & Zoina, A. (2014). Soil quality recovery and crop yield enhancement by combined application of compost and wood to vegetables grown under plastic tunnels. Agriculture, Ecosystems & Environment, 192, 1–7.

Bonilla, N., Cazorla, F. M., Martínez-Alonso, M., Hermoso, J. M., González-Fernández, J. J., Gaju, N., Landa, B. B., & de Vicente, A. (2012). Organic amendments and land management affect bacterial community composition, diversity and biomass in avocado crop soils. Plant and Soil, 357(1), 215–226.

Brito, O., Telles, T., Schnitzer, J., Gaspar, G., & Fatima, M. (2014). The influence of crop residues in vertical soil mobility of potassium. Semina: Ciências Agrárias, 35, 3043.

Brown, P. H., Weinbaum, S. A., & DeJong, T. M. (2000). Reassessment of potassium critical values. In Years of Discovery (1972-2003) Almond Board of California.

Bruggen, A., Goss, E., Havelaar, A., Diepeningen, A., Finckh, M., & Morris, J. (2019). One Health—Cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health. Science of The Total Environment, 664.

Camiré, C., Trofymow, J. A., Duschene, L., Moore, T., Kozak, L. M., Titus, B., Kranabetter, J., Prescott, C., Visser, S., Morrison, I., Siltanen, M., Smith, S. M., Fyles, J., & Wein, R. (2002). Rates of litter decomposition over 6 years in Canadian forests: Influence of litter quality and climate. Canadian Journal of Forest Research, 32, 789–804.

Campos-Vega, R., Nieto-Figueroa, K. H., & Oomah, B. D. (2018). Cocoa (Theobroma cacao L.) pod husk: Renewable source of bioactive compounds. Trends in Food Science & Technology, 81, 172–184.

Carmo, D. L. do, Lima, L. B. de, & Silva, C. A. (2016). Soil Fertility and Electrical Conductivity Affected by Organic Waste Rates and Nutrient Inputs. Revista Brasileira de Ciencia Do Solo, 40.

Cassman, K. G., Bryant, D. C., & Roberts, B. A. (1990). Comparison of soil test methods for predicting cotton response to soil and fertilizer potassium on potassium fixing soils. Communications in Soil Science and Plant Analysis, 21(13–16), 1727–1743.

Cayuela, M. L., Bernal, M. P., & Roig, A. (2004). Composting Olive Mill Waste and Sheep Manure For Orchard Use. Compost Science & Utilization, 12(2), 130–136.

Chartzoulakis, K., Psarras, G., Moutsopoulou, M., & Stefanoudaki, E. (2010). Application of olive mill wastewater to a Cretan olive orchard: Effects on soil properties, plant performance and the environment. Agriculture, Ecosystems & Environment, 138(3), 293–298.

Chen, C., Khir, R., Shen, Y., Wu, X., Zhang, R., Cao, X., Niederholzer, F., & Pan, Z. (2021). Energy consumption and product quality of off-ground harvested almonds under hot air column drying. LWT - Food Science and Technology, 138, 110768.

Cobo, J. G., Barrios, E., Kass, D. C. L., & Thomas, R. J. (2002). Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. Plant and Soil, 240(2), 331–342.

Cox, J., Van Zwieten, L., Ayres, M., & Morris, S. (2004). Macadamia husk compost improves soil health in sub-tropical horticulture. SuperSoil 2004: 3rd Australian New Zealand Soils Conference, University of Sydney, Australia.

Daly, A. B., Jilling, A., Bowles, T. M., Buchkowski, R. W., Frey, S. D., Kallenbach, C. M., Keiluweit, M., Mooshammer, M., Schimel, J. P., & Grandy, A. S. (2021). A holistic framework integrating plant-microbe-mineral regulation of soil bioavailable nitrogen. Biogeochemistry 154:211-229.

Dhanya, B., Viswanath, S., & Purushothaman, S. (2013). Decomposition and Nutrient Release Dynamics of *Ficus benghalensis* L. Litter in Traditional Agroforestry Systems of Karnataka, Southern India. International Scholarly Research Notices, Forestry, 524679.

Diehl, R. C., Miyazawa, M., & Takahashi, H. W. (2008). Water-soluble organic compounds from plant residues and their effects on soil chemical attributes. Brazilian Journal of Soil Science, 32:2653-2659.

Diepeningen, A. D. van, Vos, O. J. de, Korthals, G. W., & Bruggen, A. H. C. van. (2006). Effects of organic versus conventional management on chemical and biological parameters in agricultural soils. Applied Soil Ecology, 31(1), 120–135.

Dong, S., Ma, Z., Wang, L., Yan, C., Liu, L., Gong, Z., & Cui, G. (2019). Decomposition and nutrient release characteristics of incorporated soybean and maize straw in Northeast China. Ekoloji, 107, 2119–2129.

Doungous, O., Emile, M., Longue, E., & Nkengafac, N. (2018). Potentials of cocoa pod husk-based compost on Phytophthora pod rot disease suppression, soil fertility, and Theobroma cacao L. growth. Environmental Science and Pollution Research, 25.

Drinkwater, L. E., & Snapp, S. S. (2007). Nutrients in Agroecosystems: Rethinking the Management Paradigm. Advances in Agronomy. Academic Press, D. L. Sparks, Ed. 92,163–186.

Elsa, M., Domec, J.-C., Bosc, A., Denoroy, P., Asensio, V., Lavres Junior, J., & Lionel, J.-M. (2016). The effects of potassium nutrition on water use in field-grown maize (*Zea mays* L.). Environmental and Experimental Botany, 134.

Esmaeili, A., Khoram, M. R., Gholami, M., & Eslami, H. (2020). Pistachio waste management using combined composting-vermicomposting technique: Physico-chemical changes and worm growth analysis. Journal of Cleaner Production, 242, 118523.

Farzi, R., Gholami, M., Baninasab, B., & Gheysari, M. (2017). Evaluation of different mulch materials for reducing soil surface evaporation in semi-arid region. Soil Use and Management, 33(1), 120–128.

Fernandez-Bayo, J. D., Shea, E. A., Parr, A. E., Achmon, Y., Stapleton, J. J., VanderGheynst, J. S., Hodson, A. K., & Simmons, C. W. (2020). Almond processing residues as a source of organic acid biopesticides during biosolarization. Waste Management, 101, 74–82.

Fidelis, C., & Rao, R. (2017). Enriched cocoa pod composts and their fertilizing effects on hybrid cocoa seedlings. International Journal of Recycling of Organic Waste in Agriculture, 6.

Forge, T., Neilsen, G., Neilsen, D., O'Gorman, D., Hogue, E., & Angers, D. (2015). Organic orchard soil management practices affect soil biology and organic matter. Acta Horticulturae, 1076, 77–84.

Franchini, J. C., Hoffmann-Campo, C. B., Torres, E., Miyazawa, M., & Pavan, M. A. (2003). Organic Composition of Green Manure During Growth and Its Effect on Cation Mobilization in an Acid Oxisol. Communications in Soil Science and Plant Analysis, 34(13–14), 2045–2058.

Galanti, R., Cho, A., Ahmad, A., & Radovich, T. (2019). Soil Amendments and Soil Profiling Impact on Macadamia Growth and Yield Performance. HortScience Horts, 54(3), 519–527.

Gámez-Virués, S., Perović, D. J., Gossner, M. M., Börschig, C., Blüthgen, N., de Jong, H., Simons, N. K., Klein, A.-M., Krauss, J., Maier, G., Scherber, C., Steckel, J., Rothenwöhrer, C., Steffan-Dewenter, I., Weiner, C. N., Weisser, W., Werner, M., Tscharntke, T., & Westphal, C. (2015). Landscape simplification filters species traits and drives biotic homogenization. Nature Communications, 6(1), 8568.

Glover, J. D., Reganold, J. P., & Andrews, P. K. (2000). Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington State. Agriculture, Ecosystems & Environment, 80(1), 29–45.

Granatstein, D., Andrews, P., & Groff, A. (2014). Productivity, economics, and fruit and soil quality of weed management systems in commercial organic orchards in Washington State, USA. Organic Agriculture, 4(3), 197–207.

Granatstein, D., & Mullinix, K. (2008). Mulching Options for Northwest Organic and Conventional Orchards. HortScience: A Publication of the American Society for Horticultural Science, 43.

Gross, C. D., & Harrison, R. B. (2019). The Case for Digging Deeper: Soil Organic Carbon Storage, Dynamics, and Controls in Our Changing World. Soil Systems, 3(2).

Grzebisz, W., Gransee, A., Szczepaniak, W., & Diatta, J. (2013). The effects of potassium fertilization on water-use efficiency in crop plants. Journal of Plant Nutrition and Soil Science, 176.

Guerrero, C. C., Brito, J. C. de, Lapa, N., & Oliveira, J. F. S. (1995). Re-use of industrial orange wastes as organic fertilizers. Bioresource Technology, 53(1), 43–51.

Gupta, A. S., Berkowitz, G., & Pier, P. (1989). Maintenance of photosynthesis at low leaf water potential in wheat: Role of potassium status and irrigation history. Plant Physiology, 89(4), 1358–1365.

Hannam, K. D., Neilsen, G. H., Forge, T. A., Neilsen, D., Losso, I., Jones, M. D., Nichol, C., & Fentabil, M. M. (2016). Irrigation practices, nutrient applications, and mulches affect soil nutrient dynamics in a young Merlot (*Vitis vinifera* L.) vineyard. Canadian Journal of Soil Science, 96(1), 23–36.

Haro, R., & Benito, B. (2019). The Role of Soil Fungi in K+ Plant Nutrition. International Journal of Molecular Sciences, 20, 3169.

Hartemink, A. E. (2005). Nutrient Stocks, Nutrient Cycling, and Soil Changes in Cocoa Ecosystems: A Review. Academic Press, 86, 227-253.

Harter, T., & Lund, J. R. (2012). Addressing Nitrate in California's Drinking Water: Executive Summary. Groundwater Nitrate Project, Implementation of Senate Bill X2 1.

Hartmann, M., Frey, B., Mayer, J., Mäder, P., & Widmer, F. (2015). Distinct soil microbial diversity under long-term organic and conventional farming. The ISME Journal, 9(5), 1177–1194.

Hasanuzzaman, M., Bhuyan, M. H. M. B., Nahar, K., Hossain, Md. S., Mahmud, J. A., Hossen, Md. S., Masud, A. A. C., Moumita, & Fujita, M. (2018). Potassium: A Vital Regulator of Plant Responses and Tolerance to Abiotic Stresses. Agronomy, 8(3).

Havlin, J. L., Tisdale, S. L., Nelson, W. L., & Beaton, J. D. (2016). Soil Fertility and Fertilizers (Eighth Edition). Pearson.

Hawkesford, M., Horst, W., Kichey, T., Lambers, H., Schjoerring, J., Møller, I. S., & White, P. (2012). Chapter 6—Functions of Macronutrients. In P. Marschner (Ed.), Marschner's Mineral Nutrition of Higher Plants, Third Edition. Academic Press, 135-189.

Hernández-Montoya, V., Mendoza-Castillo, D. I., Bonilla-Petriciolet, A., Montes-Morán, M. A., & Pérez-Cruz, M. A. (2011). Role of the pericarp of Carya illinoinensis as biosorbent and as precursor of activated carbon for the removal of lead and acid blue 25 in aqueous solutions. Journal of Analytical and Applied Pyrolysis, 92(1), 143–151.

Hoagland, L., Carpenter-Boggs, L., Granatstein, D., Mazzola, M., Smith, J., Peryea, F., & Reganold, J. P. (2008). Orchard floor management effects on nitrogen fertility and soil biological activity in a newly established organic apple orchard. Biology and Fertility of Soils, 45(1), 11.

Holtz, B. A., Doll, D., & Browne, G. (2015). Whole almond orchard recycling and the effect on second generation tree growth, soil carbon, and fertility. Acta Hortic., 1112, 315–320.

Hougni, D.-G. J. M., Schut, A. G. T., Woittiez, L. S., Vanlauwe, B., & Giller, K. E. (2021). How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching. Plant and Soil, 463, 155-170.

Idowu, O. J., Sanogo, S., & Brewer, C. E. (2017). Short-Term Impacts of Pecan Waste By-Products on Soil Quality in Texturally Different Arid Soils. Communications in Soil Science and Plant Analysis, 48(15), 1781–1791.

Iqbal, M., ul-Hassan, A., & Es, H. M. van. (2011). Influence of Residue Management and Tillage Systems on Carbon Sequestration and Nitrogen, Phosphorus, and Potassium Dynamics of Soil and Plant and Wheat Production in Semi-arid Region. Communications in Soil Science and Plant Analysis, 42(5), 528–547.

Iremiren, G. O., & Ipinmoroti, R. R. (2014). Effect of organic fertilizer (cocoa pod husk) on okra and maize production under okra/maize intercrop in Uhonmora, Edo State, Nigeria. African Journal of Agricultural Research, 9(52), 3789–3796.

Jafari, M., Haghighi, J. A. P., & Zare, H. (2012). Mulching impact on plant growth and production of rainfed fig orchards under drought conditions. Journal of Food Agriculture and Environment, 10(1), 428-433.

Jahanzad, E., Holtz, B. A., Zuber, C. A., Doll, D., Brewer, K. M., Hogan, S., & Gaudin, A. C. M. (2020). Orchard recycling improves climate change adaptation and mitigation potential of almond production systems. PLOS ONE, 15(3), 1–22.

Jahanzad, E., Brewer, K.M., Poret-Peterson, A.T., Culumber, C.M., Holtz, B.A., Gaudin, A.C.M. (2022). Effects of whole-orchard recycling on nitrate leaching potential in almond production systems. Journal of Environmental Quality, 51:941-951.

Jansson, J. K., & Hofmockel, K. S. (2020). Soil microbiomes and climate change. Nature Reviews Microbiology, 18(1), 35–46.

Janzen, H. H. (2006). The soil carbon dilemma: Shall we hoard it or use it? Soil Biology and Biochemistry, 38(3), 419–424.

Jiang, N., Hu, B., Wang, X., Meng, Y., Chen, B., & Zhou, Z. (2019). Effects of crop residue incorporation and inorganic potassium fertilization on soil potassium supply power. Archives of Agronomy and Soil Science, 65(9), 1223–1236.

Kallenbach, C. M., Wallenstein, M. D., Schipanksi, M. E., & Grandy, A. S. (2019). Managing Agroecosystems for Soil Microbial Carbon Use Efficiency: Ecological Unknowns, Potential Outcomes, and a Path Forward. Frontiers in Microbiology, 10, 1146.

Karagoktas, M., Uygur, V., Aydoğdu, M., & Rastgeldi, I. (2014). The effects of pistachio nut hull compost on soil fertility: A comparative study with manure. 9th International Soil Science Congress, Soil Science Society of Turkey, Federation of Eurasian Soil Science Societies.

Karimi, H. R., Sajjadinia, A., Baghari, V., & Farahmand, H. (2013). Preliminary evaluation of composted pistachio hull and rice husk as potting medium on Scindapsus aureus vegetative and physiological characteristics in greenhouse condition. Journal of Plant Nutrition, 36(14), 2225–2235.

Karlberg, N. J., Scott, N. A., & Giardina, C. P. (2008). Chapter 8 Methods for estimating litter decomposition. In Hoover, Coeli M., ed. Field measurements for forest carbon monitoring: A landscape-scale approach. New York, NY: Springer Science + Business Media: 103-111.

Kasongo, R. K., Verdoodt, A., Kanyankagote, P., Baert, G., & Ranst, E. V. (2011). Coffee waste as an alternative fertilizer with soil improving properties for sandy soils in humid tropical environments. Soil Use and Management, 27(1), 94–102.

Kaushal, R., Verma, K., Chaturvedi, O. P., & Alam, N. M. (2012). Leaf litter decomposition and nutrient dynamics in four multipurpose tree species. Range Management and Agroforestry, 33, 20–27.

Khalsa, S. D. S., Almanza, C. A., Brown, P. H., & Smart, D. R. (2016). Leaf litter C and N cycling from a deciduous permanent crop. Soil Science and Plant Nutrition, 62(3), 271–276.

Khalsa, S. D. S., & Brown, P. H. (2017). Grower analysis of organic matter amendments in California orchards. Journal of Environmental Quality, 46(3), 649-658.

Khalsa, S. D. S., Hart, S. C., & Brown, P. H. (2021). Nutrient dynamics of surface-applied organic matter amendments on no-till orchard soil. Soil Use and Management, 38(1), 649-662.

Khalsa, S. D. S., Smart, D. R., Muhammad, S., Armstrong, C. M., Sanden, B. L., Houlton, B. Z., & Brown, P. H. (2020). Intensive fertilizer use increases orchard N cycling and lowers net global warming potential. Science of The Total Environment, 722, 137889.

Klingel, T., Kremer, J. I., Gottstein, V., Rajcic de Rezende, T., Schwarz, S., & Lachenmeier, D. W. (2020). A review of coffee by-products including leaf, flower, cherry, husk, silver skin, and spent grounds as novel foods within the European Union. Foods, 9(5).

Koné, K., Akueson, K., & Norval, G. (2020). On the Production of Potassium Carbonate from Cocoa Pod Husks. Recycling, 23.

Krishna, M. P., & Mohan, M. (2017). Litter decomposition in forest ecosystems: A review. Energy, Ecology and Environment, 2(4), 236–249.

Kuzin, A. I., Kashirskaya, N. Ya., Kochkina, A. M., & Kushner, A. V. (2020). Correction of Potassium Fertigation Rate of Apple Tree (*Malus domestica* Borkh.) in Central Russia during the Growing Season. Plants, 9(10).

Laird, D. A., & Chang, C.-W. (2013). Long-term impacts of residue harvesting on soil quality. Soil and Tillage Research, 134, 33–40.

Lal, R. (2008). Soils and sustainable agriculture. A review. Agronomy for Sustainable Development, 28(1), 57–64.

Lal, R. (2020). Soil organic matter content and crop yield. Journal of Soil and Water Conservation, 75(2), 27A-32A.

Le, Q. V., Jovanovic, G., Le, D.-T., & Cowal, S. (2020). Understanding the Perceptions of Sustainable Coffee Production: A Case Study of the K'Ho Ethnic Minority in a Small Village in Lâm Đồng Province of Vietnam. Sustainability, 12(3).

Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. Nature, 528(7580), 60–68.

Li, J., Lu, J., Li, X., Ren, T., Cong, R., & Zhou, L. (2014). Dynamics of Potassium Release and Adsorption on Rice Straw Residue. PLOS ONE, 9(2), 1–9.

Lobel, M. R., Firth, D. J., & Johns, G. G. (1994). Effect of mulch, Ca, and Mg on growth, yield, and decline of macadamia. Tropical Agriculture, 71(3), 170–175.

López, R., Burgos, P., Hermoso, J. M., Hormaza, J. I., & González-Fernández, J. J. (2014). Long term changes in soil properties and enzyme activities after almond shell mulching in avocado organic production. Soil and Tillage Research, 143, 155–163.

Lu, F., Rodriguez-Garcia, J., Damme, I. V., Westwood, N. J., Shaw, L., Robinson, J. S., Warren, G., Chatzifragkou, A., Mason, S. M., Gomez, L., Faas, L., Balcombe, K., Srinivasan, C., Picchioni, F., Hadley, P., & Charalampopoulos, D. (2018). Valorisation strategies for cocoa pod husk and its fractions. Current Opinion in Green and Sustainable Chemistry, 14, 80–88.

Lu, X. (2020). A meta-analysis of the effects of crop residue return on crop yields and water use efficiency. PLOS ONE, 15, e0231740.

Lubell, M., Niles, M., & Hoffman, M. (2014). Extension 3.0: Managing Agricultural Knowledge Systems in the Network Age. Society & Natural Resources, 27(10), 1089–1103.

Ma, B. L., & Rivero, M. C. (2010). Fertilization and crop residue management in no-till corn production. No-Till Farming: Effects on Soil, Chapter 4, 75–91.

Madar, R., Singh, Y. V., Meena, M. C., Das, T. K., Paramesh, V., Al-Mana, F. A., A. Mattar, M., & O. Elansary, H. (2020). Residue and Potassium Management Strategies to Improve Crop Productivity, Potassium Mobilization, and Assimilation under Zero-Till Maize–Wheat Cropping System. Agriculture, 10(9).

Manzoni, S., Jackson, R., Trofymow, J., & Porporato, A. (2008). The Global Stoichiometry of Litter Nitrogen Mineralization. Science (New York, N.Y.), 321, 684–686.

Meena, V. S., Maurya, B. R., & Verma, J. P. (2014). Does a rhizospheric microorganism enhance K+ availability in agricultural soils? Microbiological Research, 169(5), 337–347.

Meli, S. M., Baglieri, A., Porto, M., Belligno, A., & Gennari, M. (2007). Chemical and Microbiological Aspects of Soil Amended with Citrus Pulp. Journal of Sustainable Agriculture, 30(4), 53–66.

Miyazawa, M., Pavan, M. A., & Franchini, J. C. (2002). Evaluation of plant residues on the mobility of surface applied lime. Brazilian Archives of Biology and Technology, 45(3), 251–256.

Molina-Murguía, J. F. F., García-Calderón, N. E., & Martín, G. A. (2009). Cocoa Industrial Debris Composting in Soil and Earthworm Breeding. Compost Science & Utilization, 17(3), 197–204.

Montanaro, G., Xiloyannis, C., Nuzzo, V., & Dichio, B. (2017). Orchard management, soil organic carbon and ecosystem services in Mediterranean fruit tree crops. Scientia Horticulturae, 217, 92–101.

Moore, K. J., Anex, R. P., Elobeid, A. E., Fei, S., Flora, C. B., Goggi, A. S., Jacobs, K. L., Jha, P., Kaleita, A. L., Karlen, D. L., Laird, D. A., Lenssen, A. W., Lübberstedt, T., McDaniel, M. D., Raman, D. R., & Weyers, S. L. (2019). Regenerating Agricultural Landscapes with Perennial Groundcover for Intensive Crop Production. Agronomy, 9(8).

Moreno-Ramón, H., Quizembe, S., & Ibáñez-Asensio, S. (2014). Coffee husk mulch on soil erosion and runoff: Experiences under rainfall simulation experiment. Solid Earth Discussions, 6.

Morison, J. I. L., Baker, N. R., Mullineaux, P. M., & Davies, W. J. (2008). Improving water use in crop production. Philosophical Transactions of the Royal Society of London, Series B, 363, 639–658.

Moyin-Jesu, E. I. (2007). Use of plant residues for improving soil fertility, pod nutrients, root growth and pod weight of okra (Abelmoschus esculentum L). Bioresource Technology, 98(11), 2057–2064.

Mubarak, A. R., Elbashir, A. A., Elamin, L. A., Daldoum, D. M. A., Steffens, D., & Benckiser, G. (2008). Decomposition and Nutrient Release from Litter Fall in the Semi-arid

Tropics of Sudan. Communications in Soil Science and Plant Analysis, 39(15–16), 2359–2377.

Muhammad, S., Sanden, B. L., Lampinen, B. D., Smart, D. R., Saa, S., Shackel, K. A., & Brown, P. H. (2020). Nutrient Storage in the Perennial Organs of Deciduous Trees and Remobilization in Spring – A Study in Almond (*Prunus dulcis*) (Mill.) D. A. Webb. Frontiers in Plant Science, 11, 658.

Muhammad, S., Sanden, B. L., Saa, S., Lampinen, B. D., Smart, D. R., Shackel, K. A., DeJong, T. M., & Brown, P. H. (2018). Optimization of nitrogen and potassium nutrition to improve yield and yield parameters of irrigated almond (*Prunus dulcis* (Mill.) D. A. webb). Scientia Horticulturae, 228, 204–212.

Muhammad, S., Sanden, B., Lampinen, B., Saa, S., Siddiqui, M., Smart, D., Olivos-Del Rio, A., Shackel, K., Dejong, T., & Brown, P. (2015). Seasonal changes in nutrient content and concentrations in a mature deciduous tree species: Studies in almond (*Prunus dulcis* (Mill.) D. A. Webb). European Journal of Agronomy, 65.

Munongo, M. E., Nkeng, G. E., & Njukeng, J. N. (2017). Production and characterization of compost manure and biochar from cocoa pod husks. International Journal of Advanced Scientific Research and Management, 2(2), 26–31.

Murashkina, M. A., Southard, R. J., & Pettygrove, G. S. (2007). Silt and fine sand fractions dominate K fixation in soils derived from granitic alluvium of the San Joaquin Valley, California. Geoderma, 141(3), 283–293.

Nagao, M. A., Hirae, H. H., & Stephenson, R. A. (1992). Macadamia: Cultivation and physiology. Critical Reviews in Plant Sciences, *10*(5), 441–470.

Nasini, L., Gigliotti, G., Balduccini, M. A., Federici, E., Cenci, G., & Proietti, P. (2013). Effect of solid olive-mill waste amendment on soil fertility and olive (*Olea europaea* L.) tree activity. Agriculture, Ecosystems & Environment, 164, 292–297.

Nduka, B., Adewale, D., Akanbi, O., & Adejobi, K. (2015). Nursery Soil Amendments for Cashew Seedling Production: A Comparative Analysis of Coffee Husk and NPK. Journal of Agricultural Science, 7.

Neilsen, G., Forge, T., Angers, D., Neilsen, D., & Hogue, E. (2014). Suitable orchard floor management strategies in organic apple orchards that augment soil organic matter and maintain tree performance. Plant and Soil, 378(1), 325–335.

Neilsen, G. H., Hogue, E. J., Forge, T., & Neilsen, D. (2003a). Surface application of mulches and biosolids affect orchard soil properties after 7 years. Canadian Journal of Soil Science, 83(1), 131–137.

Neilsen, G. H., Hogue, E. J., Forge, T., & Neilsen, D. (2003b). Mulches and Biosolids Affect Vigor, Yield and Leaf Nutrition of Fertigated High Density Apple. HortScience HortSci, 38(1), 41–45.

Nogueira, W. A., Nogueira, F. N., & Devens, D. C. (1999). Temperature and pH control in composting of coffee and agricultural wastes. Water Science and Technology, 40(1), 113–119.

Öborn, I., Andrist-Rangel, Y., Askekaard, M., Grant, C. A., Watson, C. A., & Edwards, A. C. (2005). Critical aspects of potassium management in agricultural systems. Soil Use and Management, 21(1), 102–112.

Olk, D., & Cassman, K. (1995). Reduction of Potassium Fixation by Two Humic Acid Fractions in Vermiculitic Soils. Soil Science Society of America Journal - SSSAJ, 59.

Oyewole, O., Omueti, J., & Rotimi, R. (2012). Growth of cocoa *(Theobroma cacao* L.*)* seedlings on old cocoa soils amended with organic and inorganic fertilizers. 3604–3608.

Özenç, D. B., & Özenç, N. (2008). Short-Term Effects of Hazelnut Husk Compost And Organic Amendment Applications On Clay Loam Soil. Compost Science & Utilization, 16(3), 192–199.

Panak Balentić, J., Ačkar, Đ., Jokić, S., Jozinović, A., Babić, J., Miličević, B., Šubarić, D., & Pavlović, N. (2018). Cocoa Shell: A By-Product with Great Potential for Wide Application. Molecules, 23(6).

Pettygrove, S., O'Geen, T., & Southard, R. (2011). Potassium fixation and its significance for California crop production. Better Crops with Plant Food, 95(4), 16–18.

Pham, T. T., Nguyen, N. H., Yen, P. N. D., Lam, T. D., & Le, N. T. T. (2020). Proposed Techniques to Supplement the Loss in Nutrient Cycling for Replanted Coffee Plantations in Vietnam. Agronomy, 10(6).

Prescott, C. E., & Vesterdal, L. (2021). Decomposition and transformations along the continuum from litter to soil organic matter in forest soils. Forest Ecology and Management, 498, 119522.

Prgomet, I., Gonçalves, B., Domínguez-Perles, R., Pascual-Seva, N., & Barros, A. I. R. N. A. (2017). Valorization Challenges to Almond Residues: Phytochemical Composition and Functional Application. Molecules, 22(10).

Qin, W., Hu, C., & Oenema, O. (2015). Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: A meta-analysis. Scientific Reports, 5(1), 16210.

Rafique, E., Mahmood-ul-Hassan, M., Rashid, A., & Chaudhary, M. F. (2012). Nutrient balances as affected by integrated nutrient and crop residue management in cooton-wheat system in Aridisols. III. Potassium. Journal of Plant Nutrition, 35(4), 591–616.

Rahman, Z. A. (1999). Patterns of decomposition and nutrient release by fresh Gliricidia (Gliricidia sepium) leaves in an ultisol. Nutrient Cycling in Agroecosystems, 55, 269–277.

Rao, R. (2017). Enriched cocoa pod composts and their fertilizing effects on hybrid cocoa seedlings. International Journal of Recycling of Organic Waste in Agriculture, 6.

Rashid, M. I., Mujawar, L. H., Shahzad, T., Almeelbi, T., Ismail, I. M. I., & Oves, M. (2016). Bacteria and fungi can contribute to nutrients bioavailability and aggregate formation in degraded soils. Microbiological Research, 183, 26–41.

Regni, L., Nasini, L., Ilarioni, L., Brunori, A., Massaccesi, L., Agnelli, A., & Proietti, P. (2017). Long Term Amendment with Fresh and Composted Solid Olive Mill Waste on Olive Grove Affects Carbon Sequestration by Prunings, Fruits, and Soil. Frontiers in Plant Science, 7, 2042.

Rodríguez-Lizana, A., Carbonell, R., González, P., & Ordóñez-Fernández, R. (2010). N, P and K released by the field decomposition of residues of a pea-wheat-sunflower rotation. Nutrient Cycling in Agroecosystems, 87, 199–208.

Rosolem, C. A., Calonego, J. C., & Foloni, J. S. S. (2005). Potassium Leaching from Millet Straw as Affected by Rainfall and Potassium Rates. Communications in Soil Science and Plant Analysis, 36(7–8), 1063–1074.

Samuel, A., & Agbona, A. (2008). Effects of Cocoa Pod Husk Amendment on Soil and Leaf Chemical Composition and Growth of Cashew (Anacardium occidentale L.) Seedlings in the Nursery. Am.-Eurasian J. Sustain. Agric, 2, 219–224.

Sanchez, J., Edson, C., Bird, G., Whalon, M., Willson, T. C., Harwood, R., Kizilkaya, K., Nugent, J., Klein, W., Middleton, A., Loudon, T., Mutch, D., & Scrimger, J. (2003). Orchard Floor and Nitrogen Management Influences Soil and Water Quality and Tart Cherry Yields. J. Amer. Soc. Hort. Sci., 128, 277–284277.

Sardans, J., & Peñuelas, J. (2015). Potassium: A neglected nutrient in global change. Global Ecology and Biogeography, 24(3), 261–275.

Sathianarayanan, A., & Khan, A. (2008). An Eco-Biological Approach for Resource Recycling and Pathogen (*Rhizoctoniae Solani* Kuhn.) Suppression. Journal of Environmental Protection Science, 2, 36-39.

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D. A. C., Nannipieri, P., Rasse, D. P., Weiner, S., & Trumbore, S. E. (2011). Persistence of soil organic matter as an ecosystem property. Nature, 478(7367), 49–56.

Shao, Y., Xie, Y., Wang, C., Yue, J., Yao, Y., Li, X., Liu, W., Zhu, Y., & Guo, T. (2016). Effects of different soil conservation tillage approaches on soil nutrients, water use and wheat-maize yield in rainfed dry-land regions of North China. European Journal of Agronomy, 81, 37–45.

Shemekite, F., Gómez-Brandón, M., Franke-Whittle, I., Praehauser, B., Insam, H., & Assefa, F. (2013). Coffee husk composting: An investigation of the process using molecular and non-molecular tools. Waste Management (New York, N.Y.), 34.

Singh, K., Sanderson, T., Field, D., Fidelis, C., & Yinil, D. (2019). Soil security for developing and sustaining cocoa production in Papua New Guinea. Geoderma Regional, 17, e00212.

Singh, V. K., Dwivedi, B. S., Yadvinder-Singh, Singh, S. K., Mishra, R. P., Shukla, A. K., Rathore, S. S., Shekhawat, K., Majumdar, K., & Jat, M. L. (2018). Effect of tillage and crop establishment, residue management and K fertilization on yield, K use efficiency and apparent K balance under rice-maize system in north-western India. Field Crops Research, 224, 1–12.

Sui, N., Zhou, Z., Yu, C., Liu, R., Yang, C., Zhang, F., Song, G., & Meng, Y. (2015). Yield and potassium use efficiency of cotton with wheat straw incorporation and potassium fertilization on soils with various conditions in the wheat–cotton rotation system. Field Crops Research, 172, 132–144.

Tagliavini, M., Tonon, G., Scandellari, F., Quiñones, A., Palmieri, S., Menarbin, G., Gioacchini, P., & Masia, A. (2007). Nutrient recycling during the decomposition of apple leaves (Malus domestica) and mowed grasses in an orchard. Agriculture, Ecosystems & Environment, 118(1), 191–200.

Tahboub, M. B., Lindemann, W. C., & Murray, L. (2007). Nutrient Availability in Soil Amended with Pecan Wood Chips. HortScience HORTS, 42(2), 339–343.

Tahboub, M. B., Lindemann, W. C., & Murray, L. (2008). Chemical and Physical Properties of Soil Amended with Pecan Wood Chips. HortScience, 43(3), 891–896.

TerAvest, D., Smith, J. L., Carpenter-Boggs, L., Granatstein, D., Hoagland, L., & Reganold, J. P. (2011). Soil Carbon Pools, Nitrogen Supply, and Tree Performance under Several Groundcovers and Compost Rates in a Newly Planted Apple Orchard. HortScience, 46(12), 1687–1694.

Thiyageshwari, S., Gayathri, P., Krishnamoorthy, R., Anandham, R., & Paul, D. (2018). Exploration of Rice Husk Compost as an Alternate Organic Manure to Enhance the Productivity of Blackgram in Typic Haplustalf and Typic Rhodustalf. International Journal of Environmental Research and Public Health, 15(2).

Thomas, C. L., Acquah, G. E., Whitmore, A. P., McGrath, S. P., & Haefele, S. M. (2019). The Effect of Different Organic Fertilizers on Yield and Soil and Crop Nutrient Concentrations. Agronomy, 9(12).

Tripler, C. E., Kaushal, S. S., Likens, G. E., & Todd Walter, M. (2006). Patterns in potassium dynamics in forest ecosystems. Ecology Letters, 9(4), 451–466.

Urra, J., Mijangos, I., Lanzén, A., Lloveras, J., & Garbisu, C. (2018). Effects of corn stover management on soil quality. European Journal of Soil Biology, 88, 57–64.

Valenzuela-Solano, C., Crohn, D. M., & Downer, J. A. (2005). Nitrogen mineralization from eucalyptus yardwaste mulch applied to young avocado trees. Biology and Fertility of Soils, 41(1), 38–45.

van der Heijden, M. G. A., & Wagg, C. (2013). Soil microbial diversity and agro-ecosystem functioning. Plant and Soil, 363(1), 1–5.

Van Der Vossen, H. A. M. (2005). A critical analysis of the agronomic and economic sustainability of organic coffee production. Expl. Agric., 41, 449–473.

Vida, C., Bonilla, N., de Vicente, A., & Cazorla, F. M. (2016). Microbial profiling of a suppressiveness-induced agricultural soil amended with composted almond shells. Frontiers in Microbiology, 7, 4.

Wall, D. H., Nielsen, U. N., & Six, J. (2015). Soil biodiversity and human health. Nature, 528(7580), 69–76.

Walton, M., Hall, J., Guest, D., Butubu, J., Vinning, G., Black, K., & Beardsley, J. (2020). Applying one health methods to improve cocoa production in Bougainville: A case study. One Health, 10, 100143.

Wang, M., Zheng, Q., Shen, Q., & Guo, S. (2013). The Critical Role of Potassium in Plant Stress Response. International Journal of Molecular Sciences, 14(4), 7370–7390.

Wartelle, L. H., & Marshall, W. E. (2001). Nutshells as granular activated carbons: Physical, chemical and adsorptive properties. Journal of Chemical Technology & Biotechnology, 76(5), 451–455.

Winter, E., Marton, S. M. R. R., Baumgart, L., Curran, M., Stolze, M., & Schader, C. (2020). Evaluating the Sustainability Performance of Typical Conventional and Certified Coffee Production Systems in Brazil and Ethiopia Based on Expert Judgements. Frontiers in Sustainable Food Systems, 4, 49.

Wood, S. A., Karp, D. S., DeClerck, F., Kremen, C., Naeem, S., & Palm, C. A. (2015). Functional traits in agriculture: Agrobiodiversity and ecosystem services. Trends in Ecology & Evolution, 30(9), 531–539.

Wu, J., Guo, X. S., Wang, Y. Q., Xu, Z. Y., & Lu, J. W. (2011). Decomposition characteristics of rapeseed and wheat straw under different water regimes and straw incorporating models. Journal of Food, Agriculture and Environment, 9(2), 572–577.

Yadav, S. K., Benbi, D. K., & Toor, A. S. (2019). Effect of long-term application of rice straw, farmyard manure and inorganic fertilizer on potassium dynamics in soil. Archives of Agronomy and Soil Science, 65(3), 374–384.

Yan, S., Song, J., Fan, J., Yan, C., Dong, S., Ma, C., & Gong, Z. (2020). Changes in soil organic carbon fractions and microbial community under rice straw return in Northeast China. Global Ecology and Conservation, 22, e00962.

Zeng, Q., Brown, P. H., & Holtz, B. A. (2001). Potassium Fertilization Affects Soil K, Leaf K Concentration, and Nut Yield and Quality of Mature Pistachio Trees. HortScience HortSci, 36(1), 85–89.

Zimmermann, S., Braun, S., Conedera, M., & Blaser, P. (2002). Macronutrient inputs by litterfall as opposed to atmospheric deposition into two contrasting chestnut forest stands in southern Switzerland. Forest Ecology and Management, 161, 289–302.

Zipori, I., Erel, R., Yermiyahu, U., Ben-Gal, A., & Dag, A. (2020). Sustainable Management of Olive Orchard Nutrition: A Review. Agriculture, 10(1).

Zoca, S. M., Penn, C. J., Rosolem, C. A., Alves, A. R., Neto, L. O., & Martins, M. M. (2014). Coffee processing residues as a soil potassium amendment. International Journal of Recycling of Organic Waste in Agriculture, 3(4), 155–165.

### 1.13 Organization and Integration of Chapters 2, 3, and 4

The following chapters contain findings from three field trials using almond hulls and shells as organic matter amendments. Each site had different soil types, varieties, water and fertilizer management approaches, crop system goals, and motivations for applying hulls and shells as amendments. Amendment application rates ranged from 2.3-8.6 fresh metric tons (2.5-9.5 US tons $ac^{-1}$). Due to these differences, each field trial was initially approached as a case study with distinct research questions focused on addressing grower priorities and existing research gaps. Within each site, water and fertilizer application was consistent across all treatments—each grower retained their best management practices throughout each experimental site. The following chapters are organized by topic area rather than field site: soil fertility with a focus on potassium in Chapter 2, soil-water dynamics in Chapter 3, and soil health in Chapter 4. The structure of each chapter is as follows: contextual background, research questions, hypotheses, site description, experimental design, methods and analyses, results, discussion, conclusion, supplementary materials, and literature cited. The conclusion section summarizes and integrates key findings related to the benefits of almond hull/shell amendments related to nutrients, water, and soil health.

# Chapter 2: Almond hull and shell organic matter amendments increase available soil potassium and tree potassium status in California almond orchards

## 2.1 Background

Applying nutrient-rich crop residues as soil organic matter amendments can be an efficient strategy for recycling crop co-products which otherwise may pose agricultural waste management challenges (Andrews et al. 2021). Each year in California, almond hulls and shells comprise approximately 70% of crop weight leaving the orchard at harvest (Almond Almanac, 2020). Utilizing these materials as amendments at orchards near processing facilities can be a cost-effective and convenient strategy for relocating crop residues to a sustainable destination. High potassium (K) concentrations set hulls and shells apart from other types of organic matter amendments. Rather than exporting the K contained in almond hulls and shells out of the orchard, applying hulls and shells as amendments presents an opportunity to reuse K within the crop system. As an essential plant macronutrient, sufficient K supply is a critical component of optimum tree crop performance and productivity.

Potassium is highly mobile throughout plant cells and releases rapidly out of crop residues under water application into soil solution (Brito et al. 2014, Dong et al. 2019, Hougni et al. 2021, Lizana et al. 2010). While residue K release tends to occur quickly, K moves slowly through most soils, primarily by diffusion. Several studies indicate K-rich crop residue retention can enhance crop system K cycling by increasing both soil exchangeable potassium (XK) in the top 0-15 cm of soil and plant K status over time. For instance, soil XK was shown to increase under cacao husk amendments (Doungous et al., 2018; Samuel & Agbona 2008), coffee husks (Carmo et al. 2016), pecan husk mulch (Idowu et al. 2017), and macadamia nutshells (Bittenbender et al. 1998; Lobel et al. 1994). Foliar K levels have been shown to increase under macadamia husk mulch (Lobel et al. 1994; Nagao et al. 1992) and cacao pod husk amendments (Samuel & Agbona, 2008). While many studies demonstrated increased soil XK levels under K-rich crop residues used as soil amendments, fewer studies report changes in leaf K status. Less frequent observations of improved tree leaf K under high-K amendments may be partially attributed to a "dilution effect," where other effects such as plant growth and increased leaf biomass can lead to minimal relative increases in leaf K concentration (Zeng et al. 2001). Multi-year field trials with annual applications are necessary to evaluate potential improvements in K cycling and tree K status over time.

Repeated applications of tree crop residues can improve soil fertility by gradually increasing soil organic matter (SOM) over time, building nutrient reserves, and moderating soil pH. Increased SOM can provide new exchange sites and increase nutrient availability. However, site-specific factors likely impact potential improvements, for instance increases in Cation Exchange Capacity (CEC) are likely influenced by soil type (Carmo et al. 2016). Considering soil pH, some studies show tree crop residues such as cacao husks and coffee pulp and husks can improve acidic pH toward neutral (Kasongo et al. 2010, Doungous et al. 2018, Moyin-Jesu et al. 2007), while other studies show residues such as almond shells and pistachio hull compost can improve alkaline pH toward neutral (Lopez et al. 2014, Karagoktas et al. 2014). In both cases, moderating soil pH toward neutral promotes nutrient availability. In addition, the residue amendments on the soil surface can provide new sites for cation retention, adsorbing and re-releasing K later in the season (Li et al. 2014). Nutshells contain compounds that favor cation adsorption, such as high lignin content and phenolic and carboxylic functional groups (Panak Balentic et al. 2018, Hernandez-Montoya et al. 2011, Fernandez-Bayo et al. 2020). The decomposition process releases organic acids that adsorb cations as well (Singh et al. 2018, Brito et al. 2014, Miyazawa et al. 2002). The potential effects of tree crop residues on soil pH, CEC, and organic matter likely become more evident after several years of applications, while soil cations and the organic layer on the soil surface may show more dynamic nutrient fluctuations in the shorter term.

Recycling crop residues as amendments could help close yield gaps particularly in low nutrient input systems in arid climates (Andrews et al. 2021). When prior research trials found increased yields under nutshell amendments, the most cited explanations are increased nutrient uptake and higher soil water content. Potassium-rich mulches can be used to address K fertilization issues in orchards in semi-arid regions and increase tree leaf K concentrations and yields (Neilsen et al. 2002, Neilsen et al. 2003). This practice could help replenish intensively managed soils depleted of K and SOM, and address yield limitations in K-deficient soils. In apple production systems, researchers have noted the tradition of using mulches to address K deficiency (Neilsen et al. 2014). Tree crop residue K could be used to supplement or substitute for fertilizer K, which could be particularly meaningful in regions where K fertilizer is less financially or logistically accessible (Andrews et al. 2021). Providing nutrients from organic residues can be a cost-effective alternative to expensive fertilizers in tree crop systems (Kone et al. 2020, Oyewole et al. 2012).

However, field trials are needed to assess how much K nutshell amendments can provide, when it becomes available, and to what degree this may increase soil available potassium and plant uptake. While prior research consistently demonstrates K releases readily from crop residues under water application, few field trials have been conducted specifically evaluating K cycling in the orchard setting. Whereas prior research indicates that the relatively high carbon:nitrogen (C:N) ratio of nutshell amendments does not initially limit K release, it may prompt microbial biomass to immobilize N which could compete with tree N uptake. Thus, further research is needed to assess effects of hull/shell amendments on tree nutrient status over time in operational commercial orchards. Potential impacts on components of soil fertility such as pH, CEC, and SOM merit evaluation to provide a full picture of the impacts of hull/shell amendments on soil-plant nutrient dynamics and inform grower decision-making.

The objective of this paper is to evaluate the effects of almond and shell amendments on K cycling in three different almond orchard field trials. This paper seeks to highlight similarities and differences between sites regarding amendment K release, soil XK, and tree K over time to contribute to a more integrated framework for orchard K management in nut crop systems. Recycling crop residues as K-rich organic matter amendments is a renewable ecosystem-based K management approach that can enhance crop system K reservoirs and reduce dependence on K fertilizers (Drinkwater and Snapp 2007, Jiang et al. 2019, Kasongo et al. 2011, Sui et al. 2014). In addition to K cycling, this study evaluates the dynamics of other nutrients in the amendment layer, components of soil fertility, and tree nutrient status more broadly to provide an integrated picture of potential effects of this practice on related orchard nutrient dynamics. Findings can be used by researchers, growers, and policy makers to inform sustainable nutrient management practices and tailor amendment application strategies to meet the unique needs of different crop systems.

## 2.2 Research Questions

At all sites, can almond hulls and shells be used as a soil amendment over almond tree roots to supply K for crop uptake? How do amendment layer nutrients and components of soil fertility change over time? At Trial 1, Crown Nut Company, do different hull/shell materials impact soil XK and tree leaf K to different degrees? At Trial 2, Bullseye Farms, how does a fresh hull/shell mix vs. composted hull/shell/manure mix affect soil XK and other exchangeable cations? At Trial 3, Westwind Farms, does eliminating soil surface disturbance in the tree row by switching to off ground harvest equipment increase total K release from hull/shell amendments?

## 2.3 Hypotheses

At all sites, surface-applied hull/shell amendments will solubilize K rapidly and increase soil exchangeable K. Leaf K status will increase more gradually than soil K. Since all sites are commercial orchards with sufficient K fertilizer inputs at the beginning of the established trials, increased plant K status is unlikely to improve yield. High K amendment inputs could displace other soil exchangeable cations, and over time, improve soil pH, CEC, and SOM.

At Trial 1, Crown Nut Company, solubilized K from hull, shell, and hull/shell mix amendments will increase soil XK within the first several months after application. This could improve tree K status within the first three years. At Trial 2, Bullseye Farms, the lower C:N ratio hull/shell mix-based compost will decompose and release nutrients more rapidly than the higher C:N ratio shell/hull mix amendment. Compost contains higher N concentrations and may improve soil and tree N levels, though this depends on how closely compost-N supply timing matches tree N demand. At Trial 3, Westwind Farms, total K release from hull/shell amendments will be maximized by using off ground harvest to maintain the organic layer over time, instead of being swept away by on ground harvest equipment.

## 2.4 Site Descriptions

All grower collaborators were offered the option to remain anonymous but opted to share identities, thus company names are shared with growers' permission. The first field trial is in collaboration with Sandu Brothers Farm and Crown Nut Company (referred to as Crown) located in the Northern San Joaquin Valley, California. Almond hulls, shells, and mixes of hulls/shells are annually stockpiled at a processing facility approximately 1 mile from the Crown Nut Co orchard field trial. This grower/processor owns and operates many orchards surrounding the processing facility. Prior to the trial, growers applied hull and shell materials as amendments along roadsides and in orchard alleys as mulch to reduce dust and enable machinery to access fields after rain. Growers here expressed the need to find accessible waste streams for hulls and shells to move these materials out of the processing facility promptly. When piles of hulls and shells remain in the processing facility for extended periods of time, rainfall can lead to high internal temperatures that promote thermophilic bacteria which can cause fires in the processing area.

Growers expressed interest in recycling K in hull/shell materials back into nearby orchards to keep K in the crop system and reduce the need for K fertilizers while providing a convenient outlet for post-processing materials. This field trial was designed to assess the effects of hulls, shells, and a mix of hulls and shells on orchard K cycling to provide information to help guide grower decision making. At this orchard field site, Independence variety almond trees on Viking rootstock were planted in 2010. Tree spacing was 4.6 x 5.9 meters (15 x 19 ft) and trees were drip irrigated. One buffer row of trees was located between each treatment row. The soil type is Capay clay (NRCS, see Supplementary Table 2.1 for details). Soil samples taken prior to treatment application indicated that average pH was 6.2, average percent SOM was 2.5%, and average CEC was 28 meq $100g^{-1}$soil in the top 0-10 cm soil. Typical fertilizer management practices at this site include the application of 13.5-46 kg $ha^{-1}$ (12-41 lb $ac^{-1}$) K annually, and water data is provided in Supplementary Figure 2.1. Overall yield for this orchard was approximately 1680 kg $ha^{-1}$ (1500 lb $ac^{-1}$) in 2019 prior to trial establishment.

The second and third trials are in the Sacramento Valley, California, and source hull/shell materials from a processor located approximately 15 miles from both field sites. For several years prior to trial establishment, Bullseye Farms produced compost using a mixture of approximately 70% almond hull/shells and 30% dairy manure. The finished compost product contains higher concentrations of most nutrients and a much lower C:N ratio than the fresh hulls/shells alone. Bullseye growers have applied this compost material and fresh hulls and shells as organic matter amendments to many types of crop systems, including almond orchards. Growers at Bullseye were interested in evaluating how these two materials might impact soil nutrients and fertility differently. This field site is located at a 61-hectare (150-acre) orchard near Woodland, California. Nonpareil variety almond trees on Titan rootstock were planted in 2015 with alternating pollinizer varieties. Tree spacing was 5.5 x 7.3 meters (18 x 24 ft) and trees were drip-irrigated. As treatments were only applied to Nonpareil rows, pollinizer rows provided a buffer between treatment rows. The soil type is Sycamore silty clay loam soil (NRCS, see Supplementary Table 2.1). Cumulative annual fertilizer and water applications are provided in Supplementary Table 2.2 and Supplementary Figure 2.2. Soil samples prior to treatment establishment indicated that average pH was 7.6, average percent SOM was 2.5%, and average CEC was 23 meq 100 $g^{-1}$ soil in the top 0-10 cm soil.

The third field trial evaluated a hull/shell mix amendment paired with off ground harvest using catch frame equipment to minimize soil disturbance in the tree row. This trial was located at Westwind Farms, a 62-hectare (152-acre) almond orchard located near Woodland, California. Every other row was Nonpareil variety on Bright Hybrid 5 rootstock with alternating pollinizer row varieties. Trees were spaced at 4.6 x 6.7 meters (15 x 22) ft and were micro-sprinkler irrigated. The soil type is San Ysidro loam (NRCS, see Supplementary Table 2.1). Cumulative annual fertilizer and water applications are provided in Supplementary Table 2.3 and Supplementary Figure 2.3. Prior to treatment establishment, the average soil pH was 7.4, average percent SOM was 2.3%, and average CEC was 20 meq 100 $g^{-1}$ soil in the top 0-10 cm soil. Overall yield for this orchard was approximately 2580 kg $ha^{-1}$ (2300 lb $ac^{-1}$) in 2020. Each fall, the grower applied 4.4 metric tons $ha^{-1}$ (2 US tons $ac^{-1}$) compost across the entire orchard as a best management practice. During this trial, these compost applications occurred uniformly across all treatments on 11/11/2020 (around one month after the first hull/shell amendment application) and 10/8/2021 (4 days after the second hull/shell amendment application).

As the highest fertilizer costs in almond production tend to be associated with K, application of hulls and shells as organic matter amendments could provide a cost-effective source of recycled K. All three growers separately confirmed interest in potentially replacing some portion of fertilizer K with hull/shell amendment K based on the results of this research. Thus, these trials aimed to quantify K release, availability, and plant uptake over time to help inform grower K management decision-making. In addition, other soil fertility and plant nutrient dynamics were evaluated to better understand how this amendment practice might influence relevant plant-essential nutrients more broadly.

### 2.5 Experimental Design

All trials were randomized complete block designs with treatments applied to entire rows. Each experimental unit consisted of at least 40 trees within an individual row, hereafter referred to as a plot. Each plot was replicated across all four blocks. Trial location was informed by NRCS soil web database maps to find and area of a consistent soil type. At each site, no alterations were made to growers' existing fertilizer management plans and hull/shell amendments were applied in addition to existing fertilizer applications.

At the Crown field site, five treatments consisted of a control (minimal K fertilizer), hulls, shells, a hull-shell mix, and $K_2SO_4$ fertilizer. The amendments were applied with a compost spreader that placed materials only over tree roots in the tree row and not in the alley. The latter four treatments were all applied as close as possible to 140 kg ha$^{-1}$ (125 lb ac$^{-1}$) K in February 2020 and 185 kg ha$^{-1}$ (165 lb ac$^{-1}$) K in 2021. Using a compost spreader, each amendment treatment was applied to both sides of 40 trees in each row across four blocks. According to grower records, minimal baseline K fertilizer (a combination of KTS and foliar spray) totaling 33.5 kg ha$^{-1}$ (30 lb ac$^{-1}$) K was applied in 2020 across the entire orchard. The $K_2SO_4$ fertilizer treatment was applied in the fall of 2019 and fall 2020. Amendments were applied on 2/10/2020, and 11/12/2020.

The trial at Bullseye consists of three treatments: a control of no amendments, a predominantly shell-based mixture of fresh almond shells and hulls, and a compost comprised of approximately 30% manure and 70% shells/hulls created by growers Bullseye Farms. On 10/14/2020, and 11/29/2021, amendments were applied with a compost spreader that placed materials only over tree roots in the tree row and not in the alley.

At the Westwind trial, four treatments consisted of a control treatment, off ground harvest treatment, hull/shell amendment treatment, and hull/shell amendment treatment maintained with off ground harvest. Amendments were applied with a compost spreader. On 10/7/2020, 18 tons ha$^{-1}$ (8 US tons ac$^{-1}$) of fresh hull/shell mix were applied with 6.6% moisture at approximately 17 dry tons ha$^{-1}$ (7.5 dry US tons ac$^{-1}$) total. These materials were broadcasted across entire orchard soil, including the alley. The mix was comprised of 32%

hulls and 68% shells. The berm area is around 36% of the total area. On 10/4/2021, 18 tons ha$^{-1}$ (8 US tons ac$^{-1}$) of fresh hull/shell mix were applied with 2.1% moisture at approximately 17.5 dry tons ha$^{-1}$ (7.8 dry US tons ac$^{-1}$) total. During this second application, the hull/shell mix was comprised of 53% hulls and 47% shells. In contrast to the previous year, the amendment was applied in the tree row by a side-spreader and not in the alley, concentrating the amendment over tree roots.

### 2.6 Methods and Analyses

Soil. Prior to amendment application, soil samples were taken from each plot to assess components of soil fertility: nitrate-nitrogen (nitrate-N), Olsen phosphorus (Olsen-P), exchangeable potassium (XK) via ammonium acetate extraction, exchangeable sodium (XNa), exchangeable calcium (XCa), exchangeable magnesium (XMg), CEC, SOM percent, and pH. Initial soil samples were taken at 0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm depths. Three subsamples were taken for each treatment row, air dried, and ground separately with a soil pulverizer. The subsamples were aggregated for each experimental unit prior to analysis at the University of California Davis Analytical Lab. At later time points, additional soil samples were taken and analyzed for XK at intervals following amendment application at all sites (UC Davis Analytical Lab, ammonium acetate extraction). Soil XK is a commonly utilized measure of plant-available K.

Decomposition. Immediately following the first application at the Crown trial, PVC/mesh litter rings were installed to measure decomposition of amendments by mass loss over time. Each PVC ring was 30 cm in diameter and 2.54 cm in height with coarse mesh netting (0.08 cm) glued to one side of the ring and pinned to the soil surface with landscape staples (Lepsch et al. 2019). The appropriate mass of each amendment was added to each litter ring based on area, application rates, and percent moisture of each amendment. At seven time points between February application and harvest in August 2020, 12 rings from each treatment row were collected. In addition, litter rings were collected across all time points from the control rows to estimate average litter fall from blossoms, leaves, and other debris, which was subtracted out of average amendment mass at each time point to account for litterfall mass. However, litter ring data showed very high variation due to movement of the amendments in and out of the ring area.

To reduce this variation in decomposition data, litter bags were installed instead of litter rings following amendment application at all three sites in fall 2020 to exclude amendments and debris that would otherwise move into the ring area due to wind, water, equipment, etc. Net mass remaining in litter bags was used to assess general decomposition trends over time for each amendment type. Square litter bags made of 1/32-inch nylon mesh (Memphis Net and Twine Company) 20 cm x 20 cm in size were filled with the appropriate mass of each amendment on an area basis, application rates, and percent moisture of each amendment. The litter bag method was initially developed in forest ecosystem litter layer studies and has been adapted in many different agricultural systems to study residue decomposition over time (Kaushal et al. 2012, Krishna et al. 2017, Dong et al. 2020, Yang et al. 2020, Prescott and Vesterdal 2021). While litter bags with small mesh size may slightly underestimate mass loss by excluding activities of larger fauna, data from large mesh size may overestimate mass loss by not including transformed materials that move into the soil (Prescott and Vesterdal 2021). The 1/32-inch mesh size was chosen for the litter bags to strike a balance between these two extremes. Prescott and Vesterdal 2021 recommend describing the remaining biomass in litter bags as "net mass remaining" because some fraction of the measured biomass within the bags is likely microbial biomass and byproducts, in addition to lingering plant residue (Prescott and Vesterdal 2021).

At Bullseye, mesh litter bags were installed after application and collected over time on 12/13/20 (60 days after application), 2/11/21 (120 days after application), 4/12/21 (180 days after application), and 6/11/21 (240 days after application). At Westwind, mesh litter bags were installed immediately following amendment application on 10/7/2020 and collected over time on 11/6/2020 (30 days after application), 12/6/2020 (60 days after application), 2/4/2021 (120 days after application), 3/6/2021 (150 days after application), 6/6/2021 (240 days after application), 7/29/21 (293 days after application, immediately before harvest), and 10/7/21 (1 year from the 2020 application date).

Application Rates. At Crown, amendments were applied on 2/10/2020 and 11/12/2020. Nutrient concentrations in hull/shell samples taken in 2019 (Supplementary Tables 2.4a and b) were used to estimate the required rates to apply a target rate of approximately 140 kg ha$^{-1}$ (125 lb ac$^{-1}$) K applied via amendments in February 2020. Average amendment K rate applied through hull/shell amendments was found by multiplying the average dry biomass by K concentrations after application (Supplementary Table 2.5). The goal was to apply a similar K rate through the three hull/shell amendment treatments. Amendments were sourced from

Nonpareil/Independence hulls, hull/shell mix from pollinizers, and shells from many varieties.

At Bullseye, fresh and composted hull/shell amendments were applied on 10/14/2020 and 11/29/2021. In 2020, the fresh hull/shell amendment consisted of 80% shells and 20% hulls, and the texture was comparable to coarse sawdust. This treatment was applied at approximately 12.3 tons $ha^{-1}$ (5.5 fresh US tons $ac^{-1}$) at 18% moisture (10.1 dry tons $ha^{-1}$, 4.5 dry US tons $ac^{-1}$). The composted hull/shell/manure amendment consisted of approximately 30% manure and 70% shells prior to the composting process. It was applied at approximately 21.1 tons $ha^{-1}$ (9.4 fresh US tons $ac^{-1}$) at 32% moisture (12.3 dry tons $ha^{-1}$, 6.4 dry US tons $ac^{-1}$). These application rates were chosen to compare the relative value of shells applied as a fresh material delivered from the processor with shells that had been composted for 10 months with cow manure. The objective for the first year was to evaluate whether composting the shells provided added value in terms of soil fertility improvements. Amendments applied on 11/29/2021 consisted of a hull/shell mix that was 40% hulls and 60% shells and texture was slightly more coarse than the year prior. This hull/shell mix was applied at 17.9 fresh tons $ha^{-1}$ (8 fresh US tons $ac^{-1}$) at 31.8% moisture (12.3 dry tons $ha^{-1}$, 5.5 dry US tons $ac^{-1}$). The compost was comprised of approximately 30% manure and 70% shells. It was applied at 29.1 fresh tons $ha^{-1}$ (13 fresh US tons $ac^{-1}$) at 57.6% moisture (12.3 dry tons $ha^{-1}$, 5.5 US tons $ac^{-1}$ dry). Moisture content in both amendments was higher this year compared to 2020 likely due to unusually heavy October rains prior to application.

At Westwind, amendments were applied on 10/7/2020 and 10/4/2021. In fall 2020, approximately 17.9 tons ha$^{-1}$ (8 fresh US tons ac$^{-1}$) hull/shell mix were applied with 6.6% moisture 16.8 kg ha$^{-1}$ (7.5 dry US tons ac$^{-1}$). These materials were broadcasted across entire orchard soil including the alley. The mix was comprised of 32% hulls and 68% shells. On 10/4/2021, approximately 17.9 tons ha$^{-1}$ (8 US tons ac$^{-1}$) hull/shell mix were applied via side-spreader only in the tree row with 2.1% moisture (17.5 dry tons ha$^{-1}$, 7.8 dry US tons ac$^{-1}$). During this second application, the hull/shell mix was comprised of 53% hulls and 47% shells.

<u>Amendment Nutrients and K Release Model.</u> Samples from the initial applied amendments from all sites were oven-dried at 60 C, pulverized, and sent to the UC Davis Analytical Lab to be analyzed for nutrient concentrations: nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, boron, zinc, manganese, iron, and copper. After application, litter ring and litter bag samples used for net mass remaining were pulverized and analyzed for amendment nutrient concentrations across time intervals. Litter samples were analyzed via ICP-MS at the Interdisciplinary Center for Inductively Coupled Plasma Mass Spectrometry at UC Davis.

Crown amendment K concentration data from 2/10/2020 until 7/27/2020 (Figures 1 and 2) was modeled as a function of corresponding cumulative water applied. Several nonlinear and generalized additive models (GAMs) were evaluated in R. The goal of model development was to provide a framework for predicting changes amendment K concentration in hull, mix, and shell materials over time based on cumulative water applied as both irrigation and rainfall. Rainfall and irrigation at each site can be found in Supplementary Figures 2.1-3. Several nonlinear models were compared using normality of residuals assessment and analysis of variance (ANOVA). The most parsimonious model was a nonlinear mixed-effects model (*lme4* package) that allowed treatment effects on Y0 (the y-intercept) and had the lowest p-value and Aikake Information Criterion (AIC). For further comparison, GAMs were created and evaluated (*mgcv* and *performance* packages). Models were compared by generating AIC of each model, assessing posterior predictive checks, linearity, homogeneity of variances, and normality of residuals. While several GAMs were evaluated, the AICs of all GAMs were much higher than the AIC of the best nonlinear mixed effects model.

In the chosen model described in the results section, amendment K concentration is expressed as a percentage. Symbols are used as in R, e.g., "~" indicates "is modeled as" in Eq. 2.1. The first part of the model shown in Eq. 2.1. is a typical exponential formula, while C0 is the height at which K concentration ends which adds model flexibility. Y0 is equal to the y-intercept, the original K concentration in the material. B0 is a parameter that regulates the change in steepness of the curve with units that are the reciprocal of cumulative water inches. Cumulative water is the amount of water added as irrigation and rain for each specific K concentration value.

Tree Nutrient Status and Trunk Circumferences. Prior to amendment application, three sample trees were selected per treatment row to serve as consistent trees for leaf samples at each trial. To assess mid-July leaf nutrients, 100 leaves were taken per sample tree, washed twice with DI water, oven-dried, pulverized, and sent to the UC Davis Analytical Lab. Leaf samples were analyzed for concentrations of carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, boron, zinc, manganese, iron, and copper. In addition, hull samples were taken at harvest to provide a better indicator of boron status than mid-July leaf samples (CDFA FREP, Krueger 2010, Nyomora et al. 1997). Trunk circumferences were measured annually in mid-January at approximately 0.3 meter above the soil surface.

Yield. In collaboration with harvest equipment operators, yield data for each individual treatment row was collected by mechanically sweeping, picking up, and depositing the crop into a transport bin at Crown and into a Thomas nut weigh cart at Bullseye and Westwind. At Crown, yield samples were weighed using a semi-truck scale at the nearby processor. At Westwind, a catch frame harvester was used in the off ground treatments which deposited crop into the center of the alley, eliminating the sweeping step in the tree row. At all sites, yield subsamples of at least 3 kg fresh weight per sample were taken in each plot, weighed fresh, oven-dried, and weighed dry to calculate percent moisture. Then, dry whole fruits were separated from “trash” (e.g., sticks, dirt, leftover hull/shell amendments, other debris, etc.) and weighed. Hull/shell trash was separated from all other trash and weighed. One hundred dry whole fruits were separated into kernels, shells, and hulls and weighed. Crack out percentage was calculated as the dry mass of 100 kernels divided by the dry mass of 100 whole fruits. For a uniform number of trees per plot (e.g. 40 trees) within each field trial, kernel yield was calculated using dry kernel weight for the specified trees divided by the area covered.

Climate. Precipitation and evapotranspiration data were provided by the CIMIS databases, Station 249 (Ripon) for the Crown and Station 226 (Woodland) for Bullseye and Westwind.

Data Analysis. Data was analyzed in R (R version 4.1.2, 2021 The R Foundation for Statistical Computing, RStudio 2022.07.1 build 554). Data visualization was performed using the package ggplot2. All response variables were modeled using linear mixed effects models (lmer() command via the lmerTest package) as a function of treatment (a fixed effect) and block (a random effect). For response variables where subsamples were not aggregated prior to analysis (e.g., July leaf nutrients, trunk circumferences), plot was included as a random effect nested within block. Model assumptions of normality and homogeneity of variances were assessed with diagnostic plots, Normal Quantile-Quantile and Scale-Location plots. Natural log transformations were utilized occasionally as needed to improve the assumption of normality for amendment nutrient concentrations from litter bag samples. After diagnostics, analysis of variance (ANOVA) was performed, and Compact Letter Display (CLD) groupings were generated using the estimated marginal means (multcomp package) for multiple pair-wise comparisons (Tukey method). Alpha values were consistently set to 0.05. The R packages lme4, mgcv, and performance were used to develop and evaluate K release models. Linear regressions were performed using packages ggpubr and ggpubmisc for decomposition over time.

## 2.7 Results

### 2.7.1 Initial Nutrients Prior to Application

Initial average amendment nutrient concentrations for all field trials are provided in Tables 2.1-2.3. The K concentration of the hull/shell mix amendments ranged from approximately 1.5-2.9% K and hulls generally contained higher K concentrations than shells. Hull/shell materials that had been composted with manure prior to application had concentrations of approximately 1-1.8% K. Factors that may influence hull/shell K concentration include variety type, fertilization and irrigation practices, and soil type at the source location (Andrews et al. 2021). At the given rates, hull/shell amendment applications provided low quantities of micronutrients that could potentially cause toxicity in almond trees, such as boron and sodium.

Table 2.1. Initial average amendment nutrient concentrations by dry mass sampled 2/10/2020 and 11/12/2020, Crown Nut Co. At 2/10/2020, the hulls from the mix were analyzed separately from the shells and were 3.06% K, indicating that pollinizer variety hulls from these samples contained higher K concentrations compared to Nonpareil and Independence variety hulls.

| Treatments | C:N | (%) | | | | | | (ppm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| Application Date: 2/10/2020 | | | | | | | | | | | | | | |
| Hulls | 60:1 | 43.03 | 0.718 | 0.117 | 2.72 | 0.232 | 0.136 | 348 | 179.3 | 5.7 | 10.4 | 127 | 3.1 | -- |
| Mix | 64:1 | 44.40 | 0.698 | 0.093 | 2.91 | 0.222 | 0.111 | 303 | 158.9 | 5.8 | 12.0 | 126 | 3.5 | -- |
| Shells | 91:1 | 45.85 | 0.510 | 0.049 | 1.54 | 0.245 | 0.098 | 248 | 73.6 | 7.4 | 27.8 | 1013 | 4.6 | -- |
| Application Date: 11/12/2020 | | | | | | | | | | | | | | |
| Hulls | 71:1 | 42.1 | 0.59 | 0.09 | 2.07 | 0.16 | 0.08 | 249 | 77.6 | 4.4 | 10.4 | 174.7 | 2.19 | 70 |
| Mix | 65:1 | 42.1 | 0.65 | 0.07 | 2.23 | 0.21 | 0.11 | 288 | 116.5 | 4.8 | 13.0 | 224.9 | 3.30 | 120 |
| Shells | 70:1 | 42.7 | 0.61 | 0.06 | 1.84 | 0.29 | 0.11 | 264 | 81.0 | 5.5 | 21.4 | 660.6 | 3.03 | 78 |

Table 2.2. Average initial nutrient concentrations in fresh mix of shells/hulls (M) and compost (C) amendments and rates applied at Bullseye in the fall of 2020 and 2021. In 2020, the mix was 80% shells and 20% hulls, while in 2021 the mix was 60% shells and 40% hulls. All values are based on dry weight.

| **Application Date: 10/14/2020** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | C:N | (%) | | | | | | (ppm) | | | | | | |
| | | C | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M | 91:1 | 45.1 | 0.50 | 0.05 | 1.53 | 0.197 | 0.069 | 246 | 54.0 | 5.4 | 12.5 | 288 | 2.9 | 145 |
| C | 24:1 | 25.5 | 1.05 | 0.22 | 1.78 | 0.965 | 0.878 | 1757 | 101.7 | 88.1 | 88.1 | 16021 | 29.0 | 1628 |
| Nutrient rate applied (kg ha$^{-1}$) at 10,000 dry kg ha$^{-1}$shell and 14,350 kg ha$^{-1}$compost | | | | | | | | | | | | | | |
| M | -- | 4550 | 50 | 4.8 | 155 | 20 | 6.9 | 2.5 | 0.6 | 0.06 | 0.12 | 2.9 | 0.03 | 14.7 |
| C | -- | 3663 | 151 | 33 | 256 | 139 | 126 | 252 | 14.6 | 12.3 | 53.8 | 2299 | 4.5 | 234 |
| Nutrient rate applied (lb ac$^{-1}$) at 9,000 dry lb ac$^{-1}$ shell and 12,800 lb ac$^{-1}$ compost | | | | | | | | | | | | | | |
| M | -- | 4059 | 45 | 4.3 | 138 | 18 | 6.2 | 2.2 | 0.5 | 0.05 | 0.11 | 2.6 | 0.03 | 13.1 |
| C | -- | 3268 | 135 | 29 | 228 | 124 | 112 | 225 | 13 | 11 | 48 | 2051 | 4 | 208 |
| **Application Date: 11/29/2021** | | | | | | | | | | | | | | |
| | C:N | (%) | | | | | | (ppm) | | | | | | |
| | | C | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| M | 40:1 | 45.5 | 1.14 | 0.12 | 2.56 | 0.22 | 0.08 | 382.5 | 73.2 | 14.7 | 17 | 405 | 3.1 | -- |
| C | 33:1 | 28.8 | 0.87 | 0.15 | 1.04 | 0.67 | 0.97 | 1195 | 71.7 | 87.2 | 395 | 22693 | 31.9 | -- |
| Nutrient rate applied (kg ha$^{-1}$) at 12,330 dry kg ha$^{-1}$ shell and 12,330 kg ha$^{-1}$ compost | | | | | | | | | | | | | | |
| M | -- | 5604 | 140 | 14.7 | 315 | 27 | 9.3 | 47 | 9.1 | 1.8 | 2.1 | 49 | 0.3 | -- |
| C | -- | 3551 | 108 | 18.0 | 128 | 82 | 120 | 148 | 8.9 | 10.8 | 48 | 2798 | 3.9 | -- |
| Nutrient rate applied (lb ac$^{-1}$) at 11,000 dry lb ac$^{-1}$ shell and 11,000 lb ac$^{-1}$ compost | | | | | | | | | | | | | | |
| M | -- | 5000 | 125 | 13.1 | 281 | 24 | 8.3 | 42 | 8.1 | 1.6 | 1.9 | 44 | 0.3 | -- |
| C | -- | 3168 | 96 | 16.1 | 114 | 73 | 107 | 132 | 7.9 | 9.6 | 43 | 2496 | 3.5 | -- |

Table 2.3. Average applied nutrient concentrations in hull/shell mix and rates, Westwind, October 2020 and 2021. The hull/shell mix was 32% hulls and 68% shells in 2020 and 53% hulls and 47% shells in 2021.

| Application Date: 10/7/2020 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C:N | (%) | | | | | | (ppm) | | | | | | |
| | C | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| 52:1 | 44.5 | 0.85 | 0.065 | 1.85 | 0.224 | 0.067 | 301 | 53.7 | 7.9 | 22.9 | 309 | 3.3 | 128 |
| Nutrient rate applied (kg ha$^{-1}$) at 16,813 dry kg ha$^{-1}$ | | | | | | | | | | | | | |
| -- | 7484 | 143 | 11.0 | 311 | 37.7 | 11.3 | 50 | 9 | 1 | 3.4 | 52 | 0.6 | 21 |
| Nutrient rate applied (lb ac$^{-1}$) at 15,000 dry lb ac$^{-1}$ | | | | | | | | | | | | | |
| -- | 6677 | 127.5 | 9.8 | 277 | 33.6 | 10.1 | 45 | 8 | 1 | 3 | 46 | 0.5 | 19 |
| Application Date: 10/4/2021 | | | | | | | | | | | | | |
| | (%) | | | | | | (ppm) | | | | | | |
| C:N | C | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| 51:1 | 44.9 | 0.89 | 0.08 | 2.11 | 0.21 | 0.08 | 341 | 76 | 9.4 | 18 | 539 | 3.5 | -- |
| Nutrient rate applied (kg ha$^{-1}$) at 17,485 dry kg ha$^{-1}$ | | | | | | | | | | | | | |
| -- | 7845 | 155 | 15 | 369 | 35.9 | 15 | 59 | 13.2 | 1.7 | 3.1 | 94 | 0.6 | -- |
| Nutrient rate applied (lb ac$^{-1}$) at 15,600 dry pounds ac$^{-1}$ | | | | | | | | | | | | | |
| -- | 6999 | 138 | 13 | 329 | 32 | 13 | 53 | 11.8 | 1.5 | 2.8 | 84 | 0.5 | -- |

### 2.7.2 Changes in Amendment Nutrient Concentrations Over Time

At Crown, the hull/shell amendments released approximately 71-80% of total K from 2/10/2020 to 6/22/2020 under approximately 12.7 cumulative inches of water (rain and irrigation) (Figure 2.1, Supplementary Table 2.6). Most of the K was released within the first two months after application. Then after the second application from 11/12/2020 to 7/26/2021, 78-87% of total K was released under approximately 26.7 cumulative inches of water (Supplementary Table 2.6.). From 11/12/2020 until 7/26/2021, K concentrations and C:N ratio significantly decreased in all amendments. Meanwhile, C, N, Ca, Mg, Na, Si, Mn, Fe, Cu, and Zn concentrations significantly increased in all amendments and P and B significantly or slightly increased in amendments as decomposition reduced net mass over time (Supplementary Table 2.8). Initial and final C and N concentrations and corresponding dry mass can be found in Supplementary Table 2.9. Initial and final N in amendment biomass remained relatively similar from 11/12/2020 to 7/26/2020 while C declined, which may reflect microbial C respiration and N utilization by microbial biomass although these responses were not measured in the present study.

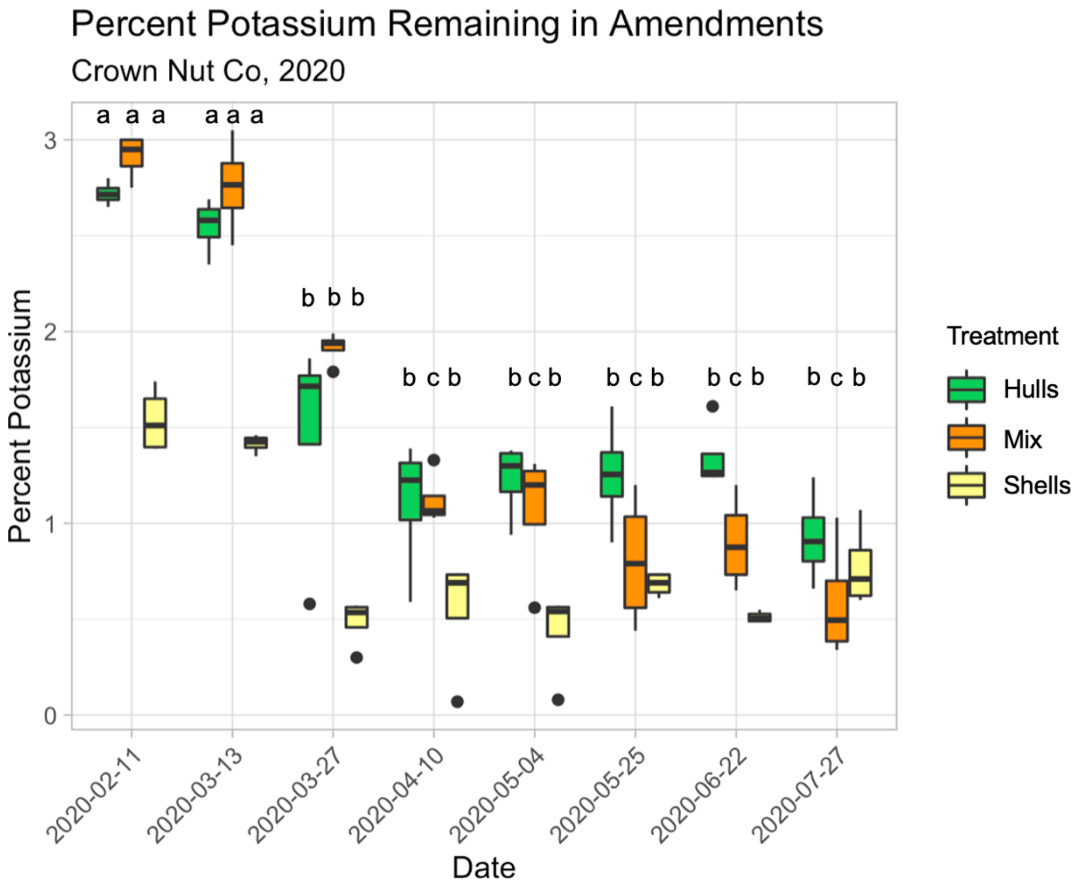


Figure 2.1. Changes in potassium concentrations in three types of amendments from application 2/10/2020 to 6/22/2020 at Crown. Letter groupings represent significant differences in K concentration over time within each separate amendment. All three amendment materials significantly decreased in K concentration within the first six and a half weeks. Potassium release occurred more rapidly than other nutrients measured. From 3/27/2020 onward, amendment K concentrations remained significantly lower than respective initial K concentrations for all three amendment materials.

As described in the Methods section, several models were evaluated and compared to describe the observed changes amendment K concentration as a function of cumulative water applied using Crown hulls, mix, and shells amendment data. The most parsimonious model was a nonlinear model with a defined formula for exponential decline with vertical offset:

$$\text{Amendment [K]} \sim Y0 * \exp(B0 * \text{cumulative water}) + C0 \qquad \text{Eq. 2.1.}$$

This model can be used to help predict K release from amendments based on cumulative applied water. A steep decline in K concentration occurred for all three materials in the first 0-5 inches of applied water, after which K concentration plateaued (Figure 2.2). This model is most appropriate for understanding amendment K concentration in orchards where additional amendments containing K are not applied after hull/shell application. For instance, at Westwind, K release much appears less predictable likely due to the ability of the hull/shell material to retain K applied through other organic matter amendments such as compost and K additions through fertigation (Figure 2.4). In addition, irrigation type could potentially influence changes in hull/shell amendment K concentration over time and could be considered in future studies.

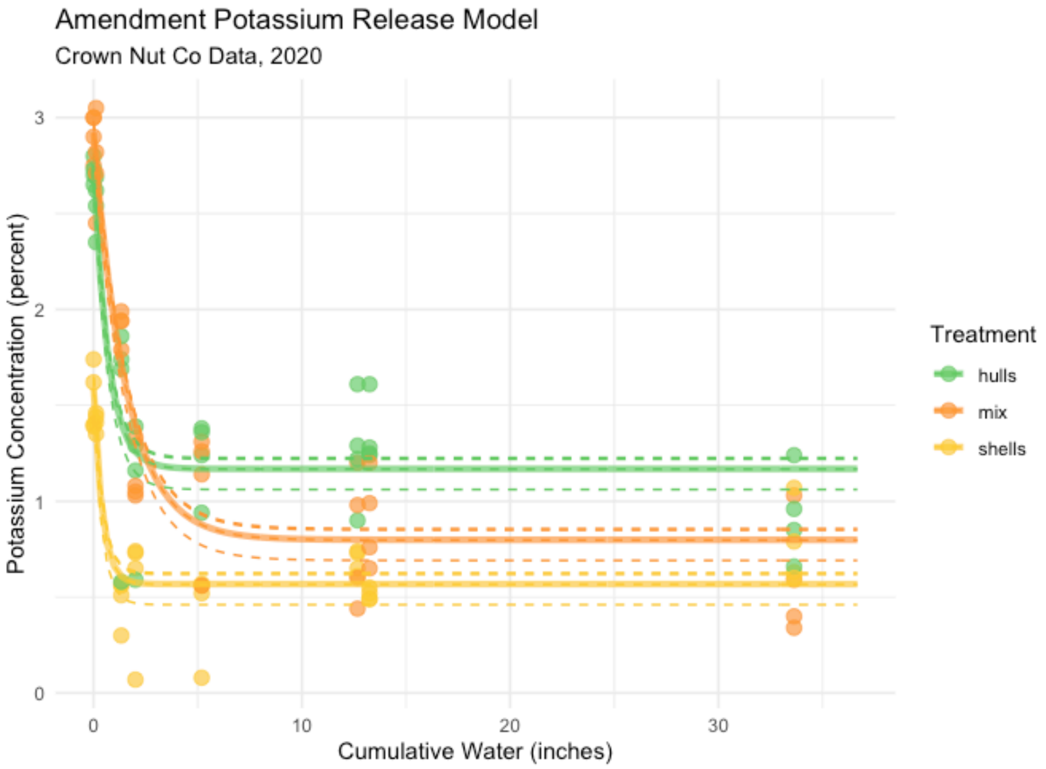


Figure 2.2. Nonlinear model with a defined formula (Eq.2.1.) for exponential decline with vertical offset predicting average K concentration as a function of cumulative water applied

for each of the three amendments applied at Crown Nut Co on 2/10/2020. No further K additions were made through fertigation or other organic matter amendments during this time frame. Dashed lines represent confidence intervals.

At Bullseye, from 10/14/2020 until 6/11/2021 the hull/shell mix released approximately 85% of total K and compost released approximately 81% of total K under 19.8 cumulative inches of water (irrigation and rainfall) between sampling dates (Supplementary Table 2.10). K concentration significantly decreased over time in both amendments (Figure 2.3). However, while the C:N ratio significantly decreased in the fresh mix, it remained largely unchanged in compost (Supplementary Table 2.11). While the mix fluctuated somewhat in C and N concentrations, compost C and N concentrations remained consistent. Phosphorus concentration significantly decreased in the compost amendment only. As dry mass decreased via decomposition, Ca, S, Fe, Na, and Zn concentrations increased significantly in both amendments by the final time point, while Al, Cu, Mn, B, and Ni significantly increased in the hull/shell mix but not compost (Supplementary Table 2.11). Considering dry mass, from 10/14/2021 to 8/10/2021 estimated initial and final N in amendments remained relatively stable for the hull/shell mix but decreased by about half of initial N for the compost, while total estimated C declined in both amendments (Supplementary Table 2.9).

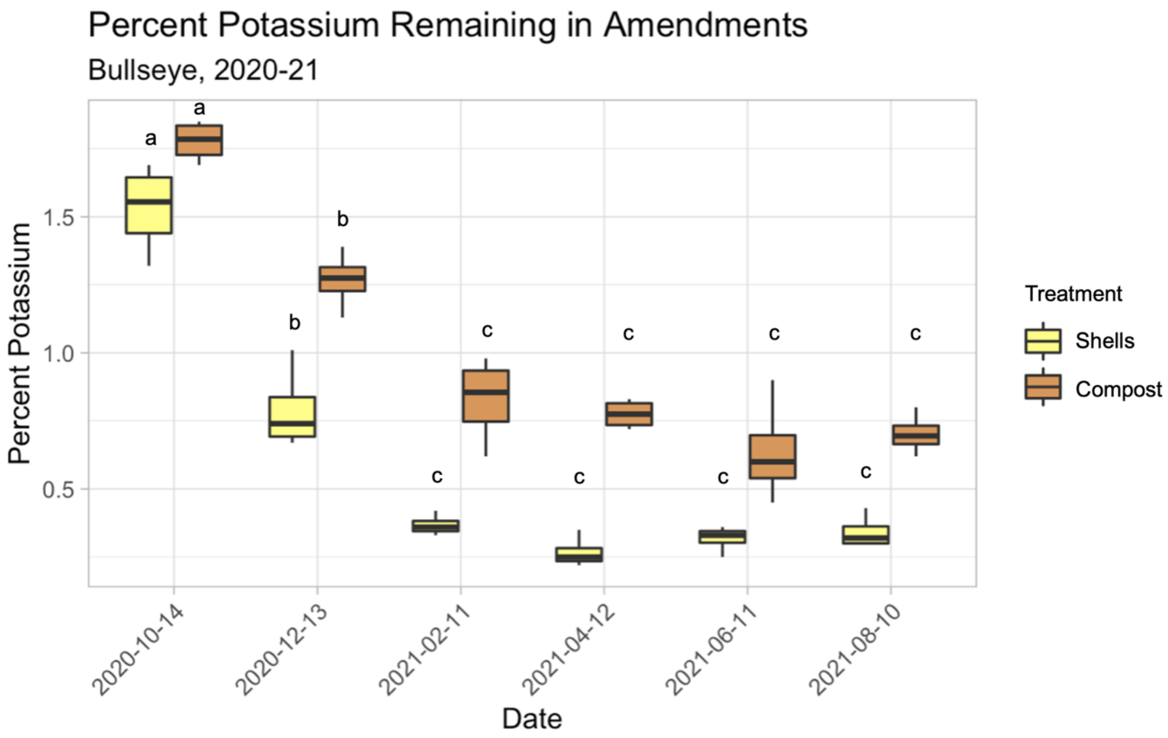


Figure 2.3. Potassium concentrations remaining in shell and compost amendments on the soil surface over time at Bullseye. Letter groupings represent significant differences in K concentration within each separate amendment over time. Two months after application, K concentration was significantly lower in both treatments than respective initial concentrations. From 12/13/2020 onward, K concentration in both materials remained significantly lower than respective initial K concentrations.

At Westwind, from 10/7/2020 until 10/7/2021 the hull/shell mix released approximately 98% of total K under 40.9 cumulative inches of water as irrigation and rainfall (Supplementary Table 2.12). Catch frame harvest enabled this extended period beyond harvest in August, as hull/shell amendments remained undisturbed after one year. This indicates minimizing soil disturbance through off ground harvest can maximize total K release over time. At this site, the amendment layer dropped dramatically in K concentration within the first 2.25 inches of water within one month (Figure 2.4). Then on 11/11/2020, 4 tons ha$^{-1}$ (2 US tons ac$^{-1}$) compost were applied across the entire orchard which led to an increase in hull/shell amendment layer K concentration when sampled in early December. Two months later after 6 inches of total water, hull/shell K had dropped substantially a second time. Then on 3/5/2021 approximately 14 kg $ha^{-1}$ (12.5 lb $ac^{-1}$) K fertilizer was applied through irrigation, leading to another increase in hull/shell amendment layer K concentration as sampled the day after fertigation. Finally, from June onward, hull/shell K concentration was 0.1% despite ongoing K fertigation events. Over the year, concentrations of N, Ca, Mg, B, Al, S, Mn, Fe, Ni, Cu, and Zn increased significantly while C, P, Si increased only slightly (Supplementary Table 2.13). Estimated initial N stored in the amendment layer was slightly lower than final amendment N, and amendment C decreased by approximately half of initial C (Supplementary Table 2.9).

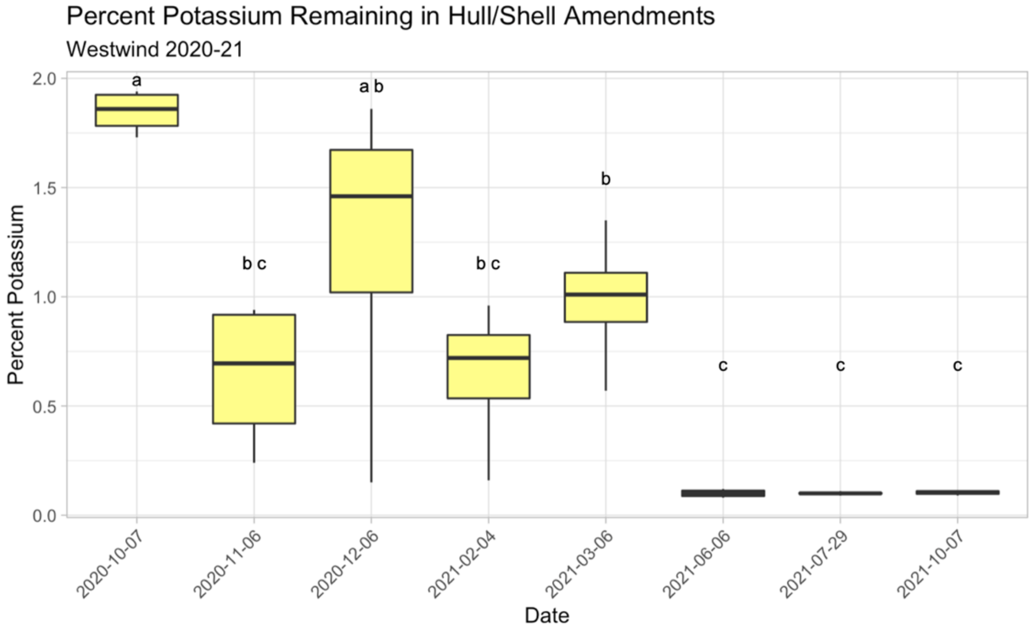


Figure 2.4. Potassium concentrations in the hull/shell mix on orchard soil over time at Westwind. Letter groupings represent significant differences in K concentration at different sampling times. Increases in amendment K in December and March likely reflect a compost application on 11/11/2020 between 11/6/2020 and 12/6/2020, and K fertilizer applied on 3/5/2021 between early November and December. While this data may not fully reflect %K release over time since it includes these additional K applications, it does suggest that the hull/shell amendment can briefly retain K applied on top of amendments that can later be solubilized and released into the soil solution over the course of one season.

### 2.7.4 Soil XK Over Time

At Crown, after both applications in February and November, the K released from amendments under water application significantly increased soil XK in the top 0-10 cm soil within the span of one to two months. After approximately 7 weeks and 1.25 inches of rainfall (irrigation had not yet begun) following amendment application in February 2020, the soils amended with hull, mix, and shell had significantly higher soil XK than the control soil (Figure 2.5). All three amendment treatments maintained higher average soil XK than the control from that time onward, though not always statistically significantly higher than the control soil. All average soil XK values above approximately 450 ppm were found under the hull/shell amendment treatments. On 10/19/2020 before the second amendment application in November 2020, amended soils maintained higher soil available K compared to the control though only the mix soil XK was statistically significant. Following the second amendment application on 11/12/2020, on 1/12/2021 after 1.35 inches of rainfall soils under hulls, mix, and shells had significantly higher XK than control soil. In October 2021, soils under all three amendments maintained higher average XK compared to control soil, significant for soils amended with hulls and shells.

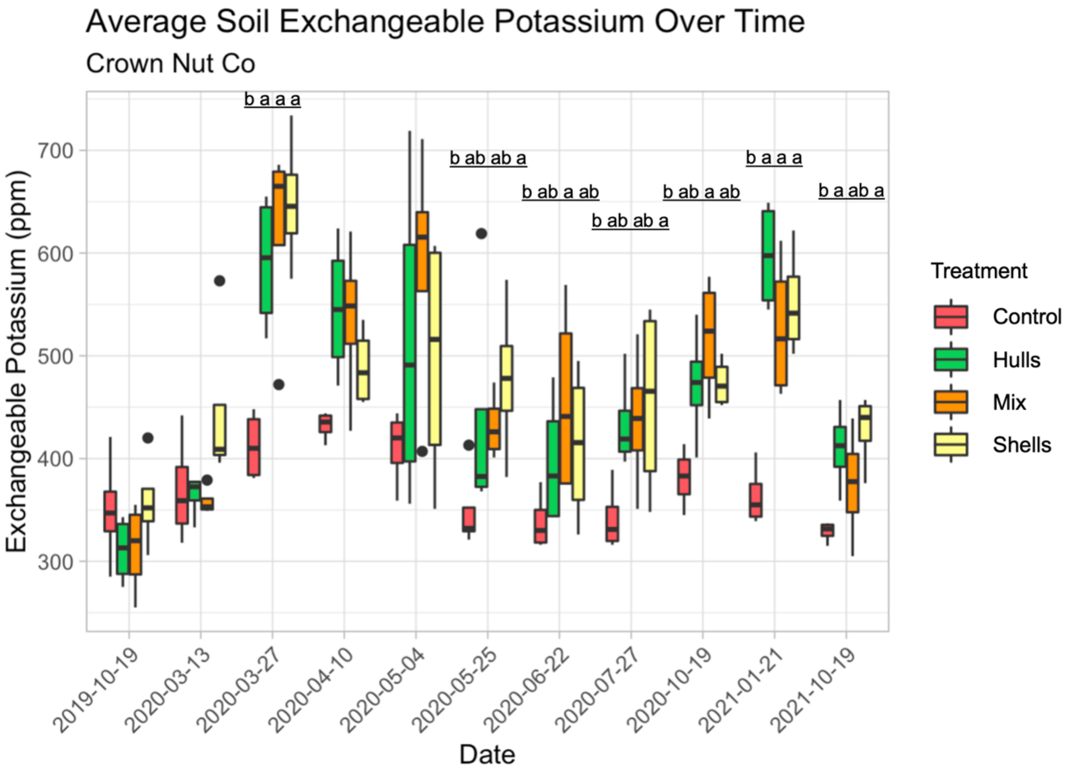


Figure 2.5. Average soil XK in the top 0-10 cm under treatments across time at Crown Nut Co. Letter groupings indicate significant differences between treatments within each time point. For time points with no letters, treatments were not significantly different.

At Bullseye, after amendment application on 10/14/2020, amended soils had higher average XK in the upper 0-10 cm depth than control soils at 11/5/2020 onward becoming statistically significant at 11/24/2020 after 0.47 inches of water (Figure 2.6). Shell amended soil XK tended to be significantly greater than control soil XK more often than compost soil. One year after the first amendment application, soil XK averages were slightly higher in both amended soils, though only statistically higher than the control in the shell amended soil. KTS fertilizer was applied uniformly across the orchard through irrigation at 149 kg ha$^{-1}$ (133 lb ac$^{-1}$) K total from 3/1/2021 until 6/15/2021 which likely explains the slight increase in soil XK in all treatments at 5/11/2021. Soil XK values above 250 ppm are generally considered high for California almond orchards (Supplementary Table 2.14). Nonetheless, significant increases in soil XK under both amendments were found despite high background XK levels.

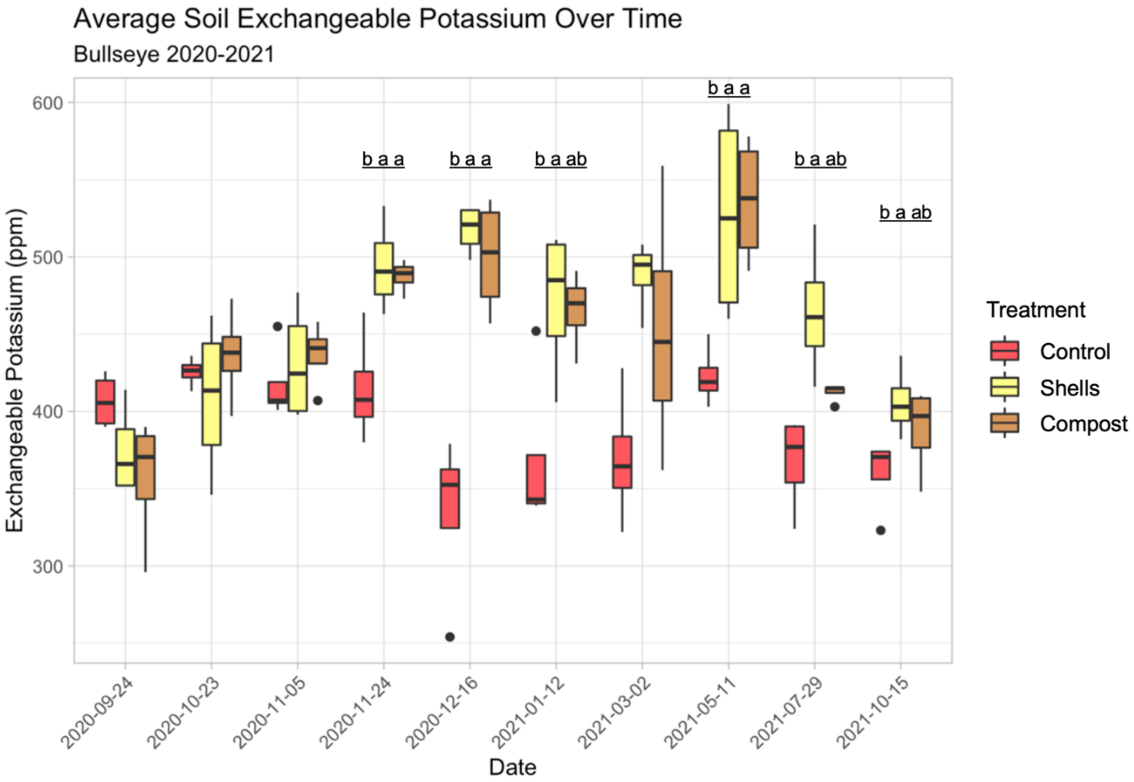


Figure 2.6. Average soil XK over time across all treatments at Bullseye in the top 0-10 cm soil. Soil XK became statistically significantly higher under shells and compost on 11/24/2020. Letter groupings indicate significant differences between treatments within each time point. For time points with no letters, treatments were not significantly different.

At Westwind, the hull/shell mix applied 10/7/2020 led to significantly higher soil XK in the upper 0-10 cm soil compared to control soil on 10/23/2020 after 16 days and 2 inches of irrigation water (Figure 2.7). Following this date, the hull/shell mix maintained higher average soil XK than the control soil, statistically significant again during January-May 2021. Approximately 131 kg ha$^{-1}$ (117 lb ac$^{-1}$) K fertilizer was applied through irrigation in six applications between 5/6/2021 and 7/27/2021 which explains the increase in control and amended soil XK during this time frame. In fall 2021 almost one year after the first hull/shell application but prior to the second fall application, soil XK was significantly higher under the amendment that was left undisturbed by using catch frame harvest compared to control soil.

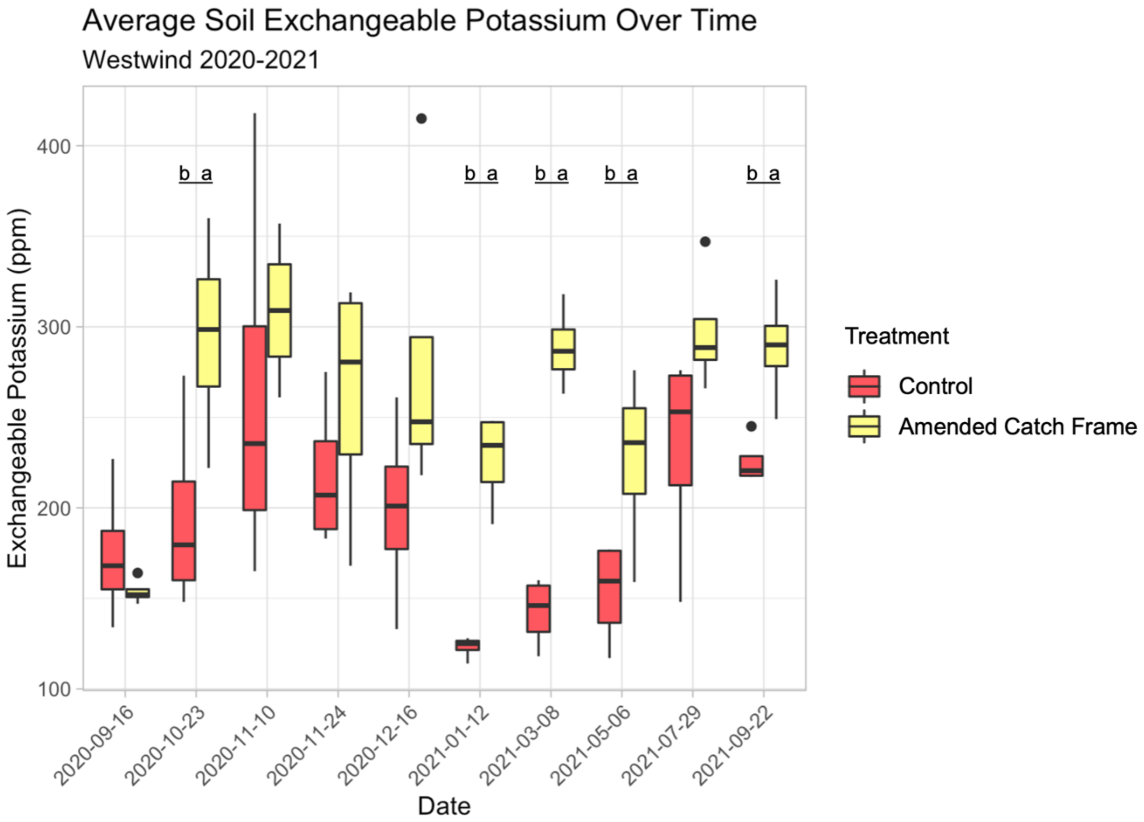


Figure 2.7. Soil exchangeable potassium at Westwind in the upper 0-10 cm soil over time. The hull/shell amendment was applied on 10/7/2020 and catch frame implemented in early August 2021. Letter groupings indicate significant differences between treatments within each time point. For time points with no letters, treatments were not significantly different.

### 2.7.5 Changes in Soil Fertility

At Crown, soil XK was the only soil fertility response variable that was significantly different between treatments at the 0-10 cm depth in fall 2020 and fall 2021 (Supplementary Table 2.15). All three amendments led to higher average fall soil XK compared to control soil, significant for the mix amended soil in fall 2020 and hull and shell amended soils in fall 2021. In fall 2021, compared to the control, mix-amended soil was significantly lower in XCa at 10-20 cm depth but significantly higher in XK at the 20-30 cm depth (Supplementary

Table 2.16). At 20-30 cm, XNa was significantly lower under the mix-amended soil compared to the hull-amended soil, which could potentially be attributed to preferential adsorption of K on exchange sites since mix-amended soils received the highest K application rates through amendments (Supplementary Table 2.5). In fall 2021, soil pH in the 0-10 cm depth was slightly closer to neutral under hull, mix, and shell amendments compared to the control though not significantly different.

At Bullseye, on 9/24/2020 prior to treatment establishment, the only soil fertility response variables that were significantly different between treatment rows in the top 0-10 cm soil were average percent organic matter (2.38% in control rows, 2.58% in shell rows, and 2.43% in compost rows) and XCa (12.78, 14.00, and 13.58 meq 100g$^{-1}$ respectively). These differences can be attributed to field site variation. After application, on 1/12/2021 compost amended soil had significantly higher XCa than the control. On 3/2/2021 at 0-10 cm and 10-20 cm depths, shell amended soil had significantly lower average XMg and slightly or significantly higher XK (Supplementary Tables 2.17 and 2.18). On 7/29/2021 XK was significantly higher in the shell amended soil. On 10/15/2021 one year after the first application, XNa in the top 0-10 cm was significantly lower for both shell and compost amended soils compared to the control (Supplementary Table 2.19). Nitrate-N and percent SOM were slightly higher and pH was slightly more neutral under amendments in the top 0-10 cm at this time, though not significantly different. At the 10-20 cm depth, shell-amended soil had significantly higher Olsen-P levels compared to the compost soil. At this time in fall 2021, no signs of reduced soil XMg levels were found under either amendment at any depths.

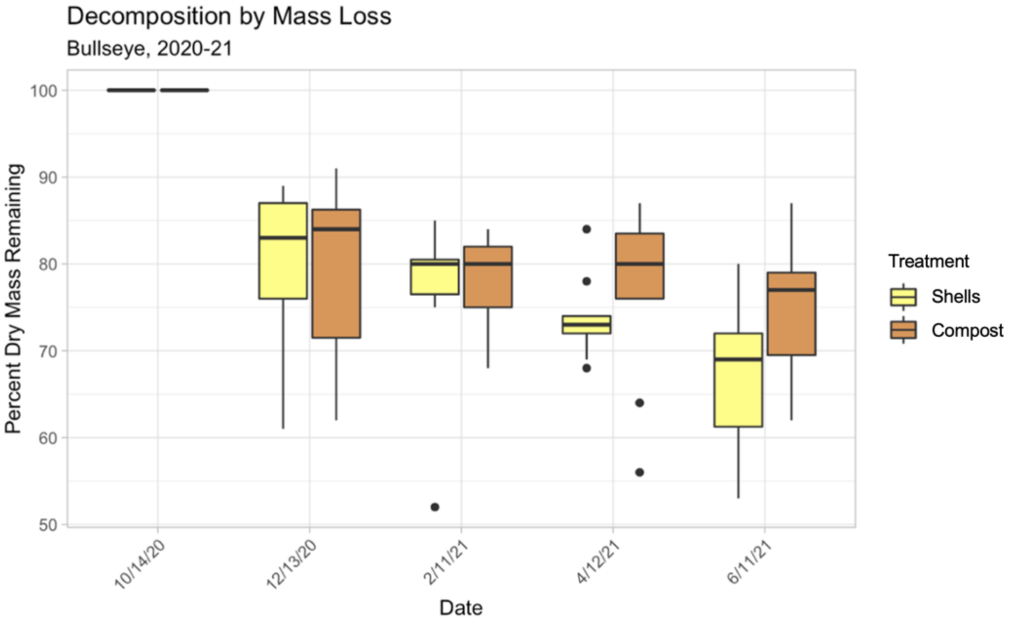
At Westwind, on 9/16/2020 baseline soil samples at 0-10 cm indicated the only soil fertility response variables that were significantly different between treatment rows prior to application was XNa, which was higher in the amended on-ground treatment, and XK which was higher in the control treatment soil than the other three treatments. Compared to the control soil, soil XK was slightly higher in the two amended treatments at 20-30 cm, with the highest average soil XK in amended catch frame soil though not statistically different. After application, the soil cation balance appeared to shift to slightly or significantly lower XNa and higher XK, slightly higher XCa, and variable XMg (Supplementary Table 2.20 and 2.21). On 3/8/2021 at 0-20 cm, amended catch frame soil had significantly higher soil XK and significantly lower XNa at 10-20 cm. On 7/29/2021, amended catch frame soil had significantly lower XMg at 0-10 cm depth and slightly higher XK and XCa. On 9/22/2021 approximately one year after the first amendment application, the only soil fertility response variable in the top 0-10 cm soil that was significantly different between treatments was soil XK, which was higher in both treatments that received amendments, statistically higher for amended catch frame only (Supplementary Table 2.22). Average soil nitrate-N and CEC were slightly higher in the two amended treatments on 9/22/2021, though not significant.

### 2.7.6 Amendment Decomposition

At Crown, litter rings were used to assess decomposition rate by net dry mass remaining from 2/10/2020 until 7/29/2020. However, increases in average percent net dry mass remaining over time and high standard deviation and standard error values indicate values were influenced by amendment materials moving in and out of the litter ring sampling area likely by wind, water, machinery, etc. (Supplementary Table 2.23). Empty litter rings were installed in the control rows to assess total litterfall (petals, twigs, leaves, etc.). Even with the control litterfall data factored into the average percent dry mass remaining of amendment treatments, substantial increases in amendment mass indicate materials moved into the sampling ring over time. Therefore, this data does not accurately represent average percent net dry mass and should be viewed only as a rough estimate.

To reduce variation and attain more accurate decomposition measurements, litter rings were replaced by mesh decomposition bags for 2020-2021 at all sites. Litter bags exclude litterfall and amendments from moving into and out of the litter bag sample area. At Crown, total decomposition from application on 11/12/2020 to 7/26/2021 was highest for hulls while mix and shells were statistically similar (Supplementary Table 2.24). The shells and mix decomposed by approximately half of their initial dry weight during this time frame, while hulls decomposed by approximately two thirds. Variation in litter bag data was substantially lower in July 2021 compared to the litter rings in July 2020.

At Bullseye on 6/11/21, the percent net dry mass remaining was 68% for shells and 75% for compost. Overall, net dry mass remaining gradually declined relatively steadily for both amendments, with final average shell percent net dry mass remaining slightly lower than compost. As shown in Figure 2.8, the materials decomposed to similar degrees within the first 4 months following application, and then the shells continued decreasing in net dry mass while the compost mass appeared to plateau. Shell net loss declined more linearly than compost net mass loss. At Westwind, the slight increase in net mass remaining at 12/6/2020 can be attributed to compost application 4 tons ha$^{-1}$ (2 US tons ac$^{-1}$) on 11/11/2020 which was applied uniformly throughout the orchard, including over litter bags. Nonetheless, the net mass remaining of the hull/shell mix declined relatively linearly with 45% remaining after one year (Figure 2.9). Final average percent net mass remaining in litter bags in 2021 for all hull/shell materials at all three sites are presented in Table 2.4.



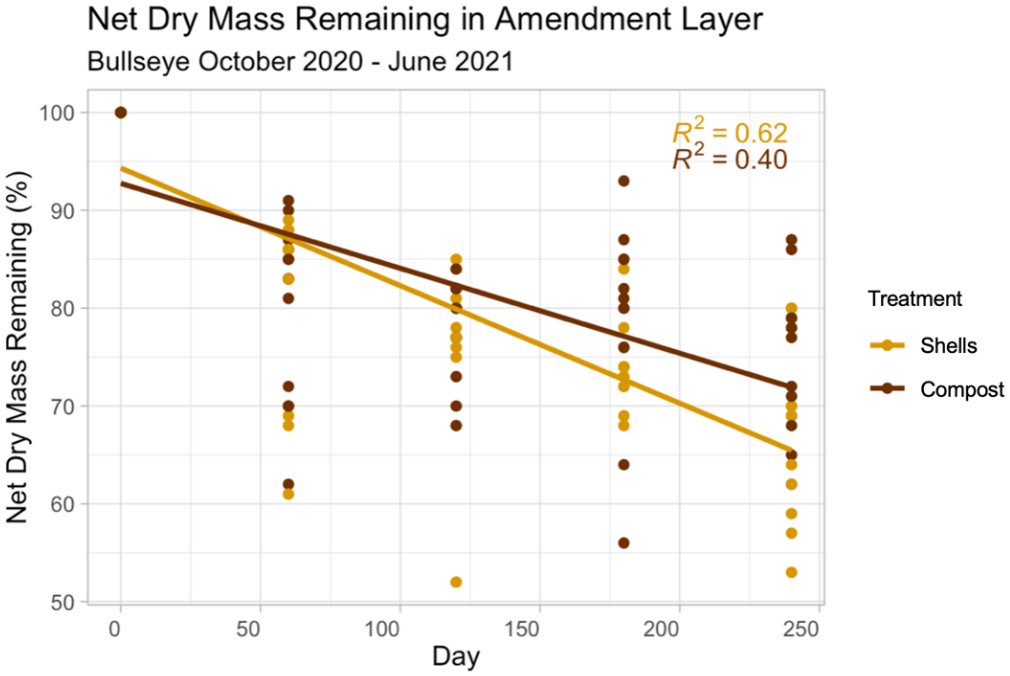
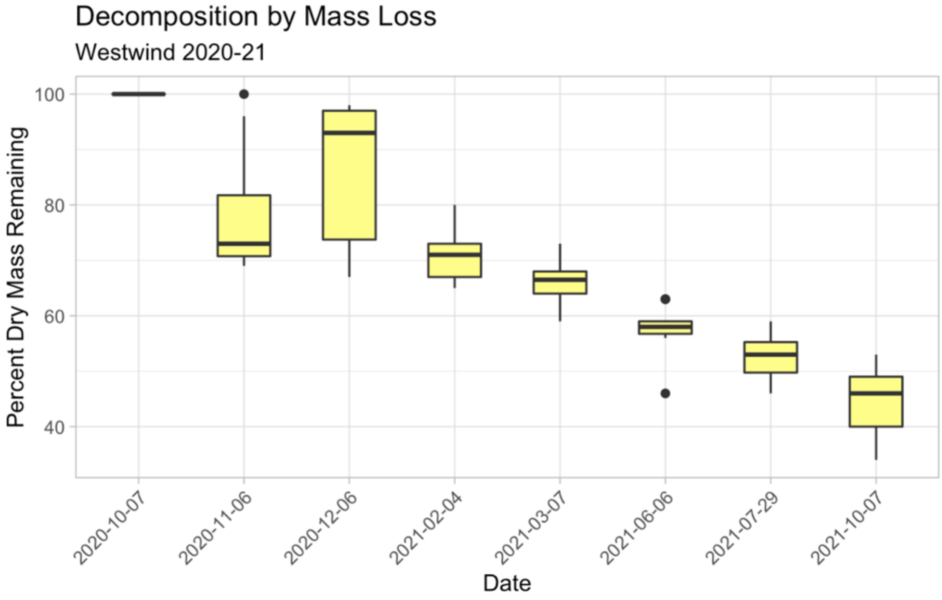


Figure 2.8a and b. Decomposition of shells and compost amendments expressed as percent net dry mass remaining in boxplots and linear regression, Bullseye 2020-2021.



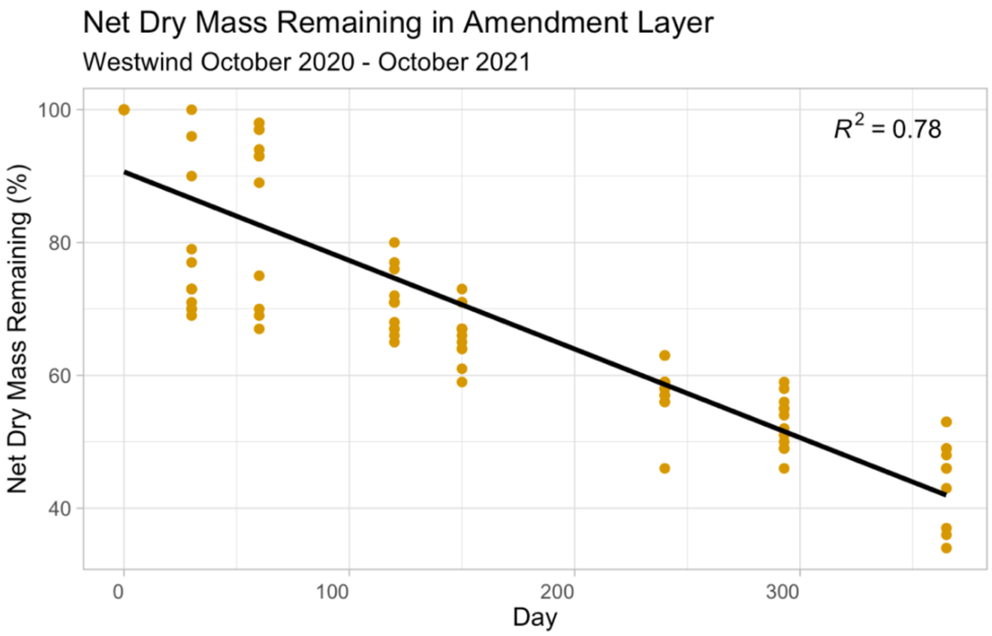


Figure 2.9a and b. Decomposition by mass loss over time expressed as percent net dry mass remaining in boxplots and linear regression, Westwind, 2020-2021.

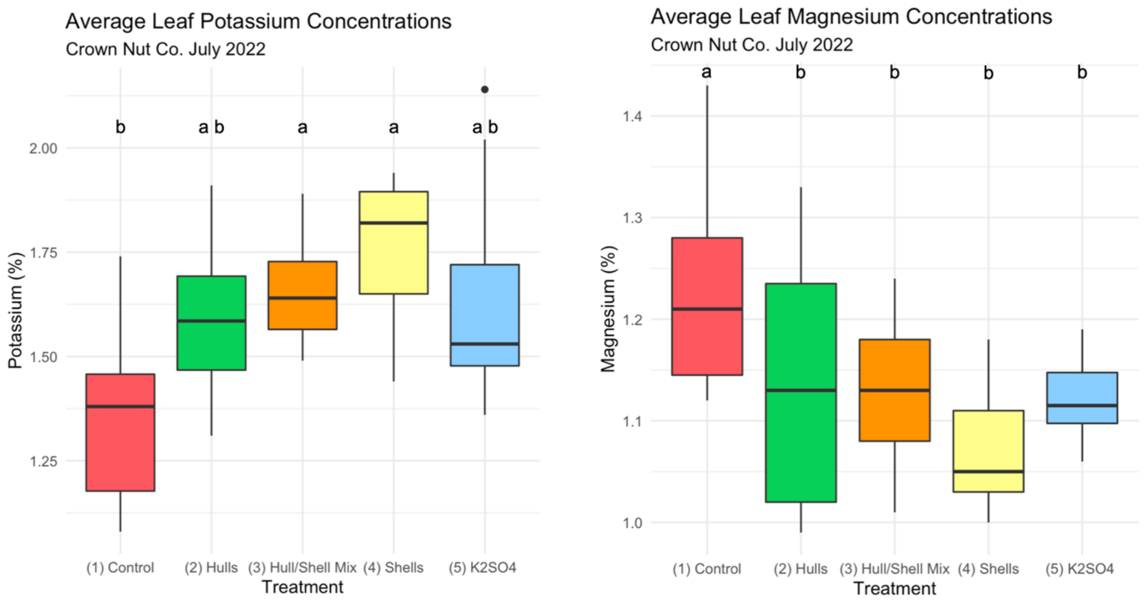
Table 2.4. After fall 2020 applications, final average percent net mass remaining in litter bags in 2021 at the last collection time point for each site. All values are dry weight.

| Treatment | C:N | Site | Time Length | Total Water Applied (inches) | Avg. % Net Mass Remaining |
|---|---|---|---|---|---|
| Hulls | 71:1 | Crown | 257 days | 26.7 | 38% |
| Hull/shell Mix | 65:1 | Crown | 257 days | 26.7 | 55% |
| Hull/shell Mix | 52:1 | Westwind | 365 days | 40.9 | 45% |
| Hull/shell Mix (predominantly shells) | 91:1 | Bullseye | 240 days | 19.9 | 68% |
| Shells | 70:1 | Crown | 257 days | 26.7 | 54% |
| Hull/shell-based Compost | 24:1 | Bullseye | 240 days | 19.9 | 75% |

### 2.7.7 July Leaf Nutrients

At Crown, in July 2020 no significant differences were found between treatments in leaf nutrients N, P, Ca, Mg, S, B, Zn, Mn, Fe, and Cu. However, the control trees showed significantly higher leaf K than trees amended with the mix and shells but was similar with the hull and $K_2SO_4$ treatments. All leaf nutrients under all treatments fell within or very close to the suggested adequate ranges for July almond leaf tissue samples (Supplementary Tables 2.25

and 2.26), indicating amendments did not cause toxicity or deficiency for any of the listed nutrients measured. No significant differences in N, P, or K were found in July 2021 leaf samples, although average percent K values were slightly higher in trees amended with hulls, mix, and shells, compared to the control and fertilizer treatments. No significant differences in boron concentrations were found in yield hulls collected at harvest in 2021, which ranged from approximately 79-86 ppm. In July 2022, leaf K concentration was significantly higher and Mg was significantly lower in hulls, mix, shells, and $K_2SO_4$ treatments compared to the control. This tradeoff between K and Mg suggests competitive nutrient uptake favoring K, however averages for both nutrients remained within sufficiency ranges in all treatments (Figures 2.10a and b). No significant differences were found in other nutrients in 2022 (Supplementary Table 2.26).


Average Leaf Potassium Concentrations
Crown Nut Co. July 2022

Average Leaf Magnesium Concentrations
Crown Nut Co. July 2022

Figure 2.10a and b. Average leaf potassium and magnesium concentrations for each treatment, July 2022, Crown. Letters indicate significant differences between treatments within each nutrient.

At Bullseye, on 7/13/2021 no statistically significant differences between treatments were found in leaf K, N, P, Ca, Mg, S, B, Zn, Mn, Fe, and Cu (Table 2.5). In both years, average leaf K in trees amended with shells and compost was slightly higher than leaf K in control trees, though not significant. Average leaf N in trees amended with shells was slightly lower compared to control and compost trees, though not significantly different. No significant differences were found in hull boron concentrations in 2021, which ranged from approximately 126-129 ppm. While compost-amended trees had slightly higher Fe status than shell-amended trees in 2022, all Fe levels were below the toxicity level established for almond trees. Na status was slightly lower in compost- and shell-amended trees, though not significant. The tradeoff between leaf K and Mg observed at the other two field sites was not observed at Bullseye, as K and Mg were both slightly higher in amended treatments compared to the control in both years.

Table 2.5. Average values for July leaf nutrients sampled on 7/13/2021 and 7/14/2022, Bullseye. Yield hull boron concentrations were 129.3 ppm, 125.9 ppm, and 125.7 ppm for the control, shells, and compost treatments, respectively, in 2021. No significant differences were found between treatments within each year for the given nutrients.

| Treatment | (%) | | | | | (ppm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| 2021 | | | | | | | | | | | | |
| Control | 2.25 | 0.12 | 2.05 | 4.24 | 0.89 | 1751 | 44.6 | 27.9 | 30.3 | 146 | 5.6 | -- |
| Shells | 2.17 | 0.12 | 2.16 | 4.20 | 0.89 | 1630 | 46.0 | 24.6 | 32.6 | 147 | 5.3 | -- |
| Compost | 2.26 | 0.12 | 2.19 | 4.19 | 0.90 | 1697 | 47.5 | 24.3 | 31.3 | 145 | 5.4 | -- |
| 2022 | | | | | | | | | | | | |
| Control | 1.94 | 0.12 | 2.75 | 4.30 | 0.86 | 1448 | 55.5 | 17.8 | 22.1 | 158 | 5.6 | 87.7 |
| Shells | 1.89 | 0.11 | 2.91 | 4.41 | 0.90 | 1385 | 56.2 | 15.4 | 24.2 | 143 | 5.3 | 71.3 |
| Compost | 1.91 | 0.12 | 2.90 | 4.42 | 0.90 | 1385 | 57.8 | 15.5 | 27.2 | 182 | 5.6 | 42.9 |

At Westwind, July 2021 leaf K was significantly higher and leaf Mg was significantly lower in the amended trees compared to control trees (Table 2.6). Average leaf N was the only macronutrient falling slightly below the recommended range but was similar between treatments. Mn, Fe, and Cu were similar in both treatments and fell slightly below the adequate ranges. No significant differences were found in hull boron concentrations in 2021, which ranged from approximately 206-220 ppm. In July 2022, leaf K concentration was higher in both amended treatments than unamended treatments, significantly greater than the control for the amended catch frame trees which had the highest average leaf K concentration. In both years, the increases in leaf K and decreases in Mg suggest some degree of competitive uptake between K and Mg, however average Mg and K levels in all treatments were within the respective recommended ranges. No significant differences found in other leaf nutrients in 2022.

Table 2.6. Average values for July leaf nutrients sampled on 7/15/2021 and 7/14/2022, Westwind. Letters indicate averages that are significantly different. Nutrients without letters were statistically similar among treatments for the given year. Hull boron concentrations from yield 2021 were 220.0 ppm and 205.8 ppm for the control and amended catch frame treatments, respectively. T1 is the control, T2 is the catch frame treatment, T3 is the amended treatment, and T4 is the amended treatment with off ground harvest.

| Treat-ment | (%) | | | | | (ppm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| 2021 | | | | | | | | | | | | |
| T1 | 1.98 | 0.11 | 1.59 b | 4.19 | 0.93 a | 1575 | 52.4 | 19.5 | 25.3 | 84.6 | 4.6 | -- |
| T4 | 1.98 | 0.11 | 1.74 a | 4.08 | 0.88 b | 1564 | 53.9 | 19.7 | 26.4 | 85.4 | 4.8 | -- |
| 2022 | | | | | | | | | | | | |
| T1 | 1.90 | 0.01 | 2.02 bc | 4.39 | 0.898 a | 1442 | 52.4 | 54.9 | 26.2 | 80.1 | 5.7 | 146 |
| T2 | 1.93 | 0.10 | 1.96 c | 4.45 | 0.895 ab | 1461 | 49.5 | 59.8 | 31.5 | 97.0 | 6.3 | 138 |
| T3 | 1.89 | 0.10 | 2.18 ab | 4.25 | 0.842 bc | 1455 | 52.2 | 71.7 | 28.1 | 88.7 | 6.1 | 169 |
| T4 | 1.90 | 0.11 | 2.22 a | 4.26 | 0.837 c | 1522 | 50.4 | 61.9 | 28.1 | 87.5 | 6.2 | 125 |

### 2.7.8 Trunk Circumferences and Yield

At all sites, no significant differences between treatments were found in trunk circumferences (Supplementary Figures 2.4-6), dry kernel yield, or crack out percentage (Supplementary Tables 2.27-29) in any year. However, at Bullseye fresh hull/shell-amended trees had slightly higher dry kernel yield in 2021 and 2022, followed by the control, and then compost. At Westwind in 2021 dry kernel yield and percent crack out were slightly higher in the amended off ground treatment compared to the control. At Crown in 2020, significantly greater percentages of leftover amendments were found in the yield trash of hull and mix treatments, but not in 2021. However, the grower/processor reported that the relatively small percentage of remaining hull/shell amendment trash in yield samples was negligible and did not cause any processing issues. Shell treatment trash contained lower percentages of leftover amendments likely due to the lower weight and smaller size of shells that filtered out during mechanical pickup. Total dry trash found in control yield samples was similar with all amended treatments at Crown in both years. At Bullseye, yield samples from shell- and compost-amended rows contained significantly higher percent amendment trash than the control treatment. However, all amendment trash weight was low both years at Bullseye ranging from 5-11% of all trash weight, and total trash percentages were statistically similar. In 2021 and 2022, yield samples from off ground treatments at Westwind had significantly lower total trash than on ground harvest treatments.

## 2.8 Discussion

### Amendment Nutrient Content Over Time and K Release Model

Hulls and hull/shell mixes contained the highest initial K concentrations (Table 2.7). The composted hull/shell mix had the lowest C:N ratio and highest concentrations of N, P, Ca, Mg, S, Zn, Mn, Fe, Cu, and Na because manure added nutrients and the composting process reduced dry mass over approximately 9 months prior to application in the orchard. Generally, almond shells had lower initial K concentration than hulls. Hull/shell mix K concentration was influenced by the proportion of hulls and shells. For instance, the 2020 hull/shell mix at Bullseye had a higher percentage of shells and lower K concentration than the 2021 mix. Similarly, at Westwind the 2020 hull/shell mix contained more shells and lower K concentration, while the 2021 hull/shell mix had higher hulls and K concentration. Hull/shell mixes with high percent hulls will likely have higher K concentration, which could influence grower decisions about application rates for K supply.

Table 2.7. Average nutrient concentrations in hull, hull/shell mix, shell, and mix-based compost materials applied at all field trials, all years (n=69 for all nutrients, except n=28 for Na).

| Treatment |  | (%) |  |  |  |  |  | (ppm) |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | C:N | C | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| Hulls | 63:1 | 39.8 | 0.63 | 0.09 | 2.4 | 0.2 | 0.11 | 286 | 121 | 5 | 12 | 204 | 3 | 153 |
| Mix | 55:1 | 41.8 | 0.79 | 0.08 | 2.4 | 0.2 | 0.10 | 314 | 100 | 8 | 15 | 350 | 3 | 155 |
| Shells | 76:1 | 41.3 | 0.57 | 0.05 | 1.5 | 0.2 | 0.08 | 248 | 58 | 6 | 18 | 477 | 3 | 122 |
| Compost | 29:1 | 27.2 | 0.96 | 0.18 | 1.4 | 0.8 | 0.92 | 1476 | 87 | 88 | 385 | 19357 | 31 | 1628 |

Different water and fertilizer management practices at orchards of origin impact nutrient concentrations in almond hulls and shells. Since processors aggregate hull/shell materials from many different orchards, achieving consistent and precise annual K application rates through amendments was challenging. If a high degree of precision is needed, stockpiled materials could be analyzed for K concentration prior to application. This could help growers and researchers tailor amendment application rates toward target K rates. Otherwise, samples of applied materials can provide information about nutrient application rates in hindsight.

The rate and total amount of K solubilized from plant material is influenced by the quantity and frequency of applied water, both irrigation and rainfall (Andrews et al. 2021). At all sites, K solubilization from hulls, mix, shells, and mix-based compost generally followed the well-established trend of rapid initial K release followed by a more gradual release stage or plateau (Andrews et al. 2021). The model developed utilizing Crown data illustrates this trend. This dramatic initial water-driven K release pattern has been observed in many prior residue studies (Dong et al. 2019, Tagliavini et al. 2007, Li et al. 2014, Rodriguez-Lizana et al. 2010). However, later stages of decomposition likely lead to the breakdown of complex plant structural components such as cellulose, hemicellulose, and lignin which may enable more complete K release after the initial water-driven stage (Rosolem et al. 2005, Cobo et al. 2002). These field trials align with evidence in the literature that the rapid initial water-driven K solubilization phase is not initially limited by C:N ratio or decomposition rate, while the small remaining fraction of residue K is released more gradually over time.

At Crown, applying amendments in the fall prior to winter rains rather than mid-winter enabled higher total K solubilization from all types of amendments into the soil with increased rainfall and therefore total water (Table 2.8). These field trials show that approximately 0.13 hectare meters (13 acre-inches) of cumulative water can lead to approximately 71% of total K release, while as much as 98% of total K can be released under approximately 42 hectare meters (41 acre-inches) of water when the amendment layer is maintained with catch frame harvest for a year. These findings align with prior studies showing that high K release rates from tree crop residues can occur under water application, such as 90% K solubilized from coffee residues (Zoca et al. 2014) and 92% total K from cacao husks (Hougni et al. 2021).

Table 2.8. Litter bag amendment K and soil XK data from all sites. Soil XK data shows the shortest length of time to increase soil XK and corresponding water applied. Initial and final litter bag data shows total K released between initial and final sampling dates and corresponding water applied. The Crown field trial was on clay soil, the Bullseye field trial was on silty clay loam soil, and the Westwind field trial was on loam soil. Crown and Bullseye were drip irrigated whereas Westwind was micro sprinkler irrigated. Water applied is listed first as hectare meters with acre-inches in parentheses.

| | | **Soil XK Data** | | **Litter Bag Data** | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Site** | **Shortest Time to Increase Soil XK** | **Water Applied, ha m (ac-in)** | **Total Days (Initial & Final Dates)** | **% Total K Released** | **Water Applied, ha m (ac-in)** |
| Hulls | Crown | 46 days | 0.013<br>(1.25) | 133 days<br>(2/10/20 – 6/22/20) | 72.4% | 0.131<br>(12.7) |
| Hulls | Crown | -- | -- | 226 days<br>(11/12/20 - 6/26/21) | 87.2% | 0.274<br>(26.7) |
| Hull/shell Mix | Crown | 46 days | 0.013<br>(1.25) | 133 days<br>(2/10/20 – 6/22/20) | 80.2% | 0.131<br>(12.7) |
| Hull/shell Mix | Crown | -- | -- | 226 days<br>(11/12/20 - 6/26/21) | 81.0% | 0.274<br>(26.7) |
| Hull/shell Mix | Bullseye | 41 days | 0.005<br>(0.47) | 240 days<br>(10/14/20 – 6/11/21) | 85.3% | 0.204<br>(19.8) |
| Hull/shell Mix | Westwind | 16 days | 0.021<br>(2.00) | 365 days<br>(10/7/20 – 10/7/21) | 97.6% | 0.420<br>(40.9) |
| Shells | Crown | 46 days | 0.013<br>(1.25) | 133 days<br>(2/10/20 – 6/22/20) | 71.3% | 0.131<br>(12.7) |
| Shells | Crown | -- | -- | 226 days<br>(11/12/20 - 6/26/21) | 78.2% | 0.274<br>(26.7) |
| Mix-based Compost | Bullseye | 41 days | 0.005<br>(0.47) | 240 days<br>(10/14/20 – 6/11/21) | 80.8% | 0.204<br>(19.8) |

However, alternate models for residue K release dynamics may be needed for orchards where additional K is applied through fertigation and other amendments added to almond hulls/shells. Plant residues have been shown to adsorb K during decomposition processes and re-release stored K later in the season; nutshells such as almond and pecan have high lignin content and functional groups that favor cation adsorption (Andrews et al. 2021). This likely explains fluctuations in hull/shell K concentration at Westwind following K fertilizer and compost additions. This suggests the hull/shell amendment can retain K applied through compost and fertigation for short periods of time before releasing the K into the soil solution within the same season. However, this capacity to retain K in the amendment layer for more gradual re-release did not last beyond 5 months after application (approximately 0.72 hectare meters or 7 acre-inches of total water), despite further K fertilizer application during the spring and summer. Further research is needed to more fully characterize the capacity of almond hulls and shells to retain and re-release K applied to amendments and under different types of irrigation.

Throughout their residence on the soil surface, amendment C concentrations tended to remain consistent or increase slightly over time while N concentrations in fresh hull/shell materials often significantly increased. As dry mass declined due to composition, this led to significant reductions in C:N ratios in fresh hull/shell amendments occurring within 2-5 months, and final C:N ratios approximately one third to half of initial C:N ratios at application after 8-10 months. C:N ratios of fresh hulls and mix appeared to decline more than shell C:N ratios (Supplementary Tables 2.7, 2.8. 2.11, 2.13). Meanwhile, compost C, N, and C:N ratios of initial and final values remained similar at Bullseye. At Westwind, after one year hull/shell C concentration was statistically similar with initial C while N concentration had doubled; net dry mass remaining and C:N were both reduced by approximately half. These consistent decreases in C:N ratio in fresh hull/shell amendments corresponding with increased N concentrations as net dry mass steadily declined indicate active decomposition processes were at work in the amendment layer within the year after application. As hulls are rich in sugars, the hull and mix amendments provide a carbon-rich substrate conducive to biotic activity and microbial growth (Aguilar et al. 1984, Prgomet et al. 2017). This may help explain the greater reduction in C:N in hull and mix materials compared to shells alone. Total annual fertilizer N applications ranging from 212-240 kg ha$^{-1}$ (189-214 lb ac$^{-1}$) likely explain the relatively stable N levels in the amendment layer on the soil surface over time (Supplementary Table 2.9), which likely promote microbial growth. However, at all sites tree July leaf N remained similar between treatments, suggesting no effects of potential microbial N immobilization on tree N status.

While K solubilized quickly with water application, many other nutrients remained in the hull/shell materials for longer periods of time. As net dry mass decreased via decomposition, many lingering nutrients increased in concentration. Across all sites in all hull/shell materials, Ca, Na, S, and Fe concentrations significantly increased over time. Final Na concentrations ranged from 9-39 times higher than initial Na concentrations for fresh hull/shell amendments (Supplementary Tables 2.8, 2.11, and 2.13). In addition, Cu and Mn significantly increased in all fresh hull/shell materials (excluding compost). At Bullseye, P concentration significantly decreased in compost but increased slightly in shells. Depending on material and site, some materials significantly increased in concentrations of P, Mg, Zn, B, Ni, and Al.

Many of these nutrients tend to be less mobile in plant cells than K ions and may remain relatively more bound in decomposing residues. In addition, almond nutshells contain high lignin content and carboxylic and phenolic functional groups which can promote cation adsorption (Balentic et al. 2018, Hernandez-Montoya et al. 2011, Fernandez-Bayo et al. 2020). The hull/shell layer may adsorb/absorb elements applied through fertilizer, compost, irrigation water (e.g., Na and B), or that are already present on the soil surface. High final Na amendment concentrations could be attributed to a combination of these factors. Sodium and other salts are known to accumulate on almond orchard soil surfaces in this dry climate particularly in drip irrigated orchards; some California almond orchards have experienced salinity increases in recent years due to increasingly low water availability (Sanden et al. 2014). Together, net dry mass loss, internal plant cell nutrient retention, negatively charged sites on decomposing residues, and nutrient additions may help explain the gradual increases in amendment concentrations that appear to favor cations. Further studies are needed to evaluate release rates and adsorption/desorption trends of plant-essential nutrients, particularly Na, during hull/shell decomposition under different irrigation approaches in the field environment.

### Changes in Soil XK, Cations, and Fertility

At all sites, soil XK in the upper 0-10 cm soil significantly increased under all amendments within approximately the first 2-7 weeks (0.005-0.02 hectare meters, or 0.5-2 inches of water) across different soil types and irrigation systems (Table 2.8). After the first amendment application, average soil XK in the upper 0-10 cm remained higher under all types of hull/shell amendments compared to control soils through the following fall, which was statistically significant in some cases but not others. In general, K moves relatively slowly through the soil profile—unless in sandy soil or under excessive water applications—and likely remained within the root zone in these soil types. Almond tree K demand increases throughout the spring and summer during kernel fill, fruit enlargement, and hull split (Muhammad et al. 2020). This plant K demand is likely reflected in the declining soil XK values in all treatments the spring prior to substantial K fertigation. Soil XK levels at all sites in the top 0-20 cm soil were above the sufficiency range for almond orchards (Supplementary Table 2.14).

Soil samples taken during the winter and spring following amendment application suggest that K from amendments may outcompete other cations for soil exchange sites in some cases, although the resulting effects on plant nutrient status are variable. At Bullseye, shell amended soil showed signs of high soil XK displacing XMg at the 0-20 cm depth during the winter, suggesting some degree of preferential adsorption of K over Mg likely occurred. However, Bullseye July leaf Mg levels were slightly higher in the two amended treatments both years, indicating that any preferential soil K adsorption did not impact tree Mg status at this site. Meanwhile at Westwind, soil XMg was slightly higher under the amended treatment than the control in the winter but significantly lower in late July, which corresponded with significantly lower amended tree July leaf Mg levels. In March 2021 at 0-20 cm depth, the mix-amended soil had lower average XNa and higher XK suggesting high K inputs likely displaced Na, although no differences were found in leaf Na values. In addition, at Bullseye the compost amendment appears to have raised soil XCa in the upper 0-10 cm in January 2021 likely due to high Ca inputs through compost (Table 2.2, Supplementary Table 2.17). These results indicate that K inputs from hull/shell materials may displace other soil cations, however the timing of this dynamic and associated effects on plant nutrient status is variable.

The impacts of elevated soil XK levels under hull/shell amendments on other more mobile soil cations and associated plant nutrient uptake appear variable across sites. High soil K availability is known to lead to decreases in plant Mg uptake, often referred to as nutrient antagonism or competition (Gransee et al. 2013). In soil, Mg tends to be more mobile and less strongly bound to CEC due to its larger hydrated radius compared to K, while high K supply can block non-selective Mg transporters in the plant (Gransee et al. 2013, Garcia et al. 2022, Xie et al. 2021). The degree to which this antagonism impacts plant Mg nutrient status appears to be variable and likely depends on many factors such as soil chemical properties and tree nutrient uptake timing. For instance, at Westwind the reduction in soil XMg appears between March and late July which corresponds with significantly lower July leaf Mg values under hull/shell amendments, while the reduction in winter XMg under shells at Bullseye did not influence July leaf Mg status. Future studies could evaluate this K-Mg competition under hull/shell amendments in the soil and the plant more closely throughout periods of nutrient uptake. This potential for antagonism be evaluated across a variety of different soil types to better understand when and to what degree this phenomenon can impact plant K and Mg status. In addition, these trials present evidence that increased soil XK could displace soil XNa as well, suggesting effects of hull/shell amendments on soil salinity could be a meaningful area for future study particularly in arid climates.

Annual fall soil samples were taken prior to amendment applications to assess changes in soil fertility. At all sites in fall 2021, in the upper 0-10 cm soil XK was significantly higher under many fresh hull/shell materials compared to control soils. Soil XK across 10-20 and 20-30 cm depths was variable at different sites. For instance, compared to their respective control soils, mix amended soil had the highest XK at 20-30 cm at Crown, no significant differences were found at 10-30 cm at Bullseye, and at Westwind amended catch frame soil had high soil XK at 10-30 cm. Maintaining hull/shell amendments with catch frame harvest led to slightly higher soil XK than amendments displaced by on-ground harvest across the top 0-30cm soil in this orchard. Amendment treatments shifted soil cations in fall 2021 to varying degrees. At Crown, soil XCa was significantly higher under shells and lower under mix at 10-20 cm depth, and soil XNa was lowest at 20-30 cm under mix. At Bullseye, XNa was significantly higher under the control than both shells and compost amended soils. No other soil fertility response variables were different between treatments within sites. These reductions in soil XNa could be attributed to preferential adsorption of K on exchange sites displacing Na cations. Several minor shifts in fall 2021 soil fertility are worth noting, though not statistically significantly different. Soil pH was approximately 0.1-0.3 more neutral under Crown and Bullseye amendments. Fall 2021 average nitrate-N, Olsen P, XK were slightly higher in both amended soils at Bullseye. At Westwind, average nitrate-N and CEC were slightly higher in both amended soils. While soil XK levels were significantly increased within the first year, long-term field trials are needed to assess potential shifts in other soil fertility variables.

### Decomposition Rates

Mesh litter bags provided more accurate and less variable estimates of hull and shell amendment mass than litter rings by eliminating the movement of hulls/shells and other organic orchard materials into and out of the sampling area. Litter bag data indicated that hull/shell amendment decomposition generally followed the expected relatively steady linear decline in net mass remaining during the first year after amendment application. The Westwind mix decomposed linearly by approximately half of its initial dry mass after one year and approximately 41 inches of water.

While high plant residue C:N ratios tend to be linked with slower decomposition over time (Dong et al. 2019, Li et al. 2014), additional hull/shell characteristics may be useful to consider at Crown and Bullseye. For instance, Crown amendments applied Fall 2020 had relatively similar initial C:N ratios between 65:1 and 71:1, yet total decomposition was significantly higher for hulls than the mix and shells. Almond hulls contain bioactive compounds and notably high sugar content, approximately 18-30% soluble sugars by dry weight (Prgomet et al. 2017, Aguilar et al. 1984, Esfahlan et al. 2010). This suggests hulls could support robust microbial life which may explain the observed higher decomposition.

The composting process likely impacts decomposition in the field as well. At Bullseye, the lower initial C:N ratio of the hull/shell/manure compost did not lead to higher net decomposition than high initial C:N ratio the fresh hull/shell mix. Composted materials had already undergone substantial microbial transformations during the composting process prior to application, leaving more recalcitrant materials to be applied in the field. In contrast, the fresh hull/shell mix began the decomposition process in the field and likely contained more simple C compounds that were readily accessible by decomposers at the time of application onward. Further studies are needed to understand microbial activity, growth, and community composition in the hull/shell amendment layer on the soil surface, how this relates to decomposition, and potential impacts on soil microbial communities beneath the amendment layer.

### Leaf Nutrients

These field trials indicate hull/shell amendments can increase almond July leaf K status slightly or significantly within the first 1-3 years. Westwind July leaf K was significantly higher in the hull/shell amended trees compared to control trees within the first and second years. At Crown and Bullseye in July 2021, leaf K was slightly higher in hull/shell amended trees compared to control trees, though not significant. Three years were required before significant increases in July leaf K status were found at Crown in trees amended with mix and shells compared to the control. The temporary higher leaf K status in control trees at Crown in the first year only (2020) may be attributed to tree K dilution effects under other treatments, though tree growth was not measured in the present study.

The degree to which hull/shell amendments may increase July leaf K is likely influenced by site-specific factors such as current plant K status, amendment rate, soil type, and irrigation and fertilizer management practices. At Crown and Bullseye in 2021, leaf K values for all treatments fell above the recommended K sufficiency range and soil XK levels were already relatively high. Thus, increases in soil XK under amendments at these two sites did not significantly affect July tree leaf values in 2021. However, at Westwind initial overall soil XK was slightly lower, micro sprinkler irrigation was used instead of drip, the soil had lower CEC and concentrations of other cations compared to the other two sites, and leaf K status was generally lower. This "room for improvement" in July leaf K, along with site factors and high application rate at Westwind, could help explain the significantly higher leaf K under amendments within only one year.

In previous studies, increased tree leaf K levels have been observed under high nutshell amendment application rates or with young seedlings in potting media. For instance, increased foliar K was found in macadamia trees after approximately 200 tons ha$^{-1}$ (100 tons ac$^{-1}$) composted macadamia husk rate of macadamia husk mulch (length of time not specified) (Nagao 1992). Coffee husk amendments that were blended and sieved to 1mm powder and incorporated at three rates into nursery soil substrate significantly increased cashew seedling leaf K after 20 weeks (Nduka et al. 2015). Cashew seedlings grown in soil substrates with incorporated cacao husk amendments increased seedling leaf K after 16 weeks and were proposed as a replacement for inorganic K fertilizer (Agele and Agbona 2008). However, few prior studies have investigated how nutshell amendments affect mature tree leaf K in orchards.

Considering other nutrient leaf status dynamics, a tradeoff between increased leaf K and reduced leaf Mg occurred under hull/shell amendments at Crown and Westwind, but not at Bullseye. However, K and Mg fell within sufficiency ranges at all sites, so this inverse relationship did not lead to Mg deficiencies. Since competitive uptake has been shown to occur between K and Mg when K is supplied at excessive rates, long term cation balance in the soil and leaf tissue analysis can help growers monitor this antagonism and prevent Mg deficiency under hull/shell amendments (Xie et al. 2021). Leaf N status remained statistically similar between treatments at all sites in all years, indicating any potential soil N immobilization had no effects on tree N status. California almond growers typically apply at least approximately 247 kg ha$^{-1}$ (220 lb ac$^{-1}$) N fertilizer annually in mature orchards (Sumner et al. 2019). This likely promoted the maintenance of leaf N levels under high C:N ratio hull/shell amendments. Amendment treatments did not lead to significant differences in leaf nutrient values at any site for N, P, K, Ca, Mg, Mn, Fe, Cu, or hull B. Future research could investigate long-term shifts in leaf nutrient status, particularly the competitive relationship between K and Mg, as well as N status to monitor for any potential effects of N immobilization in different orchard contexts.

### Yield and Trunk Circumferences

No significant differences in were found dry kernel yield or crack out percentage between the treatments at any of the field sites. However, the shell-amended trees had slightly higher average dry kernel yield both years at Bullseye, and average dry kernel yield and crack out percentage were slightly higher for amended off ground trees in 2021 at Westwind. In 2022, a severe frost in late February likely contributed to unusually low yields relative to the expected average yield of a typical mature almond orchard in this region (Sumner et al. 2019). While the hull/shell amendment materials were occasionally found in trash at harvest, overall hull/shell amendment trash in yield sample trash was low as the small size and light weight of these materials allows them to largely filter out of yield samples during mechanical pick up. Leftover amendments were more likely to be found in hull and mix treatments than shells due to the smaller size and lower weight of shells. None of the differences in hull/shell amendment trash in yield samples led to significant differences in total trash between any treatments at any sites in all years. However, off-ground harvest produced cleaner yield at Westwind in 2022. Using the catch frame harvester kept total dry trash in yield samples down to approximately 1-2% of dry yield weight, compared to 8-15% trash in on-ground treatments in 2022.

Harvest at Westwind in 2021 illustrated the necessity of properly adjusting catch frame equipment to work effectively with almond tree specifications. The catch frame harvest equipment caused trunk damage and dropped around 20% of the crop onto the amendment layer in 2021, which had to be removed by hand and relocated to the center of the alley. However, in 2022, different catch frame equipment was adjusted by engineers to almond orchard specifications and experienced equipment operators completed catch frame harvest without trunk damage or dropping crop in the tree row. Catch frame equipment adjustments to orchard specifications is a critical consideration for growers and researchers using catch frame equipment in California almond orchards. Appropriate equipment adjustments and effective machinery operation provide evidence that off ground harvest can be a viable option in almond orchards.

The three field trials occurred at relatively high-input, intensive commercial almond orchards where initial leaf K values were sufficient before trial establishment. No significant differences were found in trunk circumferences between treatments at all sites in any years, indicating the amendments did not affect this metric of tree growth. Yield effects would be more likely to occur in orchard environments where yield is limited by factors that hull/shell amendments can improve. Prior studies across different crop systems that found yields increased under nutshell amendments most often attributed yield effects to increased soil water content and uptake of K and other nutrients (Andrews et al. 2021). For instance, Jafari et al. 2012 found that almond shell mulch led to higher yields and quality fruit in a rainfed water-limited fig orchard. A trial in avocado found yield was maintained and occasionally increased under almond shell mulch which created a beneficial environment for root functioning (Lopez et al. 2014). Macadamia husk mulch was found to increase macadamia yield and foliar K levels (Nagao et al. 1992. Lobel et al. 1994), and cacao husk amendments have been shown to increase cacao seedling growth (Oyewole et al. 2012) and cashew seedling leaf K (Samuel and Agbona 2008). However, these effects of nutshell residues on leaf nutrients, growth parameters, and yield may be most apparent in seedlings and low-input systems.

Future research could evaluate effects of hull/shell amendments in K-deficient almond orchards where yield is likely to be limited by low K levels.

### Implications

Hull/shell K recycling could be particularly meaningful for growers who wish to correct K deficiencies and reduce reliance on external fertilizer inputs. Growers could use these findings to supplement or substitute a portion of inorganic K fertilizer with K supplied from hull/shell amendments to reduce fertilizer costs. Applying amendments in the Fall prior to winter rains promotes high total K release and decomposition prior to the following harvest. Practically speaking, monitoring soil XK and leaf K levels would provide useful information to guide annual application rates. Once increases in soil XK and leaf K are observed, the hull/shell application rate could be adjusted to maintain sufficient soil and plant K levels while avoiding Mg deficiencies. In orchards with K deficiencies, hull/shell application rate could be designed to help correct low soil available K levels and bring plant K status into a safe range for plant function and productivity. This practice could be impactful in low-input systems, where fertilizer is expensive, or where agricultural soil has been depleted of potassium over time.

Considering relatively high K fertilizer expenses for California almond systems, almond hull/shell amendments could help retain and reuse crop K in the orchard, maintain sufficient soil XK and plant K levels, and reduce fertilizer K costs for growers. If soil XK is between 100-150 ppm in almond orchards, applying approximately 112 kg ha$^{-1}$ (100 lb ac$^{-1}$) K can satisfy almond crop K demand (Muhammad et al. 2018). It is recommended that almond growers in the Sacramento Valley use around 493 kg $ha^{-1}$ (440 lb $ac^{-1}$) $K_2SO_4$ annually for mature orchards which cost approximately \$439 $ac^{-1}$ USD in material and operating costs in 2019 (Sumner et al. 2019). However, from 2019 to 2022 the bulk commodity traded price of potash has approximately quadrupled (The World bank, 2022). These high K fertilizer costs could be substantially reduced by retaining hull/shell K in the orchard system as organic matter amendments rather than exporting it at harvest.

This practice offers one strategy to assist the almond industry in working toward the established 2025 goal of zero waste (Almond Board of California, 2019). As demonstrated by Crown Nut Company, applying almond hulls and shells as organic matter amendments benefits almond processors by providing a convenient, sustainable outlet to relocate crop residue biomass promptly out of processing facilities and recycle them in nearby orchards. Minimizing hull/shell biomass at processing facilities would create space for incoming materials and could help reduce risk of hull/shell fires (Coalinga almond hull fire, Tracy almond hull fire, Fresno almond hull fire). Using hulls and shells as organic matter amendments could be compatible with other almond biomass recycling management strategies in orchards that provide nutrient cycling benefits, such as whole orchard recycling (Jahanzad et al. 2020, Jahanzad et al. 2022).

Further research is needed to assess the effects of integrating hull/shell amendments with other ecosystem-oriented nutrient management practices that can help match nutrient supply with crop demand. Hull/shell amendments could have the potential to complement the benefits provided by sustainable orchard nutrient and water management practices. For instance, growing evidence supports the use of cover cropping, reduced soil disturbances, and livestock integration (Fenster et al. 2021, Soto et al. 2021, Martinez-Mena et al. 2020) as well as sustainable water management practices such as strategic deficit irrigation (SDI) and regulated deficit irrigation (RDI) (Doll and Shackel 2015, Smith et al. 2022, Lipan et al. 2019). While most California almond orchards utilize on-ground harvest equipment, switching to off-ground harvest could preserve the layer of hulls and shells on the soil surface, enable more complete K solubilization, and build an organic layer on the orchard soil over time. This organic layer can be managed to optimize benefits provided by leaf litterfall biomass, hull/shell materials, shredded pruning biomass, cover crop residue, compost, or other regionally available mulch materials. Minimizing orchard soil disturbance can promote an organic layer on the soil surface in orchard systems which can enhance nutrient cycling and availability (Andrews et al. 2021).

## 2.9 Conclusion

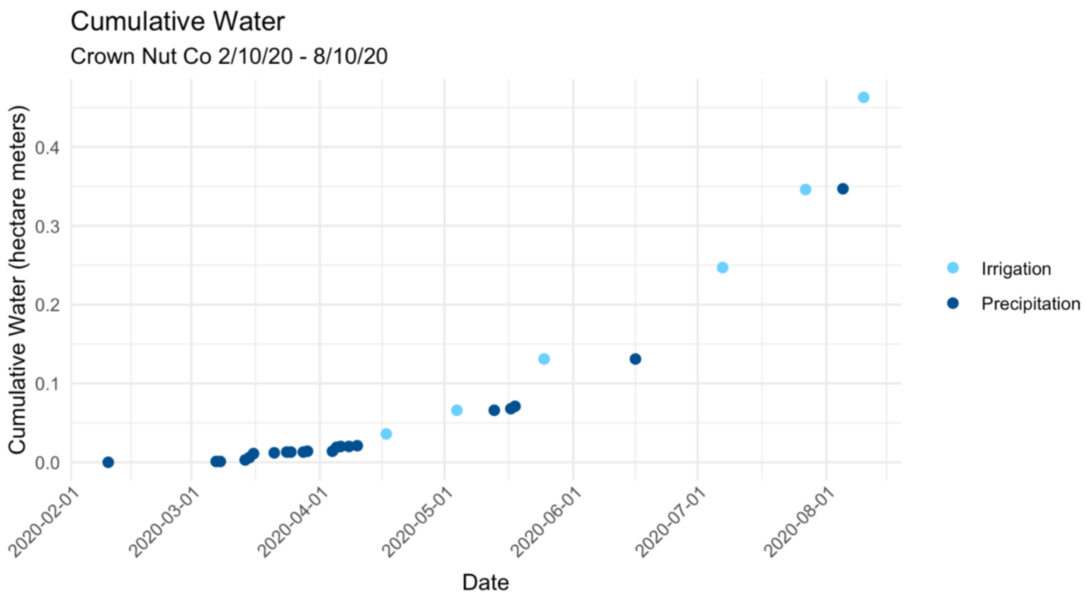
These field trials provide strong evidence that almond hulls and shells are viable materials for use as K-rich organic matter amendments applied on orchard soils. Almond hulls and shells readily solubilize K under water application, increase soil exchangeable K levels, and increase tree leaf K status to varying degrees within the first 1-3 years. Growers can use findings to tailor amendment application rates based on the target leaf K or soil XK level, or to replace the amount of K exported at harvest in fruit. High K inputs through hull/shell amendments may occasionally displace soil cations such as Na and Mg, though the degree to which this may reduce tree Mg status likely depends on application rate and site characteristics (no tree Mg deficiencies were found in these trials). Hull/shell materials that are composted with manure prior to application may have higher Ca and Fe concentrations. Any potential N immobilization that may have occurred under these high C:N ratio amendments did not significantly impact tree N status at any sites. Decomposition rates of fresh hull/shell amendments were relatively linear and total decomposition was higher for hulls than shells. Total K released and total decomposition can be maximized by using off ground harvest rather than on ground harvest. Off ground harvest significantly reduced total trash in yield samples, producing cleaner yield. Only slight and variable increases in yield under hull/shell amendments were found in these trials. Further studies are needed to determine whether meaningful yield improvements may occur in K-deficient orchards. Long-term trials are needed to examine effects of hull and shell amendments on tree nutrient status, water management, tree physiology, microbial responses, soil fertility and physical structure. Findings from field trials across many different soil types, orchard systems, and nutrient/irrigation management approaches would help inform grower management recommendations.

## 2.10 Supplementary Materials

Figures and Tables

Supplementary Table 2.1. Soil type descriptions for each field trial, NRCS Soil Web database.

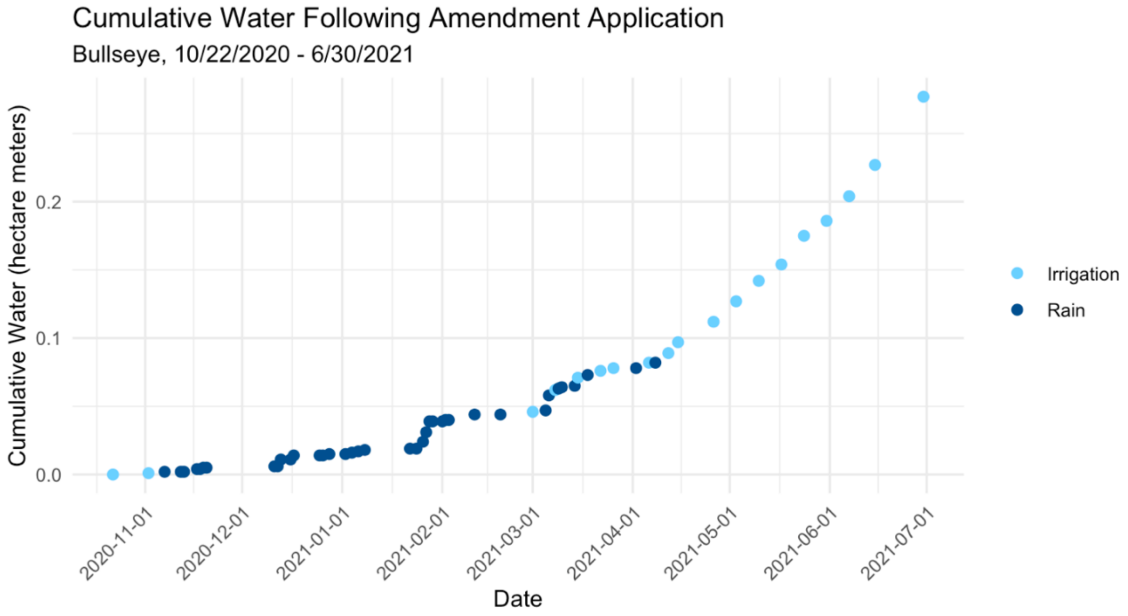
| Field Site | Location | Soil Type | Soil Data Explorer Map | Soil Series Description |
|---|---|---|---|---|
| Crown Nut Co. | Near Tracy, CA | Capay Clay | https://casoilresource.lawr.ucdavis.edu/see/#capay | https://soilseries.sc.egov.usda.gov/OSD_Docs/C/CAPAY.html |
| Bullseye | Near Woodland, CA | Sycamore Silty Clay Loam | https://casoilresource.lawr.ucdavis.edu/see/#sycamore | https://soilseries.sc.egov.usda.gov/OSD_Docs/S/SYCAMORE.html |
| Westwind | Near Woodland, CA | San Ysidro Loam | https://casoilresource.lawr.ucdavis.edu/see/#san%20ysidro | https://soilseries.sc.egov.usda.gov/OSD_Docs/S/SAN_YSIDRO.html |



Supplementary Figure 2.1. Cumulative irrigation and rainfall from amendment application (2/10/2020) until harvest (8/10/2020) at Crown. Each point represents a water event that added to cumulative total water. March rainfall and April irrigation coincided with increases in soil XK. Precipitation data are sourced from the CIMIS database (Station 249, approximately 10 miles from field site), and irrigation is based on water meter readings at the pump station in the orchard. Total water (irrigation and rainfall) was 0.46 hectare meters (45.0 inches). One acre inch of water is equivalent to 0.0103 hectare meters.

Supplementary Table 2.1. Annual fertilizer and water applications at Bullseye, 2021 (entire year) and 2022 (until 9/21/2022).

| Year | Total Annual Fertilizer/Amendments and Irrigation Water |
|---|---|
| 2021 | 224 kg ha$^{-1}$ (200 lb ac$^{-1}$) K |
| | 286 kg ha$^{-1}$ (255 lb ac$^{-1}$ ) N |
| | 45 kg ha$^{-1}$ (40 lb ac$^{-1}$ ) P |
| | 55 kg ha$^{-1}$ (49.2 lb ac$^{-1}$ ) Ca |
| | 0.35 hectare meters (34.1 acre-inches) irrigation water |
| 2022 | 126 kg ha$^{-1}$ (112 lb ac$^{-1}$ ) K |
| | 155 kg ha$^{-1}$ (138 lb ac$^{-1}$ ) N |
| | 45 kg ha$^{-1}$ (40 lb ac$^{-1}$ ) P |
| | 52 kg ha$^{-1}$ (46.6 lb ac$^{-1}$ ) Ca |
| | 0.29 hectare meters (28.6 acre-inches) irrigation water |

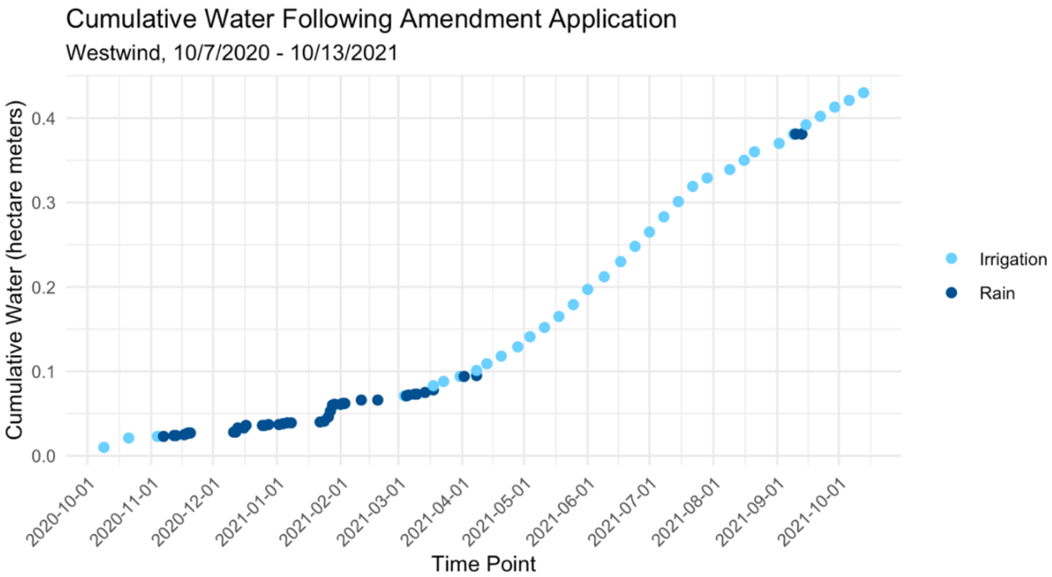


Supplementary Figure 2.2. Cumulative irrigation and rainfall at Bullseye from amendment application in fall 2020 until late June 2021.

Supplementary Table 2.3. Annual fertilizer and compost applications at Westwind, 2020-22.

| Year | Fertilizer/Amendments |
|---|---|
| 2020 | 202 kg ha$^{-1}$ (180 lb ac$^{-1}$) K applied as $KNO_3$ and ammonium split over 15 events |
| | 235 kg ha$^{-1}$ (201 lb ac$^{-1}$ ) N thru irrigation as $KNO_3$ split over 14 events |

| | |
|---|---|
| | 4483 kg ha$^{-1}$ (2 tons ac$^{-1}$ ) compost across the entire orchard on 11/11/2020, approximately one month after hull/shell amendment application |
| 2021 | 177 kg ha$^{-1}$ (158 lb ac$^{-1}$ ) K split over 9 events |
| | 240 kg ha$^{-1}$ (214 lb ac$^{-1}$ ) N split over 13 events |
| | 55 kg ha$^{-1}$ (49 lb ac$^{-1}$ ) Ca split over 5 application events |
| | 4483 kg ha$^{-1}$ (2 tons ac$^{-1}$ ) compost across the entire orchard on 10/8/2021, 4 days after hull/shell amendment application |
| 2022 (until mid-August) | 91 kg ha$^{-1}$ (81 lb ac$^{-1}$) K applied as SOP split over 3 events |
| | 114 (102 lb ac$^{-1}$ )N applied as urea split over 6 events |
| | 29 (26 lb ac$^{-1}$) P |
| | 67 (60 lb ac$^{-1}$) Ca applied via gypsum over 4 events |



Supplementary Figure 2.3. Cumulative irrigation and rainfall applied to amendments following application in October 2020, Westwind.

Supplementary Table 2.4a and 1b. Initial average amendment nutrient concentrations sampled in March 2019 at Crown Nut Co. Means ± standard error (n=3 hulls, n=6 mix, n=6 shells).

| March 2019 | (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| Materials | C | N | C:N | P | K | Ca | Mg |
| Hulls | 35.0 ± 0.3 | 0.622 ± 0.02 | 56:1 ± 1.8 | 0.076 ± 0.01 | 2.54 ± 0.08 | 0.23 ± 0.01 | 0.12 ± 0.007 |
| Mix | 35.8 ± 0.5 | 0.629 ± 0.02 | 57:1 ± 2.0 | 0.064 ± 0.004 | 2.52 ± 0.09 | 0.24 ± 0.01 | 0.11 ± 0.005 |
| Shells | 40.2 ± 0.4 | 0.536 ± 0.04 | 77:1 ± 5.8 | 0.035 ± 0.001 | 1.30 ± 0.07 | 0.27 ± 0.01 | 0.06 ± 0.003 |

| | (ppm) |
|---|---|

| March 2019 Materials | S | B | Zn | Mn | Fe | Cu | Na | Cl | Na |
|---|---|---|---|---|---|---|---|---|---|
| Hulls | 273 ± 11.0 | 108 ± 9.8 | 7.0 ± 0.6 | 16 ± 3.5 | 377 ± 141 | 2.4 ± 0.4 | 153 ± 23 | 52 ± 10 | 153 ± 13 |
| Mix | 275 ± 10.7 | 109 ± 8.0 | 5.9 ± 0.5 | 16 ± 2.5 | 322 ± 90 | 2.5 ± 0.2 | 155 ± 25 | 47 ± 6 | 109 ± 6 |
| Shells | 244 ± 14.9 | 48 ± 2.5 | 4.9 ± 0.9 | 12 ± 1.6 | 299 ± 77 | 3.3 ± 0.3 | 109 ± 14 | 28 ± 2 | 155 ± 10 |

Supplementary Table 2.5. Average potassium rates applied through each amendment treatment, Crown Nut Co, 2/10/2020 and 11/12/2020. All treatments received 30.3 kg ha$^{-1}$ (27 lb ac$^{-1}$) K minimal baseline potassium fertilizer to reduce risk of K deficiency in the control. The average dry biomass factors out moisture weight at the time of application.

| Treatment | Avg Applied Fresh Biomass, kg ha$^{-1}$ (lb ac$^{-1}$) | Avg Moisture (%) | Avg Applied Dry Biomass, kg ha$^{-1}$ (lb ac$^{-1}$) | Avg K Applied, kg ha$^{-1}$ (lb ac$^{-1}$) | Goal K, kg ha$^{-1}$ (lb ac$^{-1}$) |
|---|---|---|---|---|---|
| 2/10/2020 | | | | | |
| Hulls | 6997 (6243) | 19 | 5248 (4682) | 142 (127) | 140 (125) |
| Mix | 8095 (7222) | 18 | 6152 (5489) | 179 (160) | 140 (125) |
| Shells | 16663 (14866) | 11 | 12663 (11298) | 195 (174) | 140 (125) |
| $K_2SO_4$ | -- | -- | 230 (205) | 103 (92) | 140 (125) |
| 11/12/20209 | | | | | |
| Hulls | 8051 (7183) | 7 | 7487 (6680) | 155 (138) | 185 (165) |
| Mix | 8266 (7375) | 6 | 7771 (6933) | 174 (155) | 185 (165) |
| Shells | 16091 (14356) | 6 | 13494 (13494) | 278 (248) | 185 (165) |
| $K_2SO_4$ | -- | -- | 230 (205) | 103 (92) | 168 (150) |

Supplementary Table 2.6. Total average K release from amendments from 2/10/2020-6/22/2020 and 11/12/2020-6/26/2020, Crown. Total K release rate was calculated as Initial Dry K Rate – Final Dry K Rate. Dry K Rate at the Initial and Final time points were calculated as average %K multiplied by average dry mass rate for each material. Final Dry % Mass Remaining at 6/22/20 are estimates acknowledging that the litter ring method led to high variation and low accuracy. The 6/22/20 date was used because litter rings were disturbed between the 6/22/2020 and 7/27/2020 time points; percent dry mass remaining at 7/27/2020 was increased to 150-160% and was thus not usable. Total K release from amendments applied 11/12/2020 through 6/22/2021 utilized dry mass from litter bag samples, which provided less variable more accurate dry mass data. Sumner et al. 2019 recommend 493 kg ha$^{-1}$ (440 lb ac$^{-1}$) $K_2SO_4$ fertilizer annually (221 kg ha$^{-1}$ or 197 lb ac$^{-1}$ K) for mature almond orchards in the Sacramento Valley, which costs approximately $216 annually (Sumner et al. 2019 Table 3).

| Amendment | Initial %K | Final %K | Initial Dry Mass, kg ha$^{-1}$ (lb ac$^{-1}$) | Final Net Dry Mass % Remaining | Final Dry Mass, kg ha$^{-1}$ (lb ac$^{-1}$) | Initial Dry K, kg ha$^{-1}$ (lb ac$^{-1}$) | Final Dry K, kg ha$^{-1}$ (lb ac$^{-1}$) | Total K Released, kg ha$^{-1}$ (lb ac$^{-1}$) | Total %K Released |
|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2/10/2020 – 6/22/2020 | | | | | | | | | |
| Hulls | 2.72 | 1.35 | 5248<br>(4682) | 55.6% | 2918<br>(2603) | 143<br>(127) | 39.3<br>(35.1) | 103.5<br>(92.3) | 72.4% |
| Mix | 2.91 | 0.90 | 6152<br>(5489) | 64.0% | 3928<br>(3513) | 179<br>(160) | 35.4<br>(31.6) | 143.6<br>(128.1) | 80.2% |
| Shells | 1.54 | 0.51 | 12663<br>(11298) | 86.6% | 10966<br>(9784) | 195<br>(174) | 55.9<br>(49.9) | 139.1<br>(124.1) | 71.3% |
| 11/12/2020 – 6/26/2021 | | | | | | | | | |
| Hulls | 2.07 | 0.70 | 7487<br>(6680) | 37.8% | 2830<br>(2525) | 155<br>(138) | 19.8<br>(17.7) | 134.8<br>(120.3) | 87.2% |
| Mix | 2.23 | 0.77 | 7771<br>(6933) | 54.7% | 4250<br>(3792) | 173<br>(154) | 32.7<br>(29.2) | 140<br>(124.8) | 81.0% |
| Shells | 1.84 | 0.77 | 15125<br>(13494) | 54.0% | 8168<br>(7287) | 278<br>(248) | 62.9<br>(56.1) | 217.3<br>(193.9) | 78.2% |

Supplementary Table 2.7. Nutrient concentrations in amendments on the soil surface at application 2/10/2020 until 7/27/2020, at Crown Nut Co., analyzed via UC Davis Analytical Lab. Lowercase letters indicate significant differences in average nutrient values across time points within the same nutrient. Samples were analyzed less frequently for C, N, and P than K.

| Amendment | Nutrient | 2/11 | 3/13 | 3/27 | 4/10 | 5/4 | 5/25 | 6/22 | 7/27 |
|---|---|---|---|---|---|---|---|---|---|
| Hulls | K (%) | 2.72 a | 2.55 a | 1.45 b | 1.11 b | 1.23 b | 1.26 b | 1.35 b | 0.93 b |
| | C (%) | 43.1 c | -- | 47.4 b | -- | 49.0 a | -- | 47.0 b | -- |
| | N (%) | 0.71 c | -- | 1.09 b | -- | 1.33 a | -- | 1.23 ab | -- |
| | C:N | 60:1 a | -- | 44:1 b | -- | 37:1 b | -- | 39:1 b | |
| | P (%) | 0.12 ab | -- | 0.10 b | -- | 0.12 a | -- | 0.10 ab | -- |
| Mix | K (%) | 2.91 a | 2.76 a | 1.92 b | 1.12 c | 1.10 c | 0.81 c | 0.90 c | 0.59 c |
| | C (%) | 44.4 c | -- | 47.5 b | -- | 48.9 a | -- | 47.9 ab | -- |
| | N (%) | 0.70 b | -- | 0.83 ab | -- | 0.92 a | -- | 1.03 a | -- |
| | C:N | 65:1 a | -- | 58:1 ab | -- | 54:1 ab | -- | 47:1 b | -- |
| | P (%) | 0.09 a | -- | 0.09 a | -- | 0.08 a | -- | 0.07 a | -- |
| Shells | K (%) | 1.54 a | 1.42 a | 0.49 b | 0.55 b | 0.43 b | 0.68 b | 0.51 b | 0.77 b |
| | C (%) | 45.9 b | -- | 48.2 a | -- | 48.3 a | -- | 47.9 a | -- |
| | N (%) | 0.51 a | -- | 0.52 a | -- | 0.57 a | -- | 0.59 a | -- |
| | C:N | 91:1 a | -- | 99:1 a | -- | 86:1 a | -- | 83:1 a | -- |
| | P (%) | 0.05 a | -- | 0.03 b | -- | 0.03 b | -- | 0.03 a | -- |

Supplementary Table 2.8. Nutrient concentrations in amendments on the soil surface at application (11/12/2020, analyzed via UC Davis Analytical Lab) and in late June (7/26/2021), at Crown Nut Co., analyzed via UC Davis Interdisciplinary Center for ICPMS. Lowercase letters indicate significant differences in average nutrient values across time points within the same nutrient. Nutrients within amendment type that with unequal variances were transformed prior to analysis for Na in all three amendment materials and Zn in shells only. Tue means are presented below.

| Nutrient | Hulls | | Mix | | Shells | |
|---|---|---|---|---|---|---|
| | 11/12/20 | 6/26/21 | 11/12/20 | 6/26/21 | 11/12/20 | 6/26/21 |
| C (%) | 42.1 b | 47.8 a | 42.1 b | 47.5 a | 42.7 b | 46.2 a |
| N (%) | 0.59 b | 1.60 a | 0.65 b | 1.21 a | 0.61 b | 1.09 a |
| C:N | 71:1 a | 30:1 b | 65:1 a | 39:1 b | 70:1 a | 43:1 b |
| P (%) | 0.086 b | 0.118 a | 0.066 b | 0.078 a | 0.063 a | 0.080 a |
| K (%) | 2.073 a | 0.680 b | 2.228 a | 0.763 b | 1.840 a | 0.768 b |
| Ca (%) | 0.159 b | 0.698 a | 0.213 b | 0.673 a | 0.290 b | 0.645 a |
| Mg (%) | 0.081 b | 0.298 a | 0.110 b | 0.320 a | 0.109 b | 0.273 a |
| B (ppm) | 77.6 b | 151.6 a | 116.5 b | 161.9 a | 81.05 a | 105.63 a |
| Na (ppm) | 70 b | 2702.1 a | 120 b | 2848.9 a | 78 b | 1946.8 a |
| Al (ppm) | -- | 983.3 | -- | 807.6 | -- | 1944.1 |
| Si (ppm) | -- | 593.6 | -- | 426.7 | -- | 351.5 |
| S (ppm) | 248.5 b | 1289.5 a | 288.25 b | 1077.9 a | 264.3 b | 839.9 a |
| Mn (ppm) | 10.4 b | 47.5 a | 13.0 b | 35.7 a | 21.4 b | 60.7 a |
| Fe (ppm) | 174.8 b | 958.1 a | 225.0 b | 742.3 a | 660.5 b | 1896.7 a |
| Ni (ppm) | 4.9 | -- | 3.8 | -- | 8.1 | -- |
| Cu (ppm) | 2.23 b | 8.00 a | 3.30 b | 6.43 a | 3.03 b | 7.70 a |
| Zn (ppm) | 4.43 b | 22.98 a | 4.75 b | 17.63 a | 5.53 a | 46.13 b |

Supplementary Table 2.9. Estimated changes in total C and total N in amendment layers at Crown Nut Co. from 11/12/2020 to 7/26/2021, Bullseye from 10/14/2021 to 8/10/2021, and Westwind from 10/7/2020 to 10/7/2021.

| Site | Treatment | Initial (%) | Final (%) | Initial Amendment Dry Mass, kg ha$^{-1}$ (lb ac$^{-1}$) | Final Amendment Dry Mass, kg ha$^{-1}$ (lb ac$^{-1}$) | Final Dry Matter (%) | Initial Rate, kg ha$^{-1}$ (lb ac$^{-1}$) | Final Rate, kg ha$^{-1}$ (lb ac$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Nitrogen | | | | | | | | |
| Crown | Hulls | 0.59 | 1.60 | 7487<br>(6680) | 2830<br>(2525) | 37.8 | 44.2<br>(39.4) | 45.3<br>(40.4) |
| | Mix | 0.65 | 1.21 | 7771<br>(6933) | 4250<br>(3792) | 54.7 | 50.6<br>(45.1) | 51.3<br>(45.8) |
| | Shells | 0.61 | 1.09 | 15125<br>(13494) | 8168<br>(7287) | 54.0 | 92.2<br>(82.3) | 89.0<br>(79.4) |
| Bullseye | Mix | 0.50 | 0.7 | 10089<br>(9000) | 7092<br>(6327) | 70.3 | 50<br>(45) | 49.5<br>(44.2) |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Compost | 1.1 | 1.1 | 14347<br>(12800) | 7661<br>(6835) | 53.4 | 157<br>(140) | 84.3<br>(75.2) |
| Westwind | Mix | 0.85 | 1.6 | 16813<br>(15000) | 7532<br>(6720) | 44.8 | 142.9<br>(127.5) | 120.5<br>(107.5) |
| Carbon | | | | | | | | |
| Crown | Hulls | 42.1 | 47.8 | 7487<br>(6680) | 2830<br>(2525) | 37.8 | 3152<br>(2812) | 1353<br>(1207) |
| | Mix | 42.1 | 47.5 | 7771<br>(6933) | 4250<br>(3792) | 54.7 | 3272<br>(2919) | 2019<br>(1801) |
| | Shells | 42.7 | 46.2 | 15125<br>(13494) | 8167<br>(7287) | 54.0 | 6458<br>(5762) | 3774<br>(3367) |
| Bullseye | Mix | 45.1 | 45.3 | 10089<br>(9000) | 7092<br>(6327) | 70.3 | 4550<br>(4059) | 3212<br>(2866) |
| | Compost | 25.5 | 26.3 | 14347<br>(12800) | 7661<br>(6835) | 53.4 | 3658<br>(3264) | 2015<br>(1798) |
| Westwind | Mix | 44.5 | 45.8 | 16813<br>(15000) | 7532<br>(6720) | 44.8 | 7482<br>(6675) | 3450<br>(3078) |

Supplementary Table 2.10. Total K release from amendments applied 10/14/2020 until harvest 6/11/2021, Bullseye.

| Amendment | Initial %K | Final %K | Initial Dry Mass, kg ha$^{-1}$ (lb ac$^{-1}$) | Final Dry Mass % Remaining | Final Dry Mass, kg ha$^{-1}$ (lb ac$^{-1}$) | Initial Dry K, kg ha$^{-1}$ (lb ac$^{-1}$) | Final Dry K, kg ha$^{-1}$ (lb ac$^{-1}$) | Total K Released, kg ha$^{-1}$ (lb ac$^{-1}$) | Total %K Released |
|---|---|---|---|---|---|---|---|---|---|
| Shells | 1.53 | 0.32 | 10088<br>(9000) | 70.3 | 7092<br>(6327) | 154.3<br>(137.7) | 22.6<br>(20.2) | 131.7<br>(117.5) | 85.3% |
| Compost | 1.78 | 0.64 | 14347<br>(12800) | 53.4 | 7661<br>(6835) | 255.3<br>(227.8) | 49.0<br>(43.7) | 206.3<br>(184.1) | 80.8% |

Supplementary Table 2.11. Nutrient concentrations in amendments at Bullseye on the soil surface over time from application (10/14/2020) until harvest (8/10/2021). Lowercase letters indicate significant differences in average nutrient values across time points within the same nutrient. K, C, N, and all nutrients at Application were analyzed via UC Davis Analytical Lab. All other nutrients at other time points were analyzed via ICPMS. Letter groupings indicate significant differences over time within each nutrient. Data was transformed prior to analysis to improve conformity with model assumptions for the following nutrients: Ca, Mg, B, Na, Al, S, Mn, Fe, Ni, Cu, Zn for shells; Na, S, Mn, Fe, Cu for compost. True means are presented below.

| Amendment | Nutrient | Application 10/14/20 | Time 1 12/13/20 | Time 2 2/11/21 | Time 3 4/12/21 | Time 4 6/11/21 | Time 5 8/10/21 |
|---|---|---|---|---|---|---|---|
| Mix | C (%) | 45.1 b | 47.9 a | 46.0 ab | 44.3 b | 45.7 ab | 45.3 ab |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| (predominately shells) | N (%) | 0.50 c | 0.61 bc | 0.75 ab | 0.78 ab | 0.92 a | 0.73 abc |
|  | C:N | 91:1 a | 79:1 ab | 62:1 bc | 57:1 c | 51:1 c | 64:1 bc |
|  | P (%) | 0.048 a | 0.045 a | 0.055 a | 0.058 a | 0.083 a | 0.093 a |
|  | K (%) | 1.53 a | 0.79 b | 0.37 c | 0.27 c | 0.32 c | 0.34 c |
|  | Ca (%) | 0.197 b | 0.47 ab | 0.64 ab | 0.76 a | 0.88 a | 1.03 a |
|  | Mg (%) | 0.07 a | 0.11 a | 0.24 a | 0.28 a | 0.45 a | 0.49 a |
|  | B (ppm) | 54.1 bc | 45.2 c | 48.6 bc | 49.2 bc | 67.9 ab | 85.0 a |
|  | Na (ppm) | 145 c | 340.0 b | 330.0 b | 506.6 b | 1469.1 a | 1423.6 a |
|  | Al (ppm) | -- | 639.6 b | 1944.3 ab | 2799.2 ab | 4797.3 ab | 5085.9 a |
|  | Si (ppm) | -- | 420.6 a | 564.6 a | 641.1 a | 514.7 a | 522.0 a |
|  | S (ppm) | 246.0 d | 344.9 cd | 504.9 bc | 638.4 ab | 1214.5 a | 1184.3 a |
|  | Mn (ppm) | 12.5 c | 25.0 bc | 63.0 ab | 85.2 ab | 167.6 a | 187.1 a |
|  | Fe (ppm) | 288.3 c | 745.7 bc | 2508.7 ab | 3732.1 ab | 6815.5 ab | 7292.4 a |
|  | Ni (ppm) | -- | 4.38 b | 14.4 ab | 18.0 ab | 31.2 a | 35.3 a |
|  | Cu (ppm) | 2.88 c | 4.53 bc | 7.73 abc | 10.35 ab | 18.98 a | 16.18 a |
|  | Zn (ppm) | 5.39 c | 9.65 bc | 16.63 bc | 22.33 ab | 26.28 ab | 47.73 a |
| Compost | C (%) | 25.5 a | 26.8 a | 25.7 a | 25.0 a | 23.4 a | 26.3 a |
|  | N (%) | 1.05 a | 1.06 a | 1.03 a | 1.07 a | 1.13 a | 1.11 a |
|  | C:N | 24:1 a | 25:1 a | 25:1 a | 23:1 ab | 21:1 b | 24:1 ab |
|  | P (%) | 0.220 a | 0.193 ab | 0.173 b | 0.165 b | 0.163 b | 0.175 b |
|  | K (%) | 1.78 a | 1.27 b | 0.83 c | 0.78 c | 0.64 c | 0.70 c |
|  | Ca (%) | 0.97 b | 1.20 ab | 1.30 a | 1.32 a | 1.39 a | 1.46 a |
|  | Mg (%) | 0.88 ab | 0.87 b | 0.96 ab | 0.96 ab | 1.03 ab | 1.04 a |
|  | B (ppm) | 101.7 ab | 97.0 ab | 79.9 b | 81.3 b | 77.1 b | 111.7 a |
|  | Na (ppm) | 1628 b | 971.2 d | 607.9 e | 890.4 d | 1290.4 c | 2070.2 a |
|  | Al (ppm) | -- | 10119.9 a | 11965.4 a | 11617.3 a | 12609.7 a | 12881.8 a |
|  | Si (ppm) | -- | 534.8 b | 557.0 b | 1104.0 a | 668.7 b | 619.9 b |
|  | S (ppm) | 1757.0 b | 1482.3 c | 1387.8 c | 1464.8 c | 1766.1 b | 2201.9 a |
|  | Mn (ppm) | 375.4 a | 371.3 a | 437.1 a | 398.8 a | 481.7 a | 459.6 a |
|  | Fe (ppm) | 16021 b | 16248 b | 18814 ab | 18006 ab | 20699 a | 20160 a |
|  | Ni (ppm) | -- | 78.9 a | 87.1 a | 89.4 a | 86.8 a | 96.4 a |
|  | Cu (ppm) | 29.03 ab | 28.33 b | 30.18 ab | 29.35 ab | 35.80 a | 33.93 ab |
|  | Zn (ppm) | 88.14 c | 90.23 c | 91.85 bc | 90.23 c | 114.15 a | 108.13 ab |

Supplementary Table 2.12. Total K release from the hull/shell mix amendment applied 10/7/2020 until 10/7/2021, Westwind.

| Amendment | Initial %K | Final %K | Initial Dry Mass, kg $ha^{-1}$ (lb $ac^{-1}$) | Final Dry Mass % Remaining | Final Dry Mass, kg $ha^{-1}$ (lb $ac^{-1}$) | Initial Dry K, kg $ha^{-1}$ (lb $ac^{-1}$) | Final Dry K, kg $ha^{-1}$ (lb $ac^{-1}$) | Total K Released, kg $ha^{-1}$ (lb $ac^{-1}$) | Total %K Released |
|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Mix | 1.84 | 0.1 | 16813 (15000) | 44.8% | 7532 (6720) | 309 (276) | 7.5 (6.7) | 301.5 (269) | 97.6% |

Supplementary Table 2.13. Hull/shell amendment nutrient concentrations over time at Westwind from 10/7/2020 until 10/7/2021. C, N, and K were analyzed via UC Davis Analytical Lab. All other nutrients were analyzed via ICPMS. Letter groupings indicate significant differences over time within each nutrient. Mn, Fe, Ni, and Zn were log transformed prior to analysis to improve conformity with model assumptions. True means are presented below.

| Nutrient | Applied 10/7/20 | Time 1 11/6/20 | Time 2 12/6/20 | Time 3 2/4/21 | Time 4 3/6/21 | Time 5 6/6/21 | Time 6 7/29/21 | Time 7 10/7/21 |
|---|---|---|---|---|---|---|---|---|
| C (%) | 44.5 c | 47.8 a | 47.0 ab | 47.0 ab | 46.5 ab | 45.6 bc | 45.8 bc | 45.8 bc |
| N (%) | 0.85 e | 0.90 e | 0.91 e | 0.96 de | 1.17 cd | 1.34 bc | 1.50 ab | 1.60 a |
| C:N | 53:1 a | 54:1 a | 52:1 a | 49:1 ab | 40:1 bc | 34:1 cd | 31:1 cd | 29:1 d |
| P (%) | 0.065 a | 0.070 a | 0.085 a | 0.070 a | 0.087 a | 0.083 a | 0.078 a | 0.080 a |
| K (%) | 1.84 a | 0.64 bc | 1.23 ab | 0.64 bc | 0.98 b | 0.1 c | 0.1 c | 0.1 c |
| Ca (%) | 0.22 c | 0.36 c | 0.31 c | 0.40 c | 0.45 bc | 0.75 ab | 0.92 a | 0.94 a |
| Mg (%) | 0.07 d | 0.08 d | 0.09 d | 0.15 cd | 0.21 bc | 0.32 a | 0.25 ab | 0.29 ab |
| B (ppm) | 53.7 c | 109.5 b | 114.3 b | 106.2 b | 120.7 b | 165.7 a | 159.1 a | 174.4 a |
| Na (ppm) | 128 d | 1215 ab | 791.9 bc | 585.2 cd | 833 bc | 1427 a | 1192 ab | 1199 ab |
| Al (ppm) | -- | 438.8 c | 495.3 c | 1009 bc | 1040 bc | 1667 ab | 1652 ab | 1999.4 a |
| Si (ppm) | -- | 426.4 a | 429.3 a | 539.2 a | 484.9 a | 483.1 a | 590.5 a | 495.3 a |
| S (ppm) | 300.5 c | 670.1 b | 541.7 bc | 625.6 b | 785.7 bc | 1054 ab | 1133 a | 1179.1 a |
| Mn (ppm) | 23.0 de | 19.2 e | 22.6 cde | 34.9 cd | 38.3 bc | 67.3 ab | 88.9 a | 102.4 a |
| Fe (ppm) | 309.5 d | 483.9 cd | 577.8 c | 1176 b | 1246 b | 1956 ab | 2007 ab | 2317 a |
| Ni (ppm) | -- | 4.6 b | 4.7 b | 10.6 a | 11.0 a | 14.3 a | 11.2 a | 13.9 a |
| Cu (ppm) | 3.30 e | 4.55 de | 5.13 cde | 6.03 cd | 6.73 bc | 8.23 ab | 8.65 ab | 8.98 a |
| Zn (ppm) | 7.88 f | 10.5 ef | 13.0 de | 19.9 cd | 23.7 c | 275.4 b | 443.5 ab | 497.2 a |

Supplementary Table 2.14. Recommended soil nutrient ranges for California almond orchard soils (Dellavalle Lab soil fertility report).

| Fertility Level | NO3-N (ppm) | Olsen P (ppm) | XK (ppm) | Na (meq/L) | Ca (meq/L) | Mg (meq/L) | pH |
|---|---|---|---|---|---|---|---|
| Low | <5 | <4 | <80 | | <4 | | <6.3 |
| Medium | 8-25 | 7-25 | 100-250 | <8.0 | 5-10 | Mg<Ca | 6.7-8.0 |
| High | 35+ | 50+ | 350+ | 16+ | 20+ | 20+ | 8.4+ |

Supplementary Table 2.15. Average soil fertility values from baseline soil samples collected at 0-10 cm fall 2019, 2020, and 2021, Crown. All treatments were statistically significantly similar within each time point unless marked with differentiating letter groupings. Soil XK was the only response variable that was significantly between treatments in fall 2020 and fall 2021.

| Year | Treatment | Nitrate-N (ppm) | Olsen-P (ppm) | XK (ppm) | XNa (ppm) | XCa (meq$^{-1}$ 100g) | XMg (meq$^{-1}$ 100g) | CEC | OM (%) | pH |
|---|---|---|---|---|---|---|---|---|---|---|
| Fall 2019 | Control | 23.1 | 10.3 | 350.0 | 174.0 | 16.40 | 9.74 | 27.78 | 2.53 | 6.24 |
| | Hulls | 21.6 | 6.9 | 311.0 | 180.5 | 16.58 | 9.73 | 27.90 | 2.54 | 6.30 |
| | Mix | 50.4 | 10.0 | 312.5 | 193.0 | 16.63 | 10.23 | 28.50 | 2.50 | 6.23 |
| | Shells | 33.7 | 10.4 | 357.5 | 163.5 | 16.88 | 9.97 | 28.48 | 2.57 | 6.30 |
| Fall 2020 | Control | 1.11 | 8.2 | 381.3 b | 249.5 | 17.63 | 10.95 | 30.65 | 2.49 | 6.75 |
| | Hulls | 2.21 | 9.4 | 472.3 ab | 241.0 | 17.45 | 10.59 | 30.28 | 2.49 | 6.78 |
| | Mix | 1.44 | 10.7 | 516.0 a | 236.8 | 17.05 | 10.55 | 29.95 | 2.64 | 6.73 |
| | Shells | 1.19 | 9.1 | 473.8 ab | 247.5 | 17.41 | 10.95 | 30.65 | 2.79 | 6.83 |
| Fall 2021 | Control | 66.74 | 8.8 | 328.8 b | 302.3 | 17.21 | 10.91 | 30.25 | 2.38 | 6.24 |
| | Hulls | 70.20 | 9.7 | 410.3 a | 295.8 | 17.14 | 10.86 | 30.33 | 2.39 | 6.34 |
| | Mix | 57.32 | 5.4 | 374.8 ab | 330.5 | 17.38 | 11.17 | 30.93 | 2.35 | 6.46 |
| | Shells | 68.61 | 7.9 | 428.3 a | 295.8 | 17.23 | 10.95 | 30.53 | 2.33 | 6.35 |

Supplementary Table 2.16. Average soil fertility values collected at 0-10 cm, 10-20 cm, 20-30 cm depths on 10/19/2021 at Crown. Letters indicate groupings within the same depth and response variable. For time points with no letters, treatments were not significantly different. XK was the only response variable found to be significantly different between amendments at 0-10cm depth. At 10-20 cm, XCa was significantly lower for mix soil and significantly higher for shell soil. At 20-30 cm, soil XK was significantly higher for the soil amended with the mix. XNa was significantly lower under the mix at 20-30 cm depth, which may be attributed to competition for exchange sites between K and Na.

| Treatment | Depth (cm) | Nitrate-N (ppm) | Olsen-P (ppm) | XK (ppm) | XNa (ppm) | XCa (meq$^{-1}$ 100g) | XMg (meq$^{-1}$ 100g) | CEC | OM (%) | pH |
|---|---|---|---|---|---|---|---|---|---|---|
| Control | 0-10 | 66.7 | 8.83 | 328.8 b | 302.3 | 17.2 | 10.9 | 30.3 | 2.38 | 6.24 |
| Control | 10-20 | 40.1 | 4.08 | 253.8 | 586.0 | 18.5 ab | 10.7 | 32.4 | 2.16 | 6.89 |
| Control | 20-30 | 17.5 | 3.33 | 241.8 b | 757.5 a | 19.5 | 10.1 | 33.5 | 1.87 | 6.95 |
| Hulls | 0-10 | 70.2 | 9.68 | 410.3 a | 295.8 | 17.1 | 10.9 | 30.3 | 2.39 | 6.34 |
| Hulls | 10-20 | 37.6 | 3.48 | 285.8 | 466.5 | 18.4 ab | 10.8 | 31.9 | 2.20 | 6.90 |
| Hulls | 20-30 | 18.7 | 2.00 | 245.0 b | 759.3 a | 20.0 | 10.0 | 33.9 | 2.00 | 7.09 |
| Mix | 0-10 | 57.3 | 5.43 | 374.8 ab | 330.5 | 17.4 | 11.2 | 30.9 | 2.35 | 6.46 |
| Mix | 10-20 | 35.3 | 3.68 | 274.8 | 530.0 | 18.2 b | 10.5 | 31.6 | 2.20 | 6.70 |
| Mix | 20-30 | 24.2 | 3.33 | 276.5 a | 590.8 b | 19.3 | 9.8 | 32.5 | 2.06 | 6.77 |
| Shells | 0-10 | 68.6 | 7.88 | 428.3 a | 295.8 | 17.2 | 10.9 | 30.5 | 2.33 | 6.35 |
| Shells | 10-20 | 21.3 | 2.68 | 260.0 | 516.8 | 18.9 a | 10.6 | 32.4 | 2.08 | 7.01 |
| Shells | 20-30 | 13.4 | 2.50 | 245.0 b | 696.3 ab | 20.9 | 9.8 | 34.4 | 1.85 | 7.10 |

Supplementary Table 2.17. Average exchangeable Na, Ca, Mg, and K in the upper 0-10 cm soil across time at Bullseye, 9/24/2020 until 10/15/2021. Letter groupings indicate significant differences within time points and cation type. For time points with no letters, treatments were not significantly different.

| Treatment | 9/24/20 | 11/24/20 | 1/12/21 | 3/2/21 | 5/11/21 | 7/29/21 | 10/15/21 |
|---|---|---|---|---|---|---|---|
| | XNa (meq 100g$^{-1}$) | | | | | | |
| Control | 1.91 | 1.57 | 1.53 | 1.44 | 1.37 | 1.68 | 2.31 a |
| Shells | 1.83 | 1.42 | 1.36 | 1.38 | 1.24 | 1.56 | 1.81 b |
| Compost | 1.73 | 1.30 | 1.17 | 1.56 | 1.27 | 1.66 | 1.87 b |
| | XCa (meq 100g$^{-1}$) | | | | | | |
| Control | 12.78 | 14.15 | 13.97 b | 13.87 | 12.68 | 12.87 | 13.35 |
| Shells | 14.00 | 13.19 | 14.36 ab | 14.11 | 12.97 | 13.91 | 13.48 |
| Compost | 13.58 | 13.51 | 14.89 a | 13.42 | 12.54 | 13.19 | 12.95 |
| | XMg (meq 100g$^{-1}$) | | | | | | |
| Control | 6.54 | 5.81 | 6.78 | 6.03 ab | 5.94 | 5.95 | 6.45 |
| Shells | 6.31 | 5.96 | 6.35 | 5.45 b | 5.62 | 5.76 | 6.51 |
| Compost | 6.74 | 5.87 | 5.96 | 6.52 a | 5.16 | 5.80 | 6.89 |
| | XK (meq 100g$^{-1}$) | | | | | | |
| Control | 1.04 | 1.01 b | 0.94 b | 0.92 | 0.99 b | 0.94 b | 0.92 b |
| Shells | 0.96 | 1.18 a | 1.17 a | 1.19 | 1.25 a | 1.19 a | 1.04 a |
| Compost | 0.92 | 1.17 a | 1.15 a | 1.11 | 1.24 a | 1.05 ab | 0.99 ab |

Supplementary Table 2.18. Average exchangeable Na, Ca, Mg and K at 10-20 cm depth on 3/2/2021 at Bullseye.

| Treatment | 3/2/2021 | | | | |
|---|---|---|---|---|---|
| | XK (meq 100g$^{-1}$) | XK (ppm) | XNa (meq 100g$^{-1}$) | XCa (meq 100g$^{-1}$) | XMg (meq 100g$^{-1}$) |
| Control | 0.64 b | 248.3 b | 1.61 a | 12.04 a | 7.32 a |
| Shells | 0.81 a | 314.5 a | 1.66 a | 12.61 a | 6.46 b |
| Compost | 0.73 ab | 285.0 ab | 1.81 a | 11.94 a | 7.31 a |

Supplementary Table 2.19. Average fertility response variables at 0-10 cm, 10-20 cm, and 20-30 cm at Bullseye, fall 2021. Letters indicate groupings within the same depth and response variable. For columns and depths with no letters, treatments were not significantly different.

| Treatment | Depth (cm) | Nitrate-N (ppm) | Olsen-P (ppm) | XK (ppm) | XNa (ppm) | XCa (meq$^{-1}$ 100g) | XMg (meq$^{-1}$ 100g) | CEC | OM (%) | pH |
|---|---|---|---|---|---|---|---|---|---|---|
| Control | 0-10 | 2.09 | 17.25 | 359.5 b | 530.3 a | 13.4 | 6.45 | 23.0 | 2.57 | 7.52 |
| Control | 10-20 | 3.3 | 15.4 ab | 274.2 | 686.2 | 12.0 | 7.02 | 22.7 | 2.34 | 7.68 |
| Control | 20-30 | 1.1 | 12.4 | 237.7 | 725.2 | 11.5 | 7.95 | 23.2 | 2.30 | 7.54 |
| Shells | 0-10 | 2.21 | 23.53 | 406.0 a | 416.5 b | 13.5 | 6.51 | 22.9 | 2.65 | 7.31 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Shells | 10-20 | 1.5 | 17.7 a | 266.2 | 677.0 | 12.5 | 6.92 | 23.1 | 2.35 | 7.62 |
| Shells | 20-30 | 1.9 | 12.7 | 210.5 | 786.2 | 11.8 | 8.24 | 24.0 | 2.28 | 7.55 |
| Compost | 0-10 | 5.27 | 22.95 | 388.0 ab | 430.5 b | 13.0 | 6.89 | 22.7 | 2.76 | 7.28 |
| Compost | 10-20 | 2.7 | 12.5 b | 258.2 | 754.0 | 11.9 | 7.33 | 23.2 | 2.29 | 7.66 |
| Compost | 20-30 | 2.0 | 14.8 | 227.0 | 725.2 | 11.5 | 8.59 | 24.2 | 2.18 | 7.40 |

Supplementary Table 2.20. Exchangeable K, Na, Ca, Mg in the top 0-10 cm sampled at four time points fall 2020 through fall 2021 at Westwind. Letters indicate significant differences within each time point and exchangeable nutrient.

| Treatment | 9/16/2020 | 3/8/2021 | 7/29/2021 | 9/22/2021 |
|---|---|---|---|---|
| | XNa (meq $100g^{-1}$) | | | |
| T1: Control | 1.84 a | 1.97 a | 1.63 a | 1.64 a |
| T4: Amended Catch Frame | 2.03 a | 1.57 a | 1.43 a | 1.62 a |
| | XCa (meq $100g^{-1}$) | | | |
| T1: Control | 13.25 a | 11.79 a | 10.63 a | 11.62 a |
| T4: Amended Catch Frame | 13.03 a | 12.75 a | 12.27 a | 11.90 a |
| | XMg (meq $100g^{-1}$) | | | |
| T1: Control | 5.13 a | 3.66 a | 4.91 a | 3.88 a |
| T4: Amended Catch Frame | 4.54 a | 4.27 a | 4.70 b | 4.52 a |
| | XK (meq $100g^{-1}$) | | | |
| T1: Control | 0.44 a | 0.35 b | 0.60 a | 0.58 b |
| T4: Amended Catch Frame | 0.40 a | 0.70 a | 0.76 a | 0.74 a |

Supplementary Table 2.21. Average exchangeable Na, Ca, Mg and K at 10-20 cm depth on 3/8/2021 at Westwind. K was the only cation significantly different between treatments at this depth.

| Treatment | 3/8/2021 | | | | | |
|---|---|---|---|---|---|---|
| | XNa (meq $100g^{-1}$) | XNa (ppm) | XCa (meq $100g^{-1}$) | XMg (meq $100g^{-1}$) | XK (meq $100g^{-1}$) | XK (ppm) |
| T1: Control | 2.66 a | 612.5 a | 11.52 a | 4.15 a | 0.23 b | 225.75 b |
| T4: Amended + Catch Frame | 2.23 b | 513.0 b | 12.30 a | 4.58 a | 0.32 a | 288.75 a |

Supplementary Table 2.22. Fall baseline soil samples were taken on 9/22/21 at 0-10 cm, 10-20 cm, and 20-30 cm at Westwind. Treatment 1 is the control, treatment 2 is off ground harvest, treatment 3 is amended on ground harvest, and treatment 4 is amended off ground harvest. Letter groupings indicate significant differences within time points and soil fertility response variable. For time points with no letters, treatments were not significantly different. T1 is the control, T2 is off ground harvest, T3 is amended on ground harvest, T4 is amended off ground harvest.

| Treatment | Depth (cm) | NO3-N (ppm) | Olsen-P (ppm) | XK (ppm) | XNa (ppm) | XCa (meq $100g^{-1}$) | XMg (meq $100g^{-1}$) | CEC (meq $100g^{-1}$) | %OM | pH |
|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 0-10 | 23.8 | 2.9 | 225.8 b | 377.5 | 11.62 | 3.88 | 17.70 | 2.11 | 7.25 |
| | 10-20 | 7.3 | <2.9 | 116.8 ab | 454.0 | 11.15 | 3.99 | 17.40 | 1.69 | 7.51 |
| | 20-30 | 5.1 | <2.8 | 79.0 ab | 568.5 | 10.71 | 4.71 | 18.10 | 1.49 | 7.57 b |
| T2 | 0-10 | 23.0 | 3.95 | 225.0 b | 359.8 | 10.39 | 4.29 | 16.80 | 3.21 | 7.32 |
| | 10-20 | 7.1 | <1 | 110.0 b | 442.5 | 10.70 | 4.03 | 16.93 | 1.66 | 7.64 |
| | 20-30 | 5.1 | <1 | 71.5 b | 542.0 | 9.92 | 4.51 | 16.95 | 1.44 | 7.74 ab |
| T3 | 0-10 | 37.2 | 4.25 | 283.8 ab | 358.3 | 12.17 | 4.28 | 18.73 | 1.88 | 7.28 |
| | 10-20 | 10.5 | <1.4 | 127.8 ab | 435.8 | 11.51 | 4.50 | 18.23 | 1.66 | 7.54 |
| | 20-30 | 6.5 | <1.7 | 91.8 a | 513.3 | 10.84 | 5.25 | 18.58 | 1.49 | 7.66 ab |
| T4 | 0-10 | 37.9 | 3.53 | 288.8 a | 372.8 | 11.90 | 4.52 | 18.78 | 2.32 | 7.31 |
| | 10-20 | 10.3 | <1.4 | 156.2 a | 468.0 | 10.89 | 4.24 | 17.56 | 1.70 | 7.61 |
| | 20-30 | 5.1 | <1.3 | 92.0 a | 619.5 | 10.26 | 4.85 | 18.05 | 1.49 | 7.81 a |

Supplementary Table 2.23. Average percent net dry mass remaining, standard deviation, and standard error of amendments sampled from litter rings over time at Crown Nut Co. Increases in average % net dry mass remaining over time and high standard deviation and standard error values indicate values were influenced by amendment materials moving in and out of the litter ring sampling area. Empty litter rings were installed in the control rows to assess total litterfall (petals, twigs, leaves, etc.). Even with the control litterfall data factored into the average percent dry mass remaining of the amendment treatments, substantial amendment increases indicate materials moved into the sampling ring over time. Therefore, this data is not a reliable representation of average percent dry mass.

| Amendment | Avg. % Net Dry Mass Remaining | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2/10/20 | 3/13/20 | 3/27/20 | 4/10/20 | 5/4/20 | 5/25/20 | 6/22/20 | 7/27/20 |
| Control | 0 | 0 | 1.37 | 12.62 | 1.245 | 0.62 | 0 | NA |
| Hulls | 100 | 112.0 | 52.9 | 39.3 | 71.4 | 47.9 | 55.6 | 157.8 |
| Mix | 100 | 102.8 | 75.1 | 53.1 | 81.9 | 55.3 | 64.0 | 161.6 |
| Shells | 100 | 100.4 | 123.3 | 76.7 | 97.3 | 90.4 | 86.6 | 155.7 |
| | Std. Deviation | | | | | | | |
| Control | 0 | 0 | 1.02 | 4.58 | 0.94 | 0.26 | 3.58 | NA |
| Hulls | -- | 10.9 | 20.0 | 7.1 | 25.9 | 5.7 | 16.1 | 45.4 |
| Mix | -- | 9.0 | 17.4 | 4.2 | 15.8 | 7.9 | 10.6 | 113.8 |
| Shells | -- | 10.4 | 70.1 | 11.9 | 15.2 | 14.2 | 18.6 | 48.2 |
| | Std. Error | | | | | | | |
| Control | 0 | 0 | 0.42 | 1.87 | 0.38 | 0.11 | 1.46 | NA |
| Hulls | -- | 3.14 | 5.8 | 2.0 | 7.5 | 1.7 | 4.7 | 13.1 |
| Mix | -- | 2.61 | 5.0 | 1.2 | 4.6 | 2.3 | 3.1 | 32.8 |
| Shells | -- | 3.01 | 20.2 | 3.4 | 4.4 | 4.1 | 5.4 | 13.9 |

Supplementary Table 2.24. Average percent net dry mass remaining, standard deviation, and standard error of amendments sampled from litter bags at the final time point at Crown Nut Co., 7/26/2021.

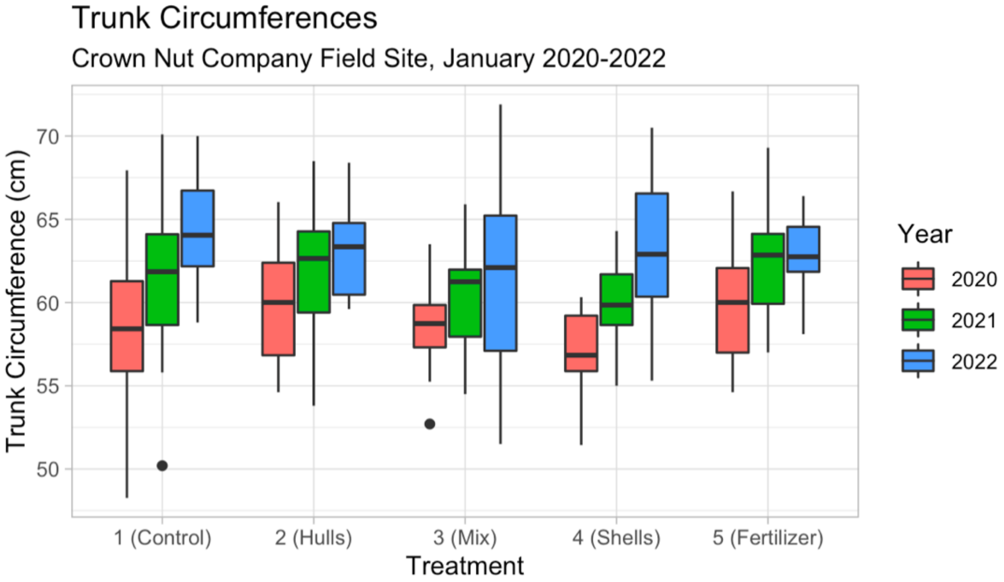
| Amendment | Avg. % Net Dry Mass Remaining | Std. Deviation | Std. Error |
|---|---|---|---|
| Hulls | 37.8 b | 3.65 | 1.05 |
| Mix | 54.7 a | 3.14 | 0.91 |
| Shells | 54.0 a | 2.88 | 0.83 |

Supplementary Table 2.25. Almond July leaf nutrient concentration ranges used to assess plant nutrient status. Hulls should be used instead of leaves for boron status. Sources: The Almond Production Manual, UC ANR website, FREP almond fertilization website, Sacramento Valley Orchard Source.

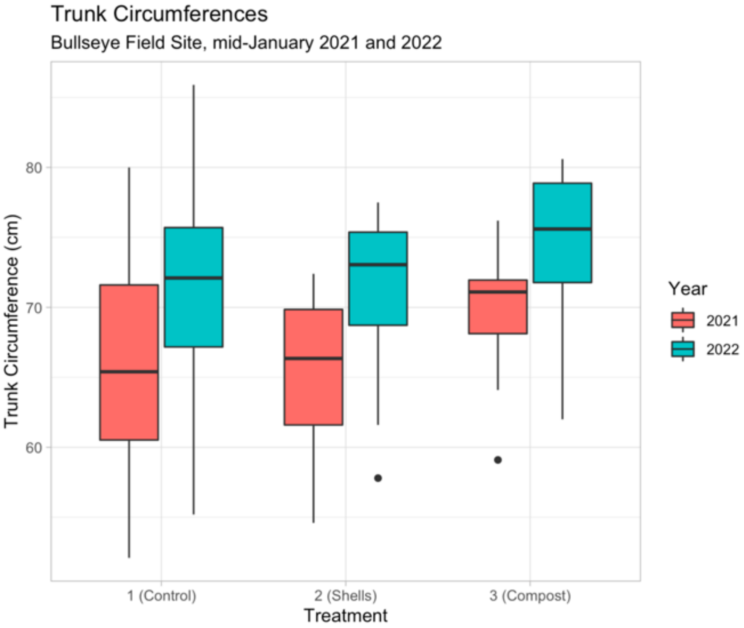
| | Percent | | | | | ppm | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| Adequate Range: | 2.2-2.5 | 0.1-0.3 | 1.4-2.0 | 2-4 | 0.6-1.2 | 1000 | 80-150 | 15-20 | 30-80 | 50-400 | 6-10 | 100-1000 |
| High: | 3.2+ | 0.6+ | 3.6+ | 5+ | 0.9+ | 1500+ | >200 | 300+ | 150+ | 600+ | 500+ | 1500+ |

Supplementary Table 2.26. Average July leaf nutrients under treatments, 2020 and 2022 Crown Nut Co. Letters indicate significant differences between treatments for each nutrient. Nutrient columns without letters have treatments that are statistically similar for the given year.

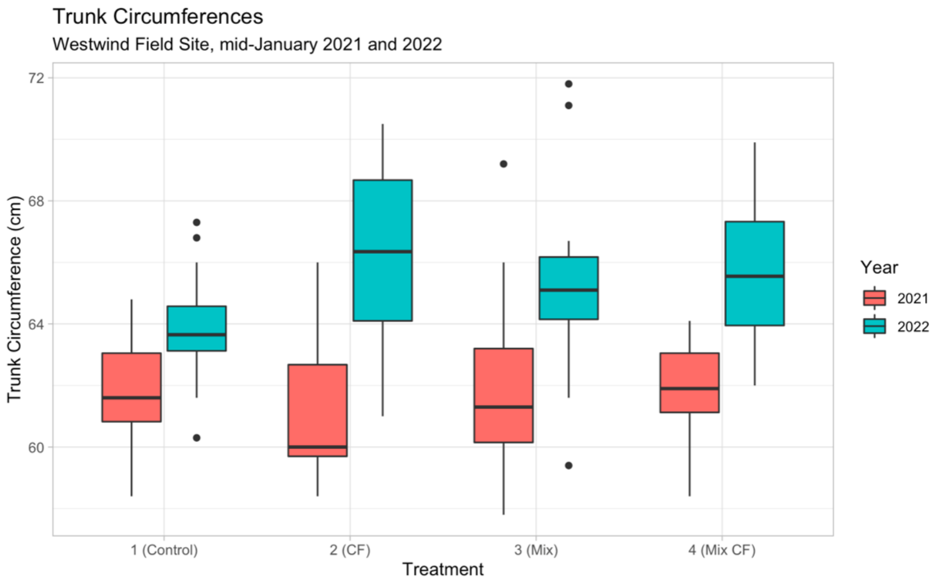
| Treatment | % | | | | | ppm | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | S | B | Zn | Mn | Fe | Cu | Na |
| 2020 | | | | | | | | | | | | |
| Control | 1.98 | 0.119 | 2.38 a | 5.78 | 1.14 | 1707 | 50 | 27 | 65 | 84 | 6 | -- |
| Hulls | 2.07 | 0.117 | 2.22 ab | 5.88 | 1.19 | 1704 | 48 | 31 | 68 | 86 | 6 | -- |
| Mix | 2.03 | 0.122 | 2.12 b | 6.05 | 1.20 | 1739 | 49 | 31 | 61 | 79 | 6 | -- |
| Shells | 2.01 | 0.116 | 2.07 b | 5.88 | 1.16 | 1747 | 46 | 28 | 60 | 81 | 5 | -- |
| K2SO4 | 2.03 | 0.116 | 2.14 ab | 5.85 | 1.15 | 1743 | 46 | 32 | 67 | 90 | 6 | -- |
| 2022 | | | | | | | | | | | | |
| Control | 1.56 | 0.083 | 1.36 b | 5.37 | 1.23 a | 1353 | 35 | 30 | 46 | 50 | 3 | 163 |
| Hulls | 1.59 | 0.083 | 1.59 ab | 5.20 | 1.14 b | 1343 | 36 | 29 | 42 | 52 | 3 | 168 |
| Mix | 1.55 | 0.082 | 1.66 a | 5.29 | 1.13 b | 1367 | 35 | 28 | 41 | 145 | 3 | 148 |
| Shells | 1.49 | 0.081 | 1.77 a | 5.18 | 1.07 b | 1344 | 36 | 27 | 43 | 49 | 3 | 149 |
| K2SO4 | 1.50 | 0.081 | 1.62 ab | 5.19 | 1.12 b | 1306 | 35 | 29 | 46 | 50 | 3 | 165 |



Supplementary Figure 2.4. January trunk circumferences in 2020, 2021, and 2022, Crown Nut Co.



Supplementary Figure 2.5. January trunk circumferences across all treatments in 2021 and 2022, Bullseye.



Supplementary Figure 2.6. January trunk circumferences, 2020 and 2021, Westwind. There were no significant differences between treatments either year. CF=catch-frame harvested.

Supplementary Table 2.27. Yield data collected in 2020 and 2021, Crown Nut Co. Letter groupings indicate significant differences between treatments. For columns within years with no letters, treatments were not significantly different. Average moisture content of yield samples can be found in Supplementary Table 15.

| Treatment | Average Dry Kernel, kg ha$^{-1}$ (lb/ac) | Std. Dev., kg ha$^{-1}$ (lb/ac) | Avg. % Crack Out | Avg. Dry HS Trash in Yield Samples (%) | Total Dry Trash in Yield Samples (%) |
|---|---|---|---|---|---|
| 2020 | | | | | |
| Control | 2466 (2200) | 395 (352) | 31.9% | 0.88% b | 16.4% ab |
| Hulls | 2436 (2436) | 270 (241) | 30.2% | 5.29% a | 15.8% ab |
| Mix | 2486 (2218) | 256 (228) | 30.1% | 4.67% a | 19.6% a |
| Shells | 2511 (2240) | 253 (226) | 30.2% | 2.35% b | 19.2% a |
| $K_2SO_4$ | 2403 (2403) | 706 (630) | 31.2% | 0.71% b | 11.6% b |
| 2021 | | | | | |
| Control | 3229 (2881) | 764 (682) | 40.5% | 12.0% | 23.5% |
| Hulls | 2317 (2067) | 511 (456) | 32.0% | 7.6% | 27.1% |
| Mix | 2245 (2003) | 239 (213) | 35.8% | 9.5% | 27.1% |
| Shells | 2960 (2641) | 946 (844) | 35.0% | 4.9% | 27.4% |
| $K_2SO_4$ | 2130 (2784) | 675 (602) | 35.8% | 11.4% | 29.4% |

Supplementary Table 2.28. Yield data collected in 2021 and 2022 at Bullseye. No significant differences in average dry kernel weight, average percent crack out, or all trash in yield samples were found between treatments. All values are reported in dry weight.

| Treatment | Average Dry Kernel, kg $ha^{-1}$ (lb/ac) | Std. Dev., kg $ha^{-1}$ (lb/ac) | Avg. % Crack Out | Avg. Dry Amendment Trash in Yield Samples (%) | Avg All Trash in Yield Samples (%) |
|---|---|---|---|---|---|
| 2021 | | | | | |
| Control | 3320 (2962) | 250 (223) | 28 | 0.93% a | 7.3% |
| Shells | 3395 (3029) | 278 (248) | 28 | 4.93% b | 9.9% |
| Compost | 3216 (2869) | 382 (341) | 26 | 0.80% a | 7.8% |
| 2022 | | | | | |
| Control | 656 (585) | 147 (131) | 27 | 0.87% a | 23.0% |
| Shells | 722 (644) | 173 (154) | 27 | 6.9% b | 26.5% |
| Compost | 615 (549) | 413 (368) | 27 | 11.3% c | 19.4% |

Supplementary Table 2.29. Yield data collected in 2021 and 2022 at Westwind. For both years, no significant differences were found between treatments in average dry kernel lb $ac^{-1}$, average percent crack out, or average percent hull/shell amendment in trash samples. However, the average percent of all dry trash in yield samples was significantly higher in the two on-ground harvested treatments (T1 and T3) compared to the off-ground treatments in 2022. All values reported in dry weight.

| Treatment | Avg. Dry Kernel, kg $ha^{-1}$ (lb/ac) | Std. Dev., kg $ha^{-1}$ (lb/ac) | Avg. % Crack Out | Avg. Dry HS Trash in Yield Samples (%) | Avg. All Dry Trash of Yield Samples (%) |
|---|---|---|---|---|---|
| 2021 | | | | | |
| T1: Control | 1212 (1081) | 52 (46) | 26% | 5.8% | 14.1% a |
| T4: Amended + Off Ground | 1248 (1113) | 267 (238) | 31% | 10.6% | 8.43% b |
| 2022 | | | | | |
| T1: Control | 1137 (1014) | 202 (180) | 26% | 14.1% | 7.75% b |
| T2: Off Ground | 1258 (1122) | 87 (78) | 26% | 34.0% | 1.01% c |
| T3: Amended | 1007 (898) | 253 (226) | 25% | 35.3% | 14.5% a |
| T4: Amended + Off Ground | 1097 (979) | 136 (121) | 25% | 16.0% | 1.78% c |

## Pictures

Amendment materials applied at Crown Nut Co February 2020

Hulls Mix Shells

2/10/2020 Application Day, Crown Nut Co.

2/26/2020, Crown Nut Co.

7/27/2020 Shells (left) and hulls (right) 1 week before the sweepers started, Crown Nut Co.

8/10/2020 on-ground harvest left the ground bare, Crown Nut Co.

## 2.11 Literature Cited

Agele, S.O., & Agbona, A.I. (2008). Effects of cocoa pod husk amendment on soil and leaf chemical composition and growth of cashew (*Anacardium occidentale* L.) seedlings in the nursery. American-Eurasian Journal of Sustainable Agriculture, 2(3), 219-224.

Aguilar, A. A., Smith, N. E., & Baldwin, R. L. (1984). Nutritional Value of Almond Hulls for Dairy Cows. Journal of Dairy Science, 67(1), 97–103.

Almond Board of California. (2020). Almond Almanac. Modesto, California. Document #2020IR0296.

Almond Board of California (2019) Committed to Continuous improvement: announcing the almond orchard 2025 goals. https://www.almonds.com/

Andrews, E.M., Kassama, S., Smith, E.E., Khalsa, S.D.S., & Brown, P.H. (2021). A review of potassium-rich crop residues used as organic matter amendments in orchard crop systems. MDPI Agriculture Special Issue, Organic Management and Productivity of Tree Crops, 11(7).

Bittenbender, H.C., Hue, N.V., Fleming, K., & Brown, H. (1998). Sustainability of organic fertilization of macadamia with macadamia husk-manure compost. Communications in Soil Science and Plant Analysis, 29(3-4), 409-419.

Brito, O., Telles, T., Schnitzer, J., Gaspar, G., & Fatima, M. (2014). The influence of crop residues in vertical soil mobility of potassium. Semina: Ciências Agrárias, 35, 3043.

Carmo, D.L., Lima, L.B., & Silva, C.A. (2016). Soil fertility and electrical conductivity affected by organic waste rates and nutrient inputs. Revista Brasileira de CIA do Solo, 40.

CDFA FREP (2022) California Crop Fertilization Guidelines: Almonds. California Depart ment of Food and Agriculture Fertilizer Research and Education Program, University of California Davis. https://www.cdfa.ca.gov/is/ffldrs/frep/FertilizationGuidelines/Almonds.html

Cobo, J. G., Barrios, E., Kass, D. C. L., & Thomas, R. J. (2002). Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. Plant and Soil, 240(2), 331–342.

Doll, D., Shackel, K. (2015). Drought Tip: Drought management for California almonds. University of California Agriculture and Natural Resources Publication 8515.

Dong, S., Ma, Z., Wang, L., Yan, C., Liu, L., Gong, Z., & Cui, G. (2019). Decomposition and nutrient release characteristics of incorporated soybean and maize straw in Northeast China. Ekoloji, 107, 2119–2129.

Doungous, O., Emile, M., Longue, E., & Nkengafac, N. (2018). Potentials of cocoa pod husk-based compost on Phytophthora pod rot disease suppression, soil fertility, and Theo broma cacao L. growth. Environmental Science and Pollution Research, 25.

Esfahlan, A.J., Jamei, R., Esfahlan R.J. (2010) The importance of almond (*Prunus amygdalus* L.) and its by-products. Food Chemistry, 120:349-360.

Fenster, T.L.D., Oikawa, P.Y., Lundgren, J.G. (2021) Regenerative almond production systems improve soil health, biodiversity, and profit. Frontiers in Sustainable Food

Systems, 5:664359.

Fernandez-Bayo, J. D., Shea, E. A., Parr, A. E., Achmon, Y., Stapleton, J. J., VanderGheynst, J. S., Hodson, A. K., & Simmons, C. W. (2020). Almond processing residues as a source of organic acid biopesticides during biosolarization. Waste Management, 101, 74–82.

Garcia, A., Crusciol, C.A.C., Rosolem, C.A., Bossolani, J.W., Nascimento, C.A.C., McCray, J.M., dos Reis, A.R., Cakmak, I. (2022) Potassium-magnesium imbalance causes detrimental effects on growth, starch allocation, and Rubisco activity in sugarcane plants. Plant Soil, 472:225-238.

Gransee, A., Fuhrs, H. (2013) Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. Plant Soil, 368:5-21.

Hernández-Montoya, V., Mendoza-Castillo, D. I., Bonilla-Petriciolet, A., Montes-Morán, M. A., & Pérez-Cruz, M. A. (2011). Role of the pericarp of *Carya illinoinensis* as biosorbent and as precursor of activated carbon for the removal of lead and acid blue 25 in aqueous solutions. Journal of Analytical and Applied Pyrolysis, 92(1), 143–151.

Idowu, O. J., Sanogo, S., & Brewer, C. E. (2017). Short-Term Impacts of Pecan Waste By-Products on Soil Quality in Texturally Different Arid Soils. Communications in Soil Science and Plant Analysis, 48(15), 1781–1791.

The World Bank (2022) Commodity Markets Outlook, Charts and Data Files, April 2022. https://www.worldbank.org/en/research/commodity-markets

Jahanzad, E., Holtz, B.A., Zuber, C.A., Doll, D., Brewer, K.M., Hogan, S., Gaudin, A.C.M. (2020) Orchard recycling improves climate change adaptation and mitigation potential of almond production systems. PLoS ONE 15(3): e0229588.

Jahanzad, E., Brewer, K.M., Poret-Peterson, A.T., Culumber, C.M., Holtz, B.A., Gaudin, A.C.M. (2022). Effects of whole-orchard recycling on nitrate leaching potential in almond production systems. Journal of Environmental Quality, 51:941-951.

Karagoktas, M., Uygur, V., Aydoğdu, M., & Rastgeldi, I. (2014). The effects of pistachio nut hull compost on soil fertility: A comparative study with manure. Soil Science Society of Turkey and Federation of Eurasian Soil Science Societies. 9th International Soil Science Congress.

Kasongo, R. K., Verdoodt, A., Kanyankagote, P., Baert, G., & Ranst, E. V. (2011). Coffee waste as an alternative fertilizer with soil improving properties for sandy soils in humid tropical environments. Soil Use and Management, 27(1), 94–102.

Kaushal, R., Verma, K., Chaturvedi, O. P., & Alam, N. M. (2012). Leaf litter decomposition and nutrient dynamics in four multipurpose tree species. Range Management and Agroforestry, 33, 20–27.

Koné, K., Akueson, K., & Norval, G. (2020). On the Production of Potassium Carbonate from Cocoa Pod Husks. Recycling, 23.

Krishna, M. P., & Mohan, M. (2017). Litter decomposition in forest ecosystems: A review. Energy, Ecology and Environment, 2(4), 236–249.

Krueger, B. (2010) Fall nutrition management. University of Cooperative Extension Tehama

County Fruit and Nut Notes, November 2010, 5.

Lepsch, H.C., Brown, P.H., Peterson, C.A., Gaudin, A.C.M., Khalsa, S.D.S. (2019) Impact of organic matter amendments on soil and tree water status in a California orchard. Agricultural Water Management 222:204-212.

Li, J., Lu, J., Li, X., Ren, T., Cong, R., & Zhou, L. (2014). Dynamics of Potassium Release and Adsorption on Rice Straw Residue. PLOS ONE, 9(2), 1–9.

Lipan, L., Martin-Palomo, M.J., Sanchez-Rodriguez, L., Cano-Lamadrid, M., Sendra, E., Hernandez, F., Burlo, F., Vazquez-Araujo, L., Andreu, L., Carbonell-Berrachina, A.A. (2019). Almond fruit quality can be improved by means of deficit irrigation. Agricultural Water Management, 217:236-242.

Lobel, M. R., Firth, D. J., & Johns, G. G. (1994). Effect of mulch, Ca, and Mg on growth, yield, and decline of macadamia. Tropical Agriculture, 71(3), 170–175.

López, R., Burgos, P., Hermoso, J. M., Hormaza, J. I., & González-Fernández, J. J. (2014). Long term changes in soil properties and enzyme activities after almond shell mulching in avocado organic production. Soil and Tillage Research, 143, 155–163.

Martinez-Mena, M., Carillo-Lopez, E., Boix-Fayos, C., Almagro, M., Franco, N.G., Diaz-Pereira, E., Montoya, I., de Vente, J. (2020) Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. Catena, 187:104352.

Miyazawa, M., Pavan, M. A., & Franchini, J. C. (2002). Evaluation of plant residues on the mobility of surface applied lime. Brazilian Archives of Biology and Technology, 45(3), 251–256.

Moyin-Jesu, E. I. (2007). Use of plant residues for improving soil fertility, pod nutrients, root growth and pod weight of okra (*Abelmoschus esculentum* L). Bioresource Technology, 98(11), 2057–2064.

Muhammad, S., Sanden, B.L., Lampinen, B.D., Smart, D.R., Saa, S., Shackel, K.A., Brown, P.H. (2020). Nutrient storage in the perennial organs of deciduous trees and remobilization in Spring—a study in almond (*Prunus dulcis*) (Mill.) D.A. Webb. Frontiers in Plant Sciences, 11, 658.

Nagao, M. A., Hirae, H. H., & Stephenson, R. A. (1992). Macadamia: Cultivation and physiology. Critical Reviews in Plant Sciences, 10(5), 441–470.

Nduka, B., Adewale, D., Akanbi, O., & Adejobi, K. (2015). Nursery Soil Amendments for Cashew Seedling Production: A Comparative Analysis of Coffee Husk and NPK. Journal of Agricultural Science, 7.

Neilsen, G. H., Hogue, E. J., Forge, T., & Neilsen, D. (2002). Surface application of mulches and biosolids affect orchard soil properties after 7 years. Canadian Journal of Soil Science, 83(1), 131–137.

Neilsen, G. H., Hogue, E. J., Forge, T., & Neilsen, D. (2003). Mulches and Biosolids Affect Vigor, Yield and Leaf Nutrition of Fertigated High Density Apple. HortScience, 38(1), 41–45.

Neilsen, G., Forge, T., Angers, D., Neilsen, D., & Hogue, E. (2014). Suitable orchard floor management strategies in organic apple orchards that augment soil organic matter and maintain tree performance. Plant and Soil, 378(1), 325–335.

Nyomora, A.M.S., Brown, P.H., Freeman, M. (1997) Fall foliar-applied boron increases tissue boron concentration and nut set of almond. Journal of the American Society of Horticultural Science, 122:405-410.

Oyewole, O., Omueti, J., & Rotimi, R. (2012). Growth of cocoa (*Theobroma cacao* L.) seedlings on old cocoa soils amended with organic and inorganic fertilizers. African Journal of Agricultural Research 7(24):3604–3608.

Panak Balentić, J., Ačkar, Đ., Jokić, S., Jozinović, A., Babić, J., Miličević, B., Šubarić, D., & Pavlović, N. (2018). Cocoa Shell: A By-Product with Great Potential for Wide Application. Molecules, 23(6).

Prescott, C. E., & Vesterdal, L. (2021). Decomposition and transformations along the continuum from litter to soil organic matter in forest soils. Forest Ecology and Management, 498, 119522.

Prgomet, I., Gonçalves, B., Domínguez-Perles, R., Pascual-Seva, N., & Barros, A. I. R. N. A. (2017) Valorization Challenges to Almond Residues: Phytochemical Composition and Functional Application. Molecules, 22(10).

Rodríguez-Lizana, A., Carbonell, R., González, P., & Ordóñez-Fernández, R. (2010). N, P and K released by the field decomposition of residues of a pea-wheat-sunflower rotation. Nutrient Cycling in Agroecosystems, 87, 199–208.

Rosolem, C. A., Calonego, J. C., & Foloni, J. S. S. (2005). Potassium leaching from millet straw as affected by rainfall and potassium rates. Communications in Soil Science and Plant Analysis, 36(7–8), 1063–1074.

Samuel, A., & Agbona, A. (2008). Effects of cocoa pod husk amendment on soil and leaf chemical composition and growth of cashew (*Anacardium occidentale* L.) seedlings in the nursery. American-Eurasian Journal of Sustainable Agriculture, 2, 219–224.

Sanden, B.L., Muhammad, S., Brown, P.H., Shackel, K.A., Snyder, R.L. (2014). Correlation of individual tree nut yield, evapotranspiration, tree stem water potential, total soil salinity and chloride in a high production almond orchard. ASABE Annual International Meeting Montreal, Quebec Canada July 13-16, American Society of Agricultural and Biological Engineers, 141912431, 8.

Singh, V. K., Dwivedi, B. S., Yadvinder-Singh, Singh, S. K., Mishra, R. P., Shukla, A. K., Rathore, S. S., Shekhawat, K., Majumdar, K., & Jat, M. L. (2018). Effect of tillage and crop establishment, residue management and K fertilization on yield, K use efficiency and apparent K balance under rice-maize system in north-western India. Field Crops Research, 224, 1–12.

Smith, E.E., Brown, P.H., Andrews, E.M., Shackel, K.A., Holtz, B.A., Rivers, D.J., Haviland, D.R., Khalsa, S.D.S. (2022). Early almond harvest as a strategy for sustainable irrigation, pest and disease management. Scientia Horticulturae 293:110651.

Soto, R.L., Martinez-Mena, M., Padilla, M.C., de Vente, J. (2021). Restoring soil quality of woody agroecosystems in Mediterranean drylands through regenerative agriculture. Agriculture, Ecosystems and Environment, 306:107191.

Sumner, D.A., Buchner, R.P., Niederholzer, F., Jarvis-Shean, K.S., Lightle, D.M., Symmes, E.J., Milliron, L., Stewart, D. (2019). Sample costs to establish an orchard and produce almonds Sacramento Valley. University of California Agriculture and Natural Resources Cooperative Extension. UC Davis Department of Agricultural and Resource Economics. https://coststudyfiles.ucdavis.edu/uploads/cs_public/67/b7/67b72c81-5ce0-4462-a396-fbb62ce8564e/2019sacvalleyalmonds.pdf

Tagliavini, M., Tonon, G., Scandellari, F., Quiñones, A., Palmieri, S., Menarbin, G., Gioacchini, P., & Masia, A. (2007). Nutrient recycling during the decomposition of apple leaves (*Malus domestica*) and mowed grasses in an orchard. Agriculture, Ecosystems & Environment, 118(1), 191–200.

Xie, K., Cakmak, I., Wang, S., Zhang, F., & Guo, S. (2020). Synergistic and antagonistic interactions between potassium and magnesium in higher plants. Crop Science Society of China, The Crop Journal, 9:249-256.

Yang, F.K., He, B., Zhang, L., Zhang, G., Gao, Y. (2020). An approach to improve soil quality: a case study of straw incorporation with a decomposer under full film-mulched ridge-furrow tillage on the semiarid loess plateau, China. Journal of Soil Science and Plant Nutrition, 20:125-138.

Zeng, Q., Brown, P. H., & Holtz, B. A. (2001). Potassium Fertilization Affects Soil K, Leaf K Concentration, and Nut Yield and Quality of Mature Pistachio Trees. HortScience, 36(1), 85–89.

Zoca, S.M., Penn, C.J., Rosolem, C.A., Alves, A.R., Neto, L.O., Martins, M.M. (2014). Coffee processing residues as a soil potassium amendment. International Journal of Recycling of Organic Waste Agriculture, 3, 155-165.

## Chapter 3: Almond hull and shell organic matter amendments provide a mulching effect that improves soil-plant water dynamics in a California almond orchard

### 3.1 Background

In 2021, California almond area was estimated at 0.538 bearing hectares (1.33 million bearing acres) with a forecast of 1.27 billion kg (2.80 billion pounds) kernels and a $5B USD production value (USDA, 2022; USDA, 2021). While many factors influence yield, irrigation is often considered a central limiting factor for almond yield and nut quality (Tejero et al. 2018, Goldhamer and Fereres 2017). High yields in California almond systems rely on high annual water inputs. Recommendations vary by region, for instance, 0.39 hectare meters (38 acre-inches) of irrigation annually are needed for a typical 2466 kg $ha^{-1}$ (2,200 lb $ac^{-1}$) kernel yield in the Sacramento Valley, while 0.53 hectare meters (52 acre-inches) are needed for a typical 3363 kg $ha^{-1}$ (3,000 lb $ac^{-1}$) kernel yield in the Southern San Joaquin Valley (Sumner et al. 2019, Sumner et al. 2019). For context, recommendations for other major permanent crops at maturity in California include 0.51 hectare meters (49.5 acre-inches) for pistachios (Sumner et al. 2020), 0.37-0.43 hectare meters (36-42 acre-inches) for walnuts (Sumner et al. 2017), and 0.15-0.37 hectare meters (15-36 acre-inches) annually for wine grapes (Sumner et al. 2019, Sumner et al. 2021). While almond trees can survive on as little as 0.078 hectare meters (7.6 acre-inches) of water, they produce maximally with 0.55-0.59 hectare meters (54-58 acre-inches) of water per year in California; almond yield is very sensitive to water stress and irrigation is critical for producing the highest possible yields (Doll and Shackel 2015, Lipan et al. 2019, Goldhamer et al. 2006, Martin-Palomo et al. 2022).

California almond crop system irrigation management has changed substantially in recent years. While yields increased by approximately 250% in the four decades leading up to 2017, estimated statewide annual almond orchard evapotranspiration was about 25% higher as well despite the switch from surface irrigation systems (e.g., flood) to pressurized systems (Goldhamer and Fereres 2017, Stewart et al. 2011). Recently, California almonds have received media scrutiny due to the substantial amount of water used for this crop in a region facing unprecedented drought conditions, aridification, and decreases in water availability that are expected to intensify (Fulton et al. 2019, Overpeck and Udall 2020). While almonds provide high nutritional benefit per unit weight and are California's top economic-value export crop, the water footprint value per crop weight is very high (Fulton et al. 2019). It has been estimated that California almonds average 12 liters (3.2 gallons) of water consumption per almond kernel (Fulton et al. 2019). The Almond Board of California's 2025 sustainability goals include, "reduce the amount of water used to grow a pound of almonds by 20%," suggesting water use efficiency could be improved in almond crop systems on a per kernel basis, or "crop per drop."

However, substantial scientific evidence shows increased water use efficiency and water saved at the farm scale reduces valuable return flows and rarely lowers overall water consumption at larger watershed scales (Ward et al. 2008, Grafton et al. 2018, Linstead 2018). Higher irrigation efficiency means the water saved can be recovered and reused at the basin and watershed scales, which can increase groundwater extractions, on-farm water consumption, and the switch to more water-intensive crops (Grafton et al. 2018). Multi-year droughts in California have reduced agricultural surface water use and increased groundwater pumping, amplifying a long-term groundwater overdraft trend which primarily supports agriculture (Mall and Herman, 2019). Overdraft leads to lower well yields, reduced water quality, higher pumping costs, and land subsidence (Mall and Herman, 2019). The burden of well water outages primarily falls on small rural communities that lack access to alternative supplies (Mall and Herman, 2019).

Groundwater issues led to the Sustainable Groundwater Management Act (SGMA) to address agriculture's increasing reliance on groundwater by developing localized groundwater sustainability plans to improve management and address issues such as over-pumping and subsidence (Drechsler et al. 2022, California DWR). Effective policy actions include the development of physical water accounts, decreases in water extractions through direct caps, irrigation efficiency risk assessments, accurate monitoring, comprehensive valuation methods, and evaluation of the behavior of irrigators (Grafton et al. 2018). Strategies to improve irrigation efficiency and reduce water use in the field must be integrated with multi-scale regional and state-wide policy implementation to effectively conserve agricultural water in watersheds and basins. At every scale, water conservation is at the center of agricultural sustainability in California as the effects of a changing climate intensify.

Within this context, considering what actions can be taken at the orchard scale, growers can integrate a variety of irrigation management options (a "toolbox" approach) to improve efficiency and reduce overall water consumption (see Supplementary Table 1). Broadly speaking, the typical California almond orchard water budget includes additions from precipitation and irrigation while water losses occur through transpiration and evaporation from the soil surface which depletes soil moisture. Efficient irrigation management strategies can help reduce water losses from the orchard, concentrate water in the root zone, more precisely match water supply with crop demand, and reduce under- or over-applications. For instance, drip irrigated systems tend to be more efficient than micro sprinkler irrigated systems; well-managed drip irrigation systems can have irrigation efficiency of 85% in almonds (Grafton et al. 2018, Fereres et al. 1982). Monitoring tools such as ETc, pressure chambers, and aerial thermal imaging can help guide irrigation scheduling. Pulse irrigation, strategic deficit irrigation (SDI) and proportional or regulated deficit irrigation (RDI) can help growers apply water based on strategic timing decisions (Supplementary Table 1). For instance, a study implementing RDI with a water stress level of -1.4 to -1.8 MPa (-14 to -18 bars) during almond hull split led to an average of 13.5 cm of annual water savings without reducing yield (Stewart et al. 2011). Further research is needed to assess potential benefits of management practices that both increase irrigation efficiency and reduce crop consumptive water use.

Mulching practices can complement sustainable irrigation strategies particularly in arid and semi-arid climates. Mulches made of materials such as crop residues, nutshells, and wood chips provide a physical barrier on the surface of the soil. This can reduce evaporative losses from the soil surface by reducing latent heat flux, radiation intensity, soil temperature, and air movement while providing physical resistance to vapor flow to the atmosphere. This modification to the soil surface energy balance can reduce soil evaporation, improve water storage, and in some cases reduce tree water stress. Lowered tree water stress can help maintain open stomata, promote transpiration, nutrient and water uptake and translocation, and carbon assimilation which can increase crop productivity if yield is water limited (Farzi et al. 2017, Jafari et al. 2012, Nielsen et al. 2002, Nielsen et al. 2003). Over time, maintaining undisturbed layers of repeated mulch applications can help build soil organic matter and improve aspects of soil physical structure such as bulk density and aggregate stability which can improve soil water retention. Together, an immediate mulching effect combined with gradual changes in soil physical properties could improve water retention in the root zone.

Nutshells used as mulches present a sustainable destination for post-processing crop biomass that can be recycled and returned the orchard. Almond hulls and shells are an abundant byproduct in California, making up approximately 70% of crop weight leaving orchards at harvest (Almond Almanac, 2020). For instance, in 2020, the 3.12 billion kernel pounds produced would correspond to approximately 7.28 billion pounds of hulls and shells (USDA 2021). While some portion of these hulls and shells are sold as dairy feed, billions of pounds of remaining hulls and shells need a practical and sustainable destination near processing facilities. In recent years, some California almond growers have started using compost spreader machinery to apply almond hulls and shells as a surface mulch in orchards close to processing facilities. However, the effects of this practice on soil-plant water dynamics have not yet been studied in this region.

California almond orchards typically utilize on-ground harvest practices which require bare orchard soil for crop pickup. Soil conditioning and herbicides are typically used to minimize organic plant debris and vegetation to ensure a bare soil surface at harvest. These practices associated with on-ground harvest can lead to soil erosion, dust pollution, low soil organic matter content, compaction from frequent machinery passes (Andrews et al. 2021). While crop residue applications such as nutshells can contribute to the formation of new organic layers in orchards over time, mechanical disturbance eliminates this organic layer and limits potential benefits gained. However, off-ground harvest equipment such as catch frame harvest machinery is currently used in prune, pistachio, and other California tree crops to avoid crop contact with the orchard soil. This off ground equipment can be modified by engineers to suit almond orchard specifications and can eliminate soil sweeping in the tree row. Off-ground harvest can help maintain an undisturbed organic hull/shell mulch layer as a barrier on the soil surface to provide benefits for orchard soil health, nutrient cycling, and water dynamics (Andrews et al. 2021). This study examines the effects of almond hulls and shells used as a surface-applied organic matter amendment on soil-plant water dynamics when maintained over time with off-ground harvest.

### 3.2 Research Question

How do almond hull and shell organic matter amendments on the soil surface affect soil and tree water dynamics?

### 3.3 Hypotheses

This amendment provides a mulching effect: a physical barrier on the soil surface that reduces surface evaporation, helps maintain soil moisture storage, and may reduce tree water stress to some degree. Maintaining the organic amendment layer with off ground harvest could increase the associated benefits over time by building a persistent organic layer on the soil surface. The hull/shell organic layer will improve soil environmental conditions near the soil surface where almond roots tend to be concentrated. These effects could potentially allow growers to extend irrigation cycles by a day or two and slightly reduce annual water use.

### 3.4 Site Description

Westwind Farms is located near Woodland, California. It is a 62-hectare (152-acre) almond orchard with Nonpareil variety on Bright Hybrid 5 rootstock and alternating pollinizer rows. All data was collected from Nonpareil rows only. Rows are oriented north-south and tree spacing is 6.7 x 4.6 meters (22 x 15 ft). The experimental area consists of 40 trees per row and is located on the southwest area of the orchard. The soil type within this experimental plot is San Ysidro loam (NRCS, see Chapter 2 for further details). Irrigation is applied by micro-sprinklers which are located approximately 2.3 meters (7.5 ft) from trees. In 2021, the irrigation schedule consisted of 24-hour sets every 6 days, whereas longer more frequent irrigation sets were used in 2022. Prior to trial establishment, in the top 0-10 cm soil average pH was 7.4, average percent organic matter was 2.3%, and average CEC was 20 meq 100 $g^{-1}$ soil. From 10/9/2020 until 10/9/2021, this orchard received approximately 5 hectare centimeters (4.9 acre-inches) of total rainfall (CIMIS station #226).

### 3.5 Experimental Design

The trial is a randomized complete block design with treatments applied to entire rows of trees, thus each individual row is referred to as a plot. The control represents typical almond orchard conditions of bare soil and on-ground harvest. Three treatments were replicated across four blocks: control, hull/shell amendments, and hull/shell amendments with catch frame (off ground) harvest. On 10/7/2020, 18 tons ha$^{-1}$ (8 US tons ac$^{-1}$) of hull/shell mix (32% hulls and 68% shells) with 6.6% moisture were applied at approximately 17 dry tons ha$^{-1}$ (7.5 dry US tons ac$^{-1}$) broadcasted by a compost spreader across the tree row and alley. On 10/4/2021, 18 tons ha$^{-1}$ (8 US tons ac$^{-1}$) hull/shell mix (53% hulls and 47% shells) were applied with 2.1% moisture at approximately 17.5 dry tons ha$^{-1}$ (7.8 dry US tons ac$^{-1}$) total concentrating the amendment over tree roots only. The tree row berm area is around 36% of the total area.

### 3.6 Methods and Analyses

3.6.1 Soil Monitoring. Acclima Time Domain Reflectometry (TDR 315) sensors were installed at 5 cm depth with Acclima DataSnap dataloggers in May 2022 to record measurements in the soil layer near the surface. TDR sensors measured volumetric moisture (percent), temperature (°C), permittivity (ε, the ability to hold an electric charge), conductivity (μS cm$^{-1}$), and pore water electrical conductivity (PWEC, μS cm$^{-1}$). Each installation consisted of one datalogger with three TDR sensors. Each installation was located next to the northern most Phytech dendrometer trees in the control and amended catch frame treatments across all four blocks, totaling 24 TDR probes (Diagram 1). Next to the middle tree in each cluster of three Phytech trees across all treatments, a Phytech soil probe was installed within the irrigation zone to measure soil moisture and temperature at depths in the 15.2-91.4 cm (6–36-inch) range. All Acclima TDR sensors were installed approximately 0.91 m (3 ft) from each micro sprinkler, halfway between the micro sprinkler and the edge of the irrigation zone at three locations: in the center of the row between the sprinkler and the north tree, toward the alley directly east of the sprinkler, and on the northeast diagonal between the other two sensors (Diagram 1). Sensors were removed from the field on 8/1/2022 immediately prior to harvest to avoid equipment damage by harvest machinery.

3.6.2 Tree Monitoring. Phytech dendrometers were installed in all treatments in mid-May 2022. Clusters of three adjacent trees with similar moderate growth were chosen based on NDVI data within each treatment row across all four blocks for a total of 36 monitoring trees. Data from dendrometers was averaged between three trees in each cluster within each plot. Two irrigation pressure sensors were installed at east and west sides of the hull/shell trial area. Mean Daily Shrinkage (MDS) and trunk growth data provided by Phytech represented the average of each cluster of three trees per treatment row. The greater the MDS (trunk contraction) the higher the tree water stress. As the difference between maximum and minimum values, MDS is an indicator commonly used for irrigation scheduling (Martin-Palomo et al. 2022). On a practical basis, the dendrometer partner company used a plant status color scheme to help growers assess tree stress status via an App. This color scheme consists of green (lowest stress), yellow, orange, red (highest stress) groups that are based on an algorithm using daily growth and MDS values. While the grower typically applied irrigation in weekly 24-hour sets in 2021, the grower used the app and provider guidance to shift to pulse irrigation in 2022.

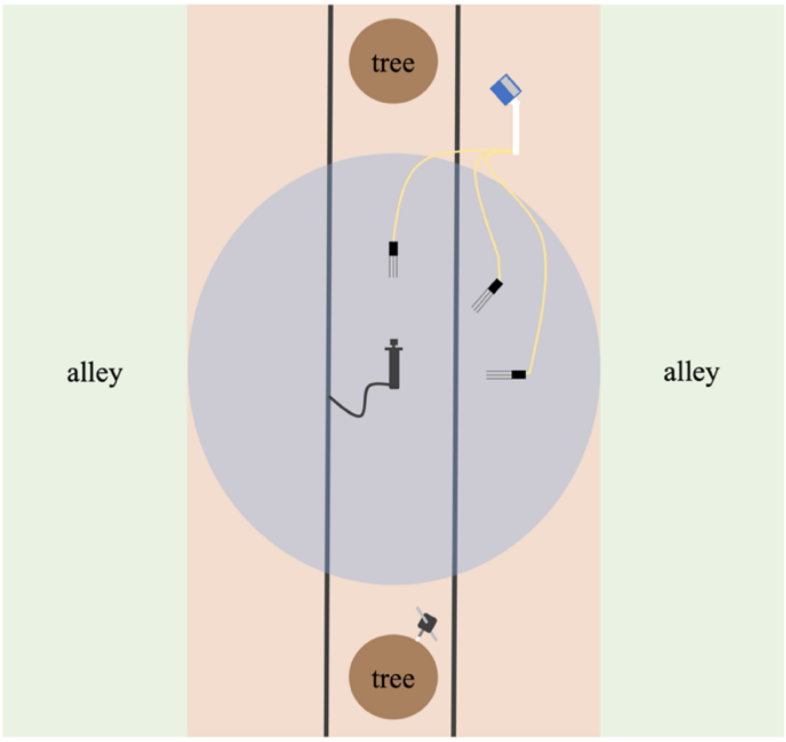


Diagram 3.1. Acclima and Phytech field installation arrangement. Three TDR probes connected to a datalogger arranged around an irrigation micro sprinkler within the wetted zone (light blue circle) north of the north most tree with a Phytech dendrometer. Within each treatment row, three dendrometers were installed in three adjacent trees.

3.6.3 Physiological Measurements. Stem water potential (SWP) measurements were taken using a pressure chamber (Soil Moisture Equipment Corp.) to assess tree water stress following the protocol outlined in Shackel et al. 2011. At midday, mature lower canopy leaves attached to stems near main scaffold limbs were enclosed for at least 10 minutes to allow equilibration. SWP Baseline values were estimated using the almond specific chart found on Sacramento Valley Orchards website (Fulton 2019, McCutchan and Shackel 1992). Baselines integrate temperature and vapor pressure deficit at the time of SWP measurements, which was provided by a local CIMIS station 226 located approximately four miles from this field site. Stomatal conductance measurements were taken on fully sunlit mature leaves on the southeast side of the canopy using a porometer (Delta-T Model AP4). On 6/7/2021, pre-dawn stem water potential ($\Psi_{pd}$), mid-day stem water potential($\Psi_{md}$), and stomatal conductance measurements ($g_s$) were taken to estimate transpiration (E) and leaf-specific hydraulic conductance ($K_{plant}$):

$$E = g_s * VPD \qquad \text{Eq. 3.1.}$$

$$K_{plant} = \frac{E}{(\Psi pd - \Psi md)} \qquad \text{Eq. 3.2.}$$

3.6.4 ERT, Neutron Probe, Flora Pulse Dendrometers, Stem and Leaf Water Potential On 8/10/2021, collaborators Dr. Isaya Kisekka and Dr. Daniela Camila conducted Electrical Resistivity Tomography (ERT) imaging. These time-lapse surveys were conducted in the control row and the amended catch frame row in Block 2 only. Images were taken at 6:00am prior to the start of irrigation, then again at 8:40am, 10:00am, 11:15am, 12:30pm, 2:00pm, and 3:45pm. Irrigation began at 7am and lasted for 24 hours. A neutron probe was used to measure soil water content (SWC) in the control and amended rows at these time points. At each of the six time points, 12 stem water potential (SWP) and 12 leaf water potential (LWP) measurements were measured from three control trees and three amended trees located within the ERT sampling area. Stem and leaf water potential measurements were compared to tree water data provided by Flora Pulse dendrometers at each time point. Together, these methods were used to evaluate the effects of the hull/shell amendment on soil and plant water dynamics during the beginning of an irrigation event.

3.6.5 Spring Root Biomass and Bulk Density. Soil samples from the upper 0-10 cm soil located halfway between the micro sprinkler and the edge of the irrigation zone were collected using a 10 cm x 3.8 cm auger for root biomass density. On 5/17/2022, samples were taken from the control and amended catch frame treatments only. Roots were separated from soil under water using a 1mm soil sieve and forceps. Fresh root biomass was weighed, oven-dried, and re-weighed for dry root biomass. On 6/21/2022, these steps were repeated with samples from all three treatments to assess whether harvest type affected root biomass. In fall 2022, bulk density measurements were taken from all three treatments using a metal ring and mallet, dried, weighed, calculated, and expressed as grams of soil cm$^{-3}$.

3.6.6. Data Analysis. All data analysis was performed in R (version 4.1.2, 2021 The R Foundation for Statistical Computing, RStudio 2022.07.1 build 554). The package ggplot2 was used for data visualization. Smoothed conditional means and local regression fitting were utilized for soil water and temperature data visualization. The lmer() command from the lmerTest package was used for linear mixed effect models, with treatments as fixed effects and plots and blocks as random effects. When subsamples within plots were kept separate prior to analysis, plots were included in the model as nested within blocks. Normal Quantile-Quantile plots and Scale-Location plots were used to test assumptions of normality and homogeneity of variances prior to analysis of variance (ANOVA). Alpha values were consistently set to 0.05. ANOVA was performed after testing assumptions and CLD groupings were generated using the estimated marginal means for multiple pairwise comparisons using the multcomp package.

## 3.7 Results

### 3.7.1 Soil Monitoring

TDR Acclima data indicated that the control soil was tended to be drier than the amended catch frame soil in the upper 0-10 cm (0-4 inches) (Table 3.1, Figures 3.1 and 3.2). When average percent moisture was used to estimate average water in the top 0-10 cm, the cumulative daily difference between treatment averages was 0.04 hectare meters (3.67 acre-inches) of water total for the 80 days studied (Table 3.2). At this shallow depth, the amended catch frame treatment appears to have increased overall soil conductivity, pore water electrical conductivity, and permittivity (Supplementary Figures 3.1-3). Under the amended catch frame treatment, average soil temperatures were higher, but daily and hourly temperature extremes were more moderated than control soil (Table 3.1, Figure 3.3).

Table 3.1. Summary of Acclima TDR probe results across time in the upper 0-10 cm (0-4 inches of soil). Descriptions are based on plots from respective time scales. Selected days for the Daily column were chosen using one low, one moderate, and one high MDS day per month: 5/21/22, 5/23/22, 5/24/22; 6/22/22, 6/23/22, 6/25/22; 7/6/22, 7/7/22, 7/10/22. Ctrl = control treatment and AC = amended catch frame treatment.

| **Response Variable** | **All Dates** | **Monthly** | **Daily** | **Hourly** |
|---|---|---|---|---|
| Water (%) | Ctrl < AC | Ctrl < AC | Ctrl < AC only as soil dries early summer | Ctrl < AC especially late morning, late afternoon, and evening |
| Temperature | Ctrl < AC | Ctrl < AC | Often statistically similar, but Ctrl more extreme & AC more moderate | Consistently statistically different, warmer in AC at night and cooler during day |
| Conductivity | Ctrl < AC | Ctrl < AC especially with high water | Ctrl < AC only with high soil water | Ctrl < AC especially at night-early morning |
| PWEC | Ctrl < AC | Ctrl < AC | Variable, Ctrl more extreme, AC more moderate | Variable, Ctrl more extreme, AC more moderate |
| Permittivity | Ctrl < AC | Ctrl < AC | Control < AC only as soil dries early summer | Ctrl < AC similar hourly times as water |

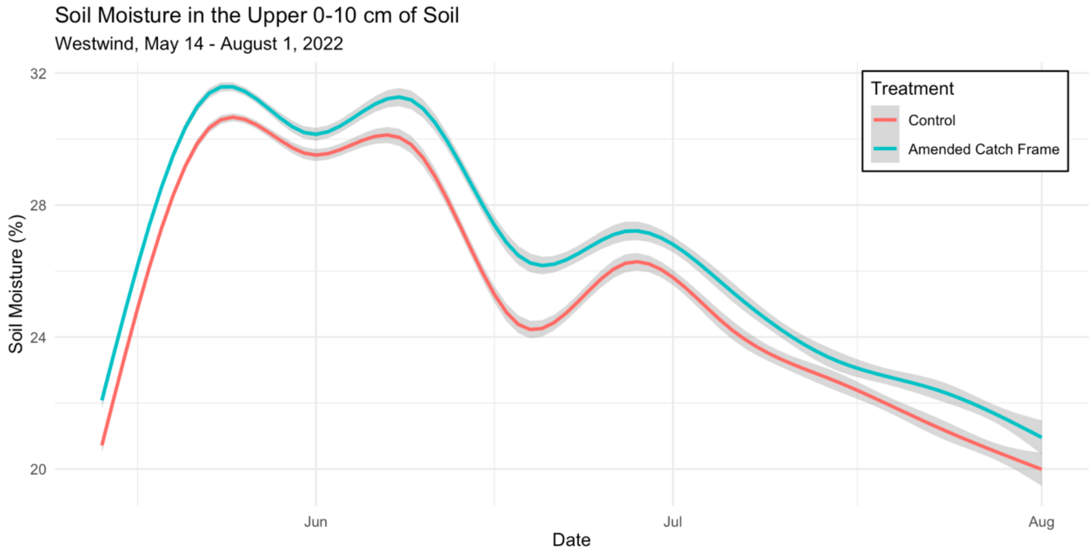


Figure 3.1. Soil moisture (percent) in the top 0-10 cm (0-4 inches) of soil measured by Acclima TDR probes, 5/14/2022-8/1/2022.

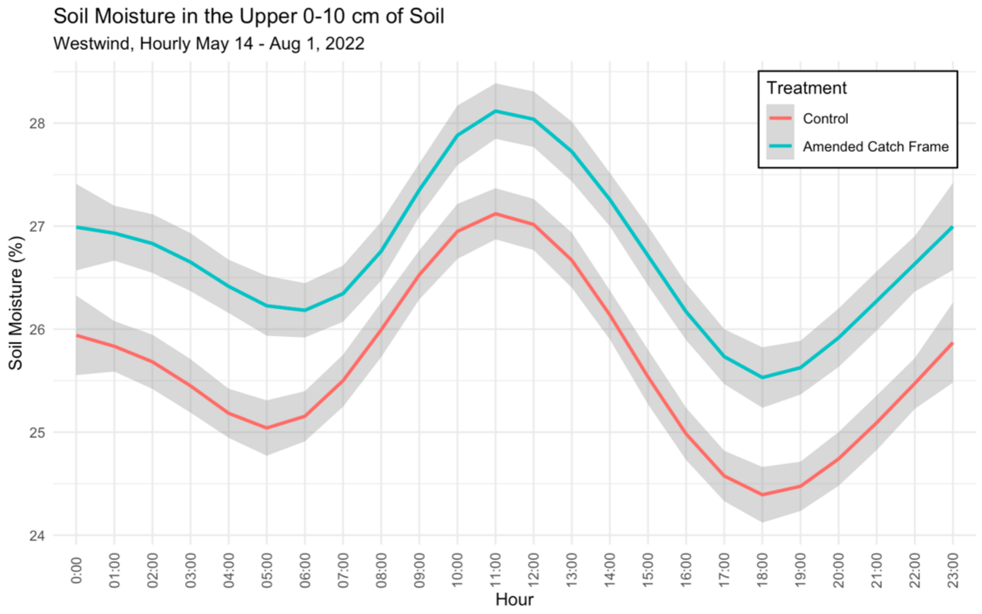


Figure 3.2. Average soil moisture (percent) by the hour across all dates measured, upper 0-10 cm (0-4 inches) soil, Acclima TDR probes.

Table 3.2. Monthly soil water data for control soil vs. amended catch frame soil. The cumulative difference between daily treatment averages was 0.04 hectare meters (3.67 acre-inches) of water total in the upper 0-10 cm (0-4 inches) soil. P-values present comparisons between average percent moisture in control vs. amended catch frame soil within the specified time frame.

|  | May 14-31 | June 1-30 | July 1-31 |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Estimated daily mean treatment difference in water content, hectare meters (acre-inches) | 0.0004<br>(0.04) | 0.0006<br>(0.059) | 0.0004<br>(0.043) |
| Cumulative estimated treatment difference in water content, hectare meters (acre-inches) | 0.0072<br>(0.70) | 0.0178<br>(1.73) | 0.0127<br>(1.24) |
| Average percent moisture: control soil | 27.9% | 27.3% | 22.6% |
| Average percent moisture: amended catch frame soil | 29.0% | 28.7% | 23.6% |
| Average percent moisture: p-value | <2.2E$^{-16}$ *** | <2.2E$^{-16}$ *** | <2.2 E$^{-16}$*** |

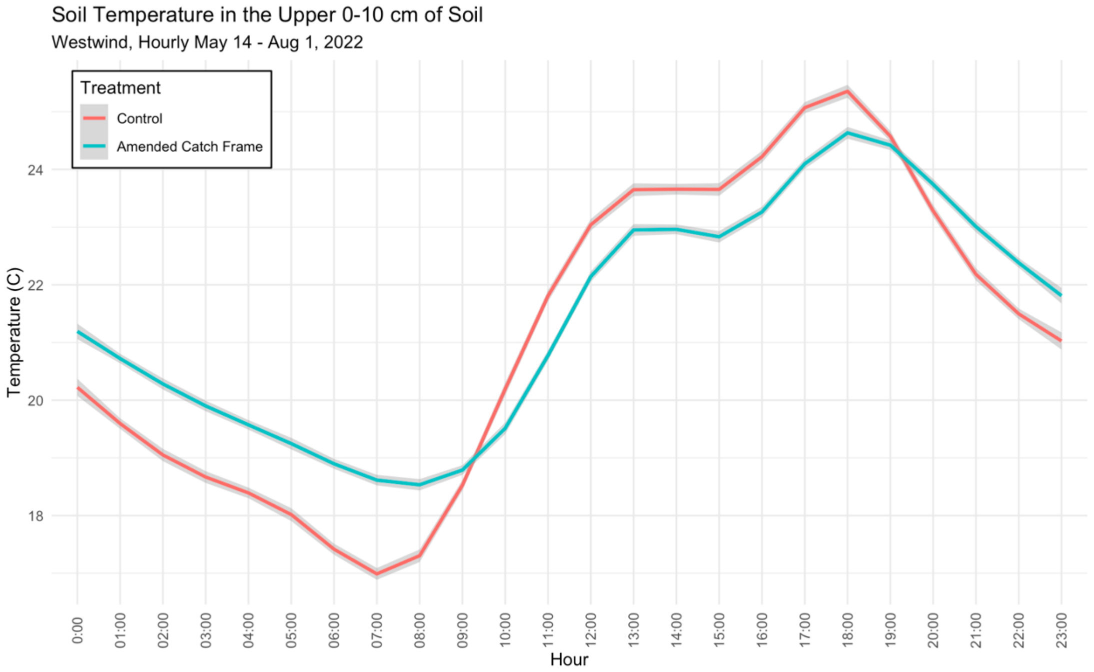


Figure 3.3. Average soil temperature by the hour across all sampling dates in the upper 0-10 cm (0-4 inches) of soil. While average monthly and overall temperature tended to be higher in the amended catch frame treatment, daily soil temperature tended to be more moderate than the control soil, with less extreme highs and lows. Amended catch frame soil tended to be warmer at night and cooler during the day.

Phytech soil probes provided data that illustrated SWC and temperature at deeper soil levels. Cumulative average SWC was slightly lower in amended soils at 15, 41, and 36 cm depths than control soil, though statistically similar (Table 3.3, Supplementary Figure 3.4a). Amended catch frame soil had the lowest SWC at 91 cm depth which was 6.2% lower SWC than control soil, though not significantly different. This suggests treatments only slightly influence cumulative average SWC throughout the rootzone at 15-91 cm depths. In addition, seasonal timing may slightly influence SWC across depths (Supplementary Figures 3.5a-f). In the late spring, at 15, 31, and 46 cm depths, average SWC was higher in the amended catch frame soil but higher in the control in the summer. At 61 and 91 cm depths, the amended on-ground soil tended to have higher SWC than amended catch frame. At the 91 cm depth, SWC was consistently lower for the amended catch frame soil than the other two treatments. At 23, 38, 53, and 69 cm depths, soil temperatures were slightly lower in the two amended treatments compared to the control, though nonsignificant (Table 3.3). High control soil temperatures across all depths were especially evident in July (Supplementary Figures 3.6a-d).

Table 3.3. Cumulative average (estimated marginal means) from Phytech soil probe temperature and moisture data across all dates. No significant differences were found between treatments within each depth and response variable.

| Treatment | Soil Water Content (%) | | | | | | Temperature (°C) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Depth, cm (inches) | | | | | | Depth, cm (inches) | | | |
| | 15.2 (6) | 30.5 (12) | 45.7 (18) | 61.0 (24) | 76.2 (30) | 91.4 (36) | 22.9 (9) | 38.1 (15) | 53.3 (21) | 68.6 (27) |
| Control | 30.9 | 29.6 | 32.1 | 34.7 | 34.1 | 40.0 | 23.5 | 21.8 | 20.9 | 20.2 |
| Amended | 30.4 | 29.5 | 29.0 | 35.5 | 36.0 | 38.4 | 23.0 | 21.6 | 20.6 | 20.0 |
| Amended Catch Frame | 30.2 | 27.2 | 30.9 | 33.9 | 35.2 | 33.8 | 23.2 | 21.7 | 20.6 | 19.9 |

### 3.7.2 Tree Monitoring

Average MDS and TGR were similar across treatments in May, June, and July (Table 3.4, daily MDS provided in Supplementary Figures 3.7a-c). The amended treatments showed slightly higher average monthly cumulative trunk growth rate, though not statistically significant (Table 3.4, Supplementary Figure 3.8). Average weekly cumulative trunk growth rate was higher for the two amended treatments compared to the control in eight of the eleven weeks measured, though no significant differences were found between treatments. Daily air temperature from mid-May through the end of July can be found in Supplementary Figure 3.9.

Table 3.4. Estimated marginal means for monthly MDS and cumulative trunk growth on an individual tree basis in May, June, and July, 2022. Note: some data was missing for blocks 3 and 4 in May. No significant differences were found between treatments within each depth and response variable.

| Treatment | May 15-31 (Nut Fill) | June 1-30 (Nut Fill) | July 1-31 (Hull Split) |
|---|---|---|---|
| | Average MDS | | |
| Control | 97 | 96 | 103 |
| Amended On Ground | 115 | 109 | 115 |
| Amended Catch Frame | 93 | 111 | 121 |
| | Cumulative trunk growth per tree (micrometers) | | |
| Control | 34.6 | 29.2 | 0.74 |
| Amended On Ground | 40.1 | 36.1 | 7.97 |
| Amended Catch Frame | 55.8 | 39.4 | 2.88 |

### 3.7.3 Physiological Measurements. SWP, $g_s$, E, $K_{plant}$

Amended catch frame trees were less water stressed than control trees when measured 6 days after irrigation events in 2021, but not when taken only 3 days after an irrigation event (Figure 3.4). In 2022, no differences in SWP were found when measured early in the season or immediately following or during irrigation (Supplementary Figure 3.10, Supplementary Table 3.2). Six days after an irrigation event on 6/7/2021, amended trees had slightly higher $g_s$, significantly less negative midday SWP, slightly increased transpiration rate, significantly increased leaf-level hydraulic conductance (Table 3.5). Overall, the amended catch frame trees tended to be at least slightly less water stress than control trees, with greater differences occurring before less frequent irrigation events in 2021 and smaller differences in 2022 after the switch to pulse irrigation. Pearson correlation indicated mid-day SWP was more closely correlated with soil water in the upper soil layer (0-10 cm) than MDS values. (Supplementary Figures 3.11a and b).

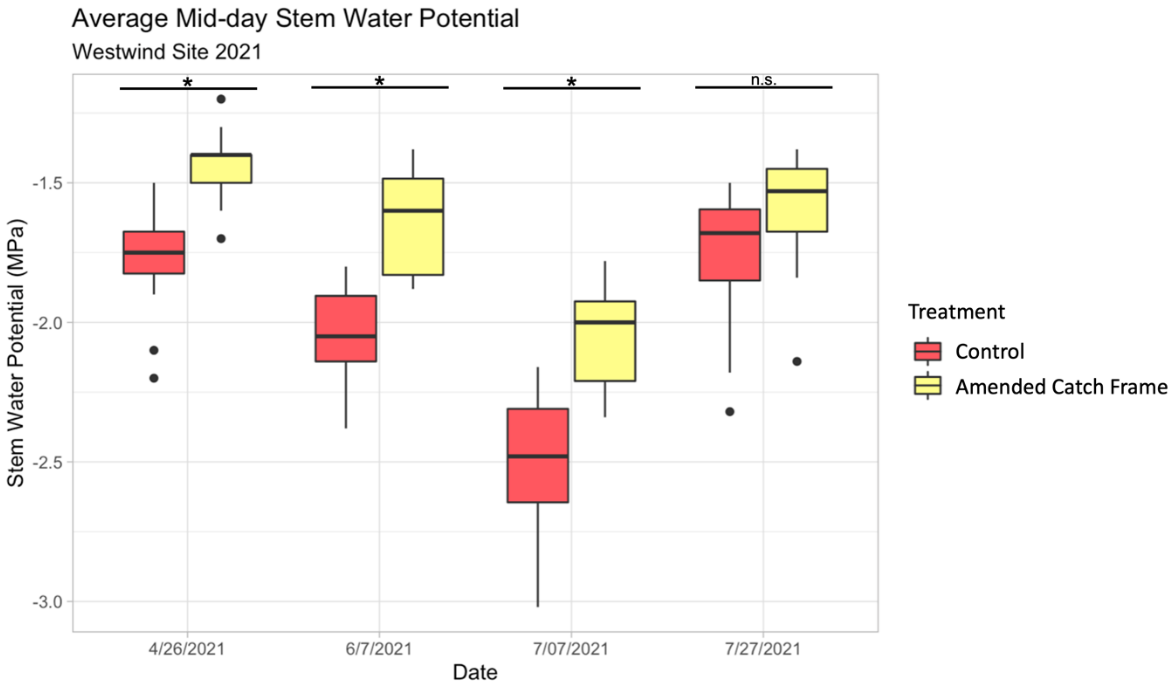


Figure 3.4. Average mid-day stem water potential at Westwind across times sampled in 2021. Asterisks indicate significant differences between treatments within each date (n.s. indicates treatments are not significantly different for the given date). Well-watered baseline values were -0.54 MPa on 4/26/21, -0.75 MPa on 6/7/21, -0.77 MPa on 7/7/21, and -0.81 on 7/27/21.

Table 3.5. Pre-dawn stem water potential, mid-day stem water potential, and stomatal conductance were taken on 6/7/2021, six days after an irrigation event. Stomatal conductance and VPD were used to estimate leaf-level transpiration, which was used with pre-dawn and mid-day SWP to estimate leaf-level hydraulic conductance (formulas can be found in the methods section).

| Treatment | Pre-Dawn SWP (bars) | Pre-Dawn SWP (MPa) | Mid-Day SWP (bars) | Mid-Day SWP (MPa) | Stomatal Conductance (mmol $m^{-2}$ $s^{-1}$) | Transpiration (mmol $m^{-2}$ $s^{-1}$) | Hydraulic Conductance (mmol $m^{-2}$ $s^{-1}$ $MPa^{-1}$) |
|---|---|---|---|---|---|---|---|
| Control | -7.77 a | -0.78 a | -20.5 b | -2.05 b | 57.2 a | 1.62 a | 1.33 b |
| Amended Catch Frame | -7.23 a | -0.72 a | -16.3 a | -1.63 a | 62.8 a | 1.79 a | 2.04 a |

### 3.7.4 ERT, Neutron Probe, Flora Pulse Dendrometers, Stem and Leaf Water Potential

On 8/10/2021, ERT, neutron probe, dendrometer, and stem and leaf water potential measurements were taken to assess water dynamics in the control vs. amended catch frame soils. These results will be reported in more detail Kisekka et al. currently in process of publication. To summarize, measurements were taken before and during an irrigation event that began at 7:00 am on 8/10/2021. ERT image results indicated that the amendment increased water infiltration rate and reduced soil surface evaporation beginning at approximately 12:30 pm and continuing through the afternoon. Neutron probe readings indicated that infiltration rate was higher for the amended treatment within the first three hours following the start of irrigation. The most negative SWP for both treatments peaked around 11:15 am and steadily became less negative throughout the afternoon as the trees continued receiving water. LWP remained highly negative further into the early afternoon before declining. Flora Pulse sensor data reflected the same trend as the water potential measurements and correlated with an $R^2$=0.77 (Kisekka et al. in publication).

### 3.7.5 Spring Root Biomass and Bulk Density

On 5/17/2022, average fresh and dry total root biomass in the upper 0-10 cm soil were both significantly higher in the amended catch frame soil compared to the control (Figures 3.5a and b). Average dry root biomass in the amended catch frame soil was approximately double that of the control. Average percent moisture for all roots was 41% moisture (standard deviation=12.7%). On 6/21/2022, average total fresh root biomass in the top 0-10 cm soil was slightly but not significantly higher in the amended on-ground soil and amended catch frame soil compared to the control. June root biomass averages were notably higher than May root biomass averages, demonstrating substantial almond root growth occurred in the month of June. In fall 2022, bulk density was slightly lower and moisture was slightly higher at time of sample collection for the two amended treatments compared to the control soil, although non-significant (Supplementary Table 3.2). Similarly, bulk density was slightly lower under the predominately shell-based mix at Bullseye in October 2022 compared to control soil (field trial design discussed in Chapter 2), though no significant differences were found.

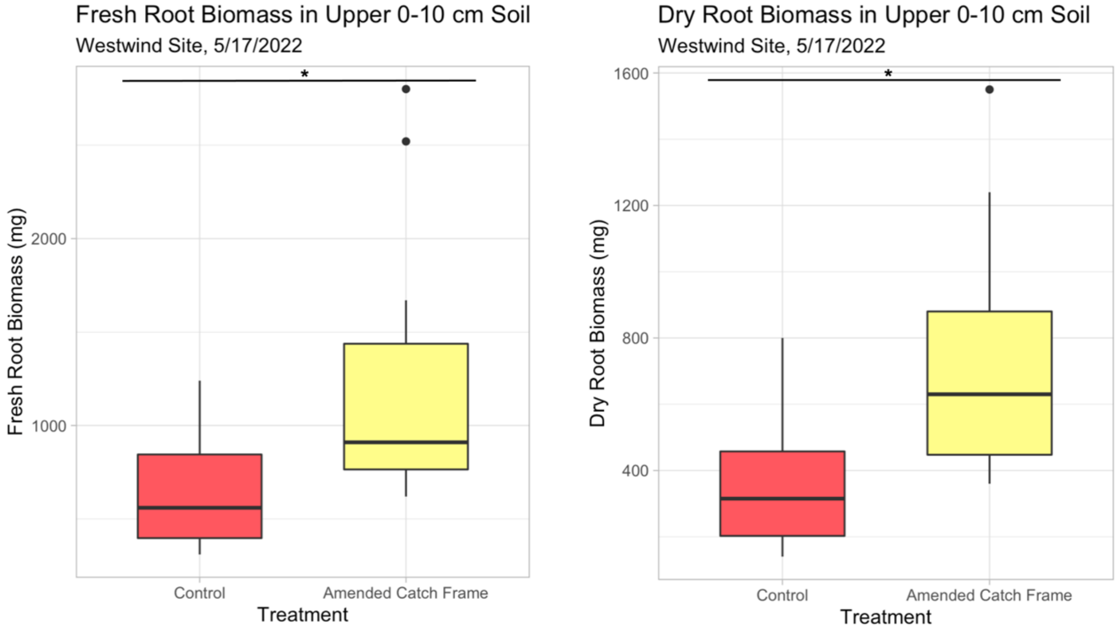


Figure 3.5a and b. Fresh and dry root biomass in 10 cm x 3.8 cm soil cores from the upper 0-10 cm soil on 5/17/2022. Fresh root biomass in amended catch frame soil was significantly higher than control root biomass.

Table 3.6. Fresh root biomass on 6/21/2022, within 10 cm x 3.8 cm soil core. Average fresh root biomass was highest for amended catch frame soil, followed by amended on ground harvest, and lowest for the control, though no differences between treatments were significant. Roots were used for mycorrhizal colonization (data not presented here) thus roots could not be dried for dry root biomass from this sampling time. Fresh root biomass in all samples at this time was substantially higher than in May one month prior, suggesting that almond root growth in all trees occurred between 5/17/2022 and 6/21/2022.

| Treatment | Fresh Root Biomass (mg) |
|---|---|
| Control | 1185.8 a |
| Amended | 1345.0 a |
| Amended Catch Frame | 1835.8 a |

## 3.8 Discussion

### 3.8.1 Soil Monitoring.

Compared to the control soil, the amended catch frame soil maintained higher average soil water, moderated daily soil temperature, increased conductivity, PWEC, and permittivity in the top 0-10 cm soil (approximately 0-4 inches). Overall and monthly soil water was significantly higher in amended catch frame soil. Daily differences between treatments fluctuated, with greatest differences detected during soil drying in the range of approximately 1.9-3.0 cm (0.75-1.2 inches) of water. For 76 of the 80 days studied, average soil water was higher in amended catch frame soil than the control. Summing cumulative daily average differences between treatments indicated the amended catch frame treatment maintained an estimated 0.04 hectare meters (3.67 acre-inches) more water in the top 0-10 cm soil over the measured 80 days. However, this excludes any potential differences below this upper 0-10 cm layer and does not account for water taken up by higher root biomass density, so this estimate is likely conservative when considering potential total differences in soil water. Overall and monthly soil conductivity was significantly higher for the amended catch frame soil and tended to be higher on days with higher soil water, during wetter months, and during nighttime hours. Overall and monthly PWEC and permittivity were higher in the amended catch frame soil, while daily values were variable. Daily and hourly PWEC tended to be more extreme in the control and more moderate in amended catch frame soil. Daily and hourly permittivity followed similar trends as soil water.

In deeper soil layers, cumulative average SWC was similar across 15-91 cm depths, indicating only slight differences between treatments. Time of year may influence SWC across treatments, as average SWC tended to be higher in the amended catch frame soil in the spring across several depths but lower than the control in the summer. These dynamics are likely influenced by potential differences in soil energy balance, root biomass and architecture, and plant water uptake across different depths. The amended catch frame soil consistently had the lowest average SWC at the deepest sampling depth which may suggest higher root water capture in the soil layers above it in the 0-91 cm (0-36 inch) profile. Taken together, soil probe data indicate the amended catch frame treatment maintained higher soil moisture at the 0-10 cm (0-4 inch) depth over time and slightly higher SWC at deeper depths only in the spring.

While overall, monthly, and daily average temperatures in the top 0-10 cm soil were lower in the control soil, the amended catch frame soil temperature extremes were more moderate. This temperature buffering effect appears to maintain cooler soil temperatures during the day from approximately 9am-7pm and warmer soil temperatures at night when compared to control soil. Overall soil temperatures across deeper sampling depths were generally similar between treatments, though slightly lower in the two amended treatments. As temperatures rose in July and August, increases in control soil temperatures compared to the two amended soils became more pronounced at all depths measured.

In prior studies, higher levels of available soil water content have been found under nutshell amendments such as almond shells (Jafari et al. 2012), pecan husks (Idowu et al. 2017), macadamia husks (Cox et al. 2004), and hazelnut husk compost (Ozenc et al. 2008). In semi-arid regions, increased yield, quality, and plant growth in several prior studies have been attributed to increased soil water content under nutshell amendments (Jafari et al. 2012, Farzi et al. 2017). Farzi et al. (2017) found that pistachio-shell mulch and de-oiled olive pomace maintained higher soil water content, lowered soil water evaporation, and maintained less negative stem water potential. Jafari et al. (2012) found that almond shell mulch lowered soil temperature at 15 cm depth compared to the control in the warmest month, while it increased soil temperature during colder periods. During warm conditions, the almond shells created a barrier on the soil surface that reduced the solar energy reaching the soil and the magnitude of soil temperature increases. The greatest increase in soil moisture under almond shell treatment occurred in April, when soil moisture storage was approximately double that of the control soil (Jafari et al. 2012). Jafari et al. (2012) concluded that almond shells are especially well-suited affordable and long-lasting amendments due to their ability to moderate soil temperature, reduce evaporation, maintain higher moisture content, and increase yield quality and quantity in this rainfed fig crop system. Taken together with the present study, almond shell amendments have potential to improve soil water dynamics in orchards in arid and semi-arid climates. Future research is needed across time, depths, soil types, climates, and water management approaches to better understand potential water savings under almond shell amendments.

### 3.8.2 Tree Monitoring.

Digitization provided by continuous monitoring devices such as trunk diameter fluctuation (TDF) technology (i.e., dendrometers) can aid the irrigation decision making process in almond orchards (Goldhamer and Fereres 2001b, Martin-Palomo et al. 2022). TDF measurements reflect the combined effects of several physiological components and diameter fluctuations can be closely related to changes in whole plant water content in *Prunus* species (Simonneau et al. 1993, Ortuno et al. 2010). MDS values can be used as an indicator of transpiration intensity, provided soil water content is not severely low (Ortuno et al. 2010). While MDS and evaporative demand can be strongly related, MDS and SWP have a parabolic relationship indicating the need for cultivar and time-specific baselines (Martin-Palomo et al. 2022, Ortuno et al. 2010). Recent research indicates Trunk Growth Rate (TGR) may be a more reliable indicator of water stress in olives, while it is highly variable on different days and phenological stages in peaches and almonds (Martin-Palomo et al. 2022). However, other authors suggest that TGR is a useful parameter for quantifying water deficit intensity and duration in almond trees (Nortes et al. 2005). In some cases, it may be difficult to distinguish differences or clear patterns in MDS between full- and deficit-irrigated almond trees (Nortes et al. 2005, Martin-Palomo et al. 2022).

Even within crop types, researchers have reached different conclusions about the efficacy of MDS to fine tune irrigation management decisions. For instance, Martin-Palomo et al. (2022) concluded SWP was a clearer and more consistent water status measurement than MDS and TGR for almond in Spain when comparing several different irrigation approaches.

However, Goldhamer et al. (2004) found that almond irrigation scheduling can be accomplished based solely on MDS signals tailored to a target stress pattern in the San Joaquin Valley of California. Previously, these authors emphasized the need to compare trunk diameter measurements of plants under stress with fully irrigated values derived from reference trees or by using relationships with environmental indicators such as ETo or VPD (Goldhamer and Fereres 2001b). Egea et al. (2009a) found that average VPD at 10.0-15.0 hours correlated well with MDS and proposed utilizing almond seasonal growth stages to determine MDS baselines. While SWP baselines have been shown to be consistent across years, locations, and different *Prunus* species, MDS baselines for almond trees vary across different orchards likely due to the many factors affect MDS (e.g., crop load, trunk diameter, tree size, etc.) (Tejero et al. 2018).

In the present study, dendrometers were utilized by the grower to schedule pulse irrigation across the entire orchard (high frequency low-dose irrigation events). Dendrometer data from the field trial indicates only slight differences in MDS and TGR between treatments were detected by dendrometers. Neither MDS nor TGR values were correlated with SWP on 5/17/2022, 6/16/2022, or 7/20/2022. Cumulative average TGR was highest for amended catch frame trees in late May and throughout June, and higher for amended trees in July, though no significant differences were found. This suggests the two amended treatments maintained only slightly higher average trunk growth rates compared to the control treatment. Dendrometer MDS and TGR data provided convenient digitization of tree stress levels that guided irrigation decision making in 2022 as the grower adopted a pulse irrigation approach.

### 3.8.3 Physiological Measurements.

In this study, SWP was significantly less negative for amended catch frame trees compared to control trees when measured 6 days after irrigation events in 2021. However, no differences between treatments were found when SWP was taken only 3 days after an irrigation event in 2021, immediately following or during irrigation in 2022, or early in the season in 2022 (Supplementary Figure 3.10, Supplementary Table 3.2). At all times sampled, average SWP was at least slightly less negative in the amended catch frame trees compared with the control trees, with greater differences emerging over time between irrigation events as water potential declined. The Acclima soil water data showed the amended soil tended to maintain higher moisture content in the upper 0-10 cm of soil over time following irrigation events. Soil water in the upper 0-10 cm was more closely correlated to SWP than MDS on three days in 2022 (Supplementary Figures 3.11a and b). Thus, Acclima and SWP data suggest the amendment may provide the greatest benefit for reducing tree drought stress after an irrigation event as the soil becomes drier over time.

On one day in early June, six days after an irrigation event, a combination of plant physiological measurements were taken. While the trees began the day with similar pre-dawn water stress levels, the amendment facilitated slightly higher stomatal conductance and significantly less negative midday SWP. Together these effects appear to have slightly increased transpiration rate and significantly increased hydraulic conductance at the leaf level. This indicates the hull/shell amendment can have beneficial effects on several almond tree physiological responses at the leaf-level. The mulching effect provided by surface-applied nutshell and crop residue organic matter amendments has been shown to maintain lower stem water potential compared to bare soils in other studies as well. For instance, pistachio shell mulch maintained less negative stem water potential status in young olive trees, increasing stomatal conductance ($g_s$) and chlorophyll fluorescence ratio (Farzi et al. 2017). Future research could investigate whether these beneficial effects translate to whole-canopy or field scale levels across different types of amendments, sites, and irrigation management strategies.

Midday SWP is widely acknowledged as a valuable method for quantifying water stress in woody crop species including almonds (Shackel 2011). Plant water status reflects the balance between soil water supply and atmospheric demand, and thus ET and soil water monitoring can provide useful environmental information that influences plant water stress (Goldhamer and Fereres 2001b). However, plant-based measures are the most direct indicator of plant water stress and crop biological water needs (Shackel 2011). Water potential measurements integrate the combined environmental effects across the soil-plant-atmospheric continuum (Shackel 2011). Baseline SWP values provide a “fully irrigated” reference to compare with observed SWP values, thus accounting for site-specific environmental factors such as soil type (Shackel 2011). Midday SWP is a useful method for understanding tree water stress both research and industry settings is often used to evaluate the effects of water-limited conditions or different deficit irrigation regimes. However, SWP requires substantial investment in time and labor to collect replicated and representative data and cannot be automated (Goldhamer and Fereres 2001b).

While stomatal behavior responds to many factors, research suggests the association between stomatal conductance and SWP becomes more evident with moderate to severe water stress in almond (Espadafor et al. 2017). Changes in $g_s$ is an early response to water stress in almonds (Prgomet et al. 2020). Declines in $g_s$ have been shown to correspond with declining SWP in almond leaves in mid-July through September (Shackel 2007) and with a reduction in $g_s$ of approximately 50% for the -0.8 to -2.0 MPa range of SWP (both shaded and sunlit leaves) (Spinelli et al. 2016). Espadafor et al. 2017 found that almond tree (cv. Guara) transpiration was lowered as midday SWP fell below -1.1MPa, indicating a mild/moderate response to water deficits and high sensitivity of transpiration to water stress which authors suggest may be cultivar dependent. Hernandez-Santana et al. 2015 found that SWP lower than -1.2MPa resulted in exponential decline in $K_{leaf}$ which is strongly related to $g_s$ response to water stress in almonds. Reduced $g_s$ has been correlated with declining midday stem water potential, but not necessarily canopy ET (Spinelli et al. 2016). Further data at the whole-canopy level would help us understand effects of the hull/shell amendment layer maintained by catch frame harvest across scales.

Plant water stress induces stomatal closure and can lead to a loss of turgor, reduced leaf expansion, limits net $CO_2$ assimilation and transpiration, increases ROS, and can decrease root elongation in dry soil areas. Severe water stress can eventually reduce translocation and lead to cavitation, leaf senescence, and abscission. Prior research indicates that during almond tree water stress, stomatal closure is likely the main limit on photosynthesis (Prgomet et al. 2020). Prolonged or poorly timed water stress in almonds can lead to reduced kernel weight (Doll et al. 2018). In one study, almond whole tree transpiration showed high sensitivity to water deficits especially as midday stem water potential decreased below -1.1MPa (Espadafor et al. 2017). Almonds can demonstrate isohydric behavior during drought (cv. Guara) and a direct stomatal response to leaf turgor may largely explain changes in stomatal conductance (Rodriguez-Dominguez et al. 2016). However, other sources indicate that almond trees may not exhibit isohydric stomatal responses (Tejero et al. 2018). More research is needed to evaluate the responses of different almond varieties to drought stress.

### 3.8.4 8/10/2021: ERT, Neutron Probe, Dendrometers, Stem and Leaf Water Potential

In August 2021, Electrical Resistivity Tomography imaging and neutron probe measurements at the start of an irrigation event showed the amended catch frame soil had lower soil evaporation and higher water infiltration compared to the control soil. During the first three hours of irrigation, infiltration rate was higher in the amended catch frame soil (Kisekka et al. to be published 2023). The most negative SWP for both treatments peaked around late morning and steadily became less negative throughout the afternoon as tree water uptake progressed. Overall, these results indicate that the amended soil provides a mulching effect, creating a physical barrier on the soil surface that reduces evaporation and increases water infiltration. These findings led to the installation of TDR Acclima probes the following year to examine soil water dynamics close the soil surface. TDR results complement ERT findings, indicating the hull/shell amendment maintained higher soil water content and moderated soil temperature. As a barrier on the soil surface, nutshell-based amendments have been shown to reduce surface evaporation in prior studies (Farzi et al. 2017, Karagoktas et al 2014).

Relatively higher available water content has been found under almond shells (Jafari et al. 2012), pecan husk mulch (Idowu et al 2017), and hazelnut husk compost (Ozenc et al. 2008). Mulching with crop residues has been shown to increase water infiltration rates and moderate the effects of salt buildup (Andrews et al. 2021).

### 3.8.5 Root Biomass Density and Bulk Density

Improved environmental conditions in the upper soil layer promoted root growth. Average fresh root biomass density in the top 0-10 cm soil was significantly higher in the amended catch frame soil than control soil in May, and slightly higher in the two amended treatments compared to the control in June. Overall, this root biomass data indicates the amended catch frame soil can increase root biomass in this upper soil layer, especially in the late spring during periods of root development near the soil surface. The undisturbed amendment layer creates a beneficial environment for almond root development by maintaining higher soil water and moderating temperature near the soil surface. While machinery disturbances can damage feeder roots and reduce the benefits provided by organic matter amendments in orchards, maintaining undisturbed mulch layer on the soil surface has been shown to encourage tree root proliferation (Andrews et al. 2021). For instance, studies indicate mulches such as almond shell mulch, macadamia husk mulch, and bark mulch can lead to fine root growth (Jafari et al. 2012, Lobel et al. 1994, Forge et al. 2015, Granatstein et al. 2008). In a study with apple trees, wood chip mulch led to a 20-30% savings in irrigation water while improving tree growth and extensive fine root growth near the soil surface due to improved soil conditions (Granatstein et al. 2008). Fine root growth can provide crop benefits such as increased nutrient and water uptake.

The slight but nonsignificant reduction in soil bulk density under the hull/shell amendments compared to control soil indicate that this soil physical property may potentially begin to shift over longer periods of time. Soil bulk density has been shown to decrease in a sandy clay loam under pulverized cocoa pod husk (Moyin-Jesu et al. 2007) and in a clay-loam soil under hazelnut husk compost (Ozenc et al. 2008). However, contextual factors such as soil type, soil management, length of time, and irrigation and fertilizer management likely influence whether hull/shell amendments could meaningfully modify soil bulk density.

### 3.8.6 Yield and Harvest Equipment

In both years, no significant differences were found in yield (Chapter 2). Overall, dry kernel yield was low relative to a typical almond orchard of this age in this region (Sumner et al. 2019). This may be due to a combination of factors including boron toxicity from irrigation water, high summer temperatures and water stress in 2021, and a severe frost in late February of 2022. Catch frame harvest maintained the hull/shell organic layer create a beneficial mulching effect on the soil surface which improved soil moisture and temperature conditions near the soil surface, increased root biomass production, and moderated SWP toward the end of dry periods. Similar effects have been demonstrated in prior studies, in some cases increasing yield as well. In semi-arid regions, mulches have been shown to moderate tree water stress, increase tree size, yields, leaf nutrient concentrations, and soil physical properties (Neilsen et al. 2002, Neilsen et al. 2003). Similarly, studies in row crop systems indicate mulching can increase water use efficiency, delay the onset of crop water stress, improve root development and soil water utilization (Iqbal et al. 2011, Qin et al. 2015, Lu 2020). Almond shells have been shown to increase yield and tree growth in a water-limited fig orchard (Jafari et al. 2012). Considering water availability will become increasingly unreliable in the future, potential gains in conserving water are especially high in semi-arid regions (Hannam et al. 2016, Farzi et al. 2017). Further research is needed to better understand how on- and off-ground harvest equipment impact soil water dynamics under hull/shell amendments throughout the soil profile and associated effects on root biomass, tree water uptake, and yield.

### 3.8.7 Areas for Future Study

This research indicates that almond hulls and shells used as organic matter amendments can help improve soil-plant water dynamics. Further field trials are needed to assess how this amendment influences root water uptake, increased root biomass near the surface, potential shifts in root architecture, and tree water status. Future data analysis could be performed utilizing splines and correlation structures to examine autocorrelation with time series data. Future trials could evaluate this practice across orchards with different irrigation management approaches, soil types, amendment rates, and associated effects on root responses, tree-level, whole-canopy, and field-scale physiological responses, yield, orchard water use efficiency, and potential cumulative water savings.

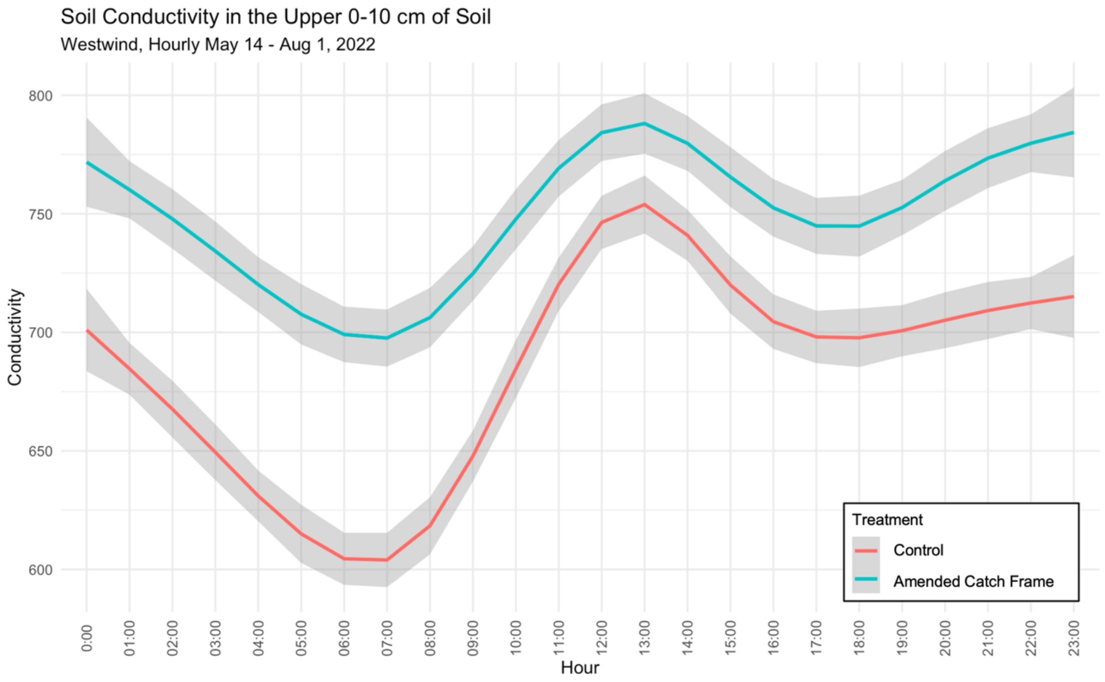
## 3.9 Conclusion

The hull/shell amendment maintained by catch frame harvest provided a mulching effect on the soil surface, increased water infiltration rate, and reduced evaporation. In the upper soil layer near the surface, these combined treatments maintained higher soil moisture, moderated daily temperature, increased conductivity, PWEC, permittivity, and late spring root growth within two years. As a physical barrier on the soil surface, the hull/shell amendment modified the energy balance, reducing the amount of energy going to sensible heat flux and evaporation from the soil surface and maintaining higher soil water content near the soil surface. From a tree water stress perspective, the amended catch frame treatment may only have significant effects moderating SWP in orchards using irrigation sets with long soil drying time frames up to six days. However, this is likely affected by contextual factors such as soil type and irrigation duration as well. Hull/shell mulches could be integrated with multiple sustainable irrigation approaches (e.g., strategic deficit irrigation, multi-scale water monitoring, etc.) to assess the full water saving potential of this practice in California almond systems. These farm-scale water use management improvements have the potential complement regional and statewide efforts toward sustainable agricultural water consumption.

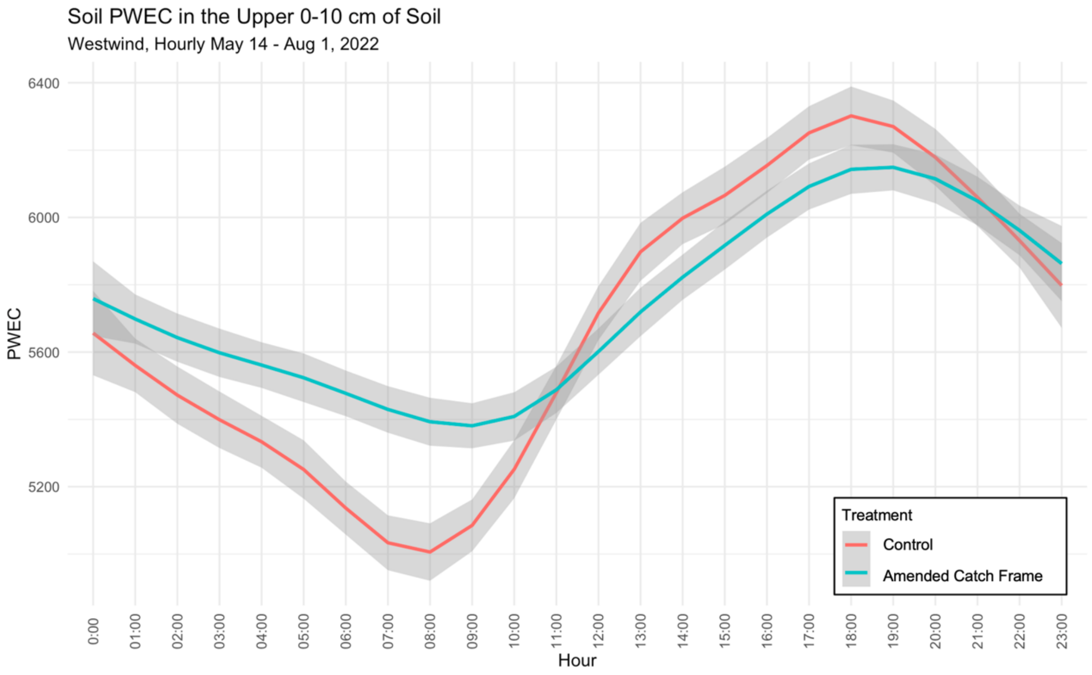
## 3.10 Supplementary Materials

Supplementary Table 3.1. Examples of sustainable irrigation management practices in California almond systems.

| Practice | Description |
|---|---|
| Scheduling and monitoring tools | Approaches and tools for guiding irrigation timing and duration. For example:<br>-The soil water balance approach: match net applied water to evapotranspiration (ETc)<br>-Tree-scale site-specific water stress measurements: e.g., pressure chamber measurements for stem water potential; trunk sensors for maximum daily trunk shrinkage<br>-Whole orchard-scale monitoring: aerial imaging, e.g., NDVI |
| Drip irrigation | Water is gradually applied to the root zone through drip tape, reducing evaporative losses compared to micro sprinklers or flood irrigation; allows grower to reduce the application rate to match plant water demand as closely as possible to improve WUE (Phogat et al. 2013) |
| Pulse Irrigation | An irrigation approach using high frequency and short duration irrigation intervals; each irrigation cycle is composed of an irrigation phase and a resting phase (Phogat et al. 2013, Egea et al. 2011, Dry and Loveys 1999, Kang et al. 2003, Costa et al. 2007) |
| Partial Root Zone Drying | Alternate the spatial pattern of the wetted zone; alternate root drying and wetting cycles via two separate drip lines on either side of the tree row (Costa et al. 2007, Egea et al. 2011) |
| Deficit Irrigation | The application of water below maximum ETc (Egea et al. 2011) |
| Proportional Deficit Irrigation | The amount of water available for the season should be calculated as a percentage of full ETc and applied at a uniform rate to spread the deficit evenly across the season; this can help minimize losses for expected large irrigation deficits (Doll and Shackel 2015, Goldhamer et al. 2006) |
| Regulated Deficit Irrigation | Reducing consumptive water use during periods of plant growth when crops have lower sensitivity to water stress (e.g., almond kernel filling stage), but not during water stress sensitive stages (e.g., flowering, rapid spring growth, postharvest) (Egea et al. 2011, Goldhamer et al. 2006, Goldhamer and Smith 1995, Goldhamer and Viveros 2000). |
| Strategic Deficit Irrigation | Applying water during periods of critical almond development and limiting water application during less critical periods (e.g. between kernel fill and 90% hull split) (Doll and Shackel 2015) |

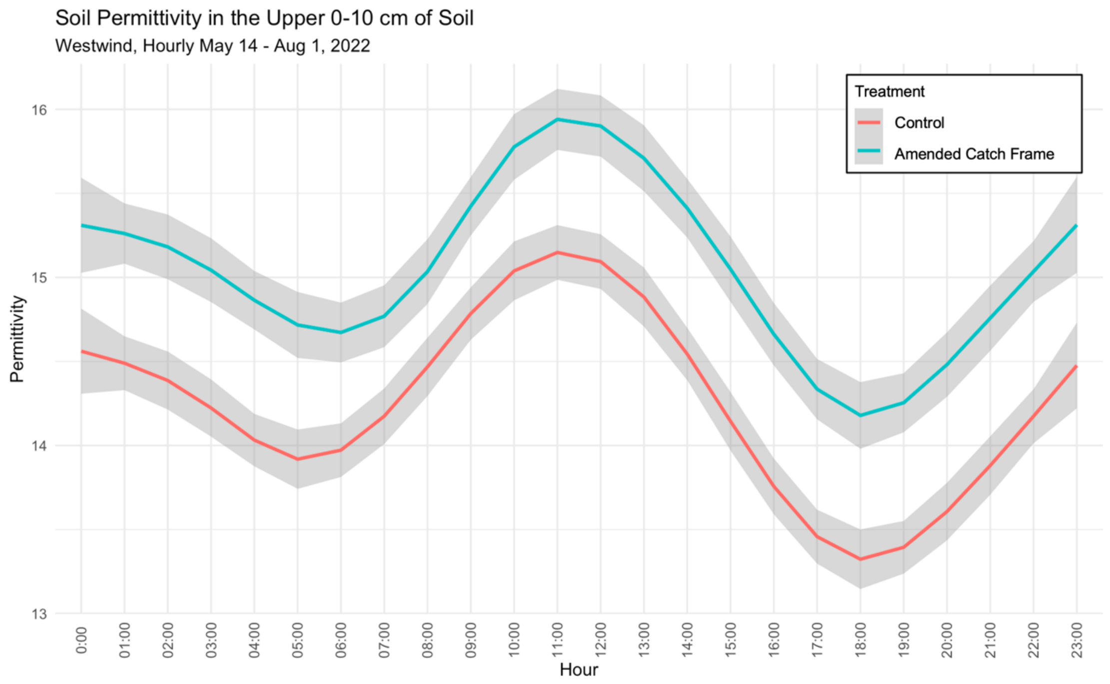


Supplementary Figure 3.1. Soil conductivity in the upper 0-10 cm (0-4 inches) of soil by the hour across all dates measured. Amended catch frame soil tended to have higher soil conductivity particularly at night and early morning.

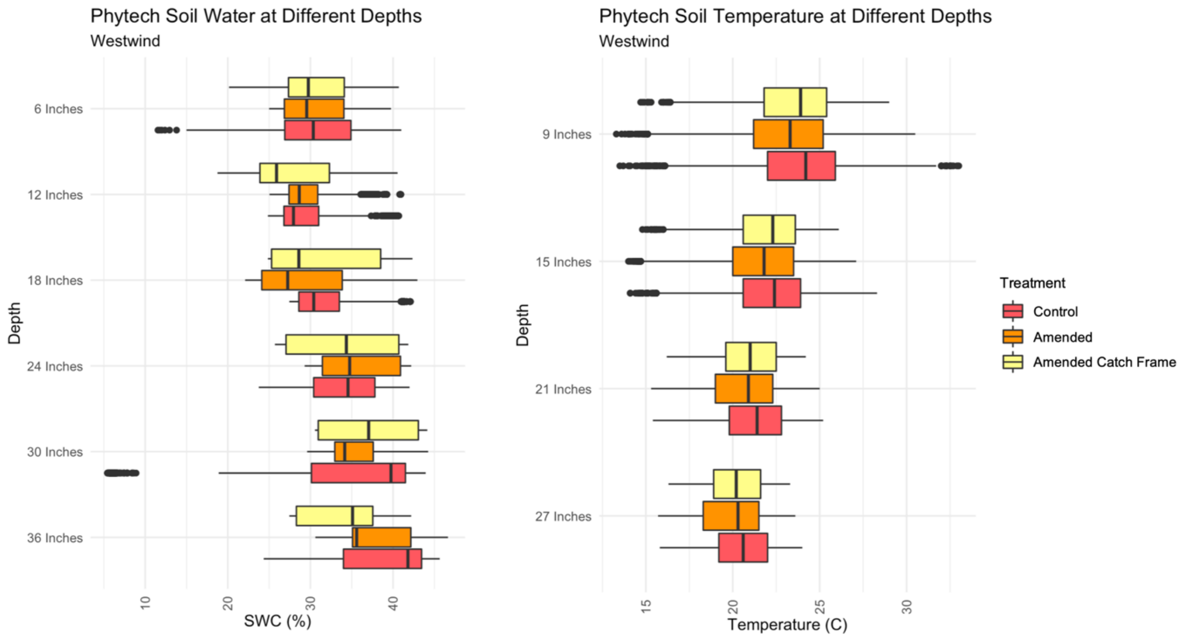


Supplementary Figure 3.2. Soil pore water electrical conductivity (PWEC) in the upper 0-10 cm (0-4 inches) of soil by the hour across all dates. Control soil tended to have slightly higher

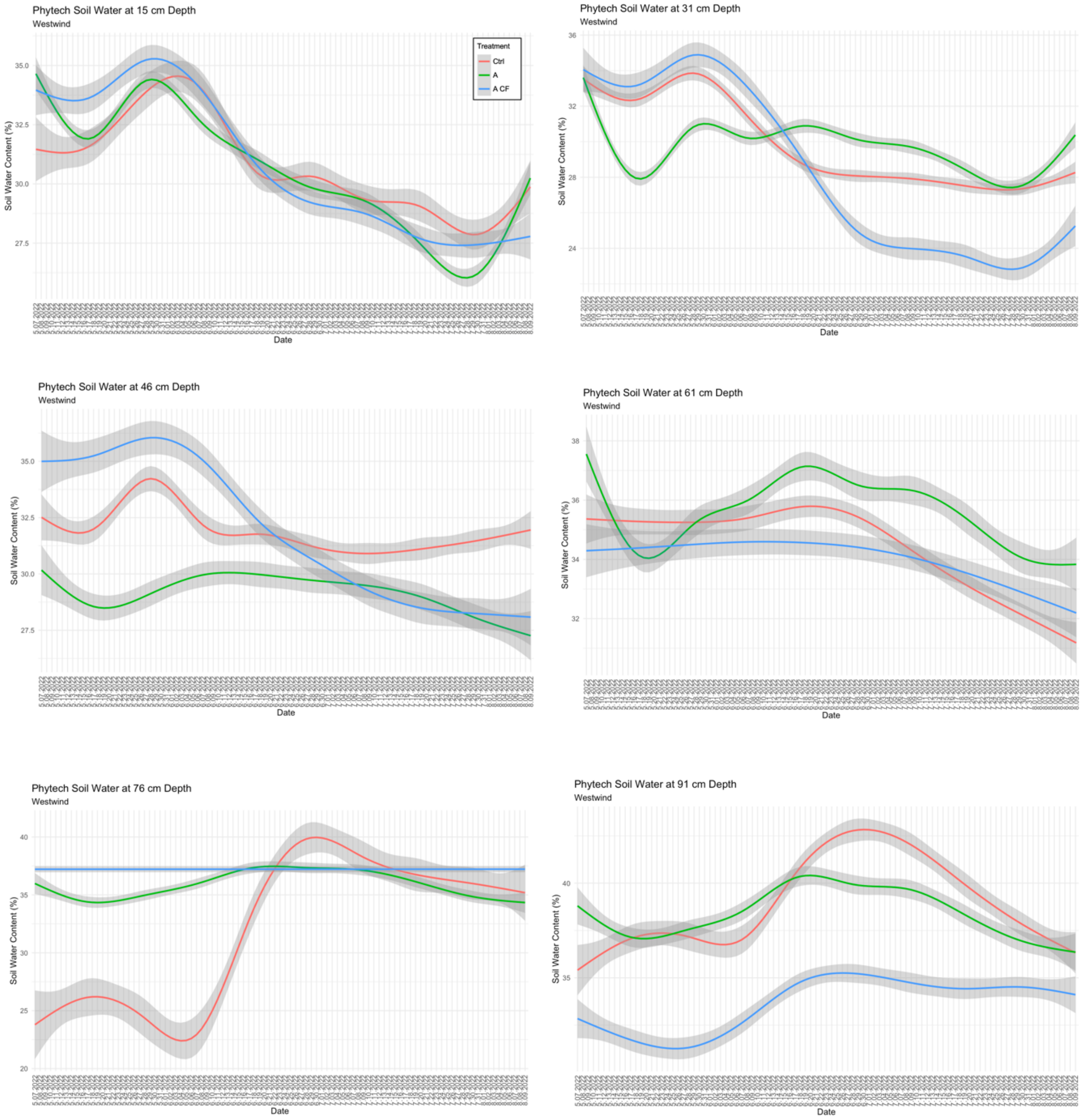
PWEC in the afternoon and amended catch frame soil tended to have higher PWEC at night and in the early morning.



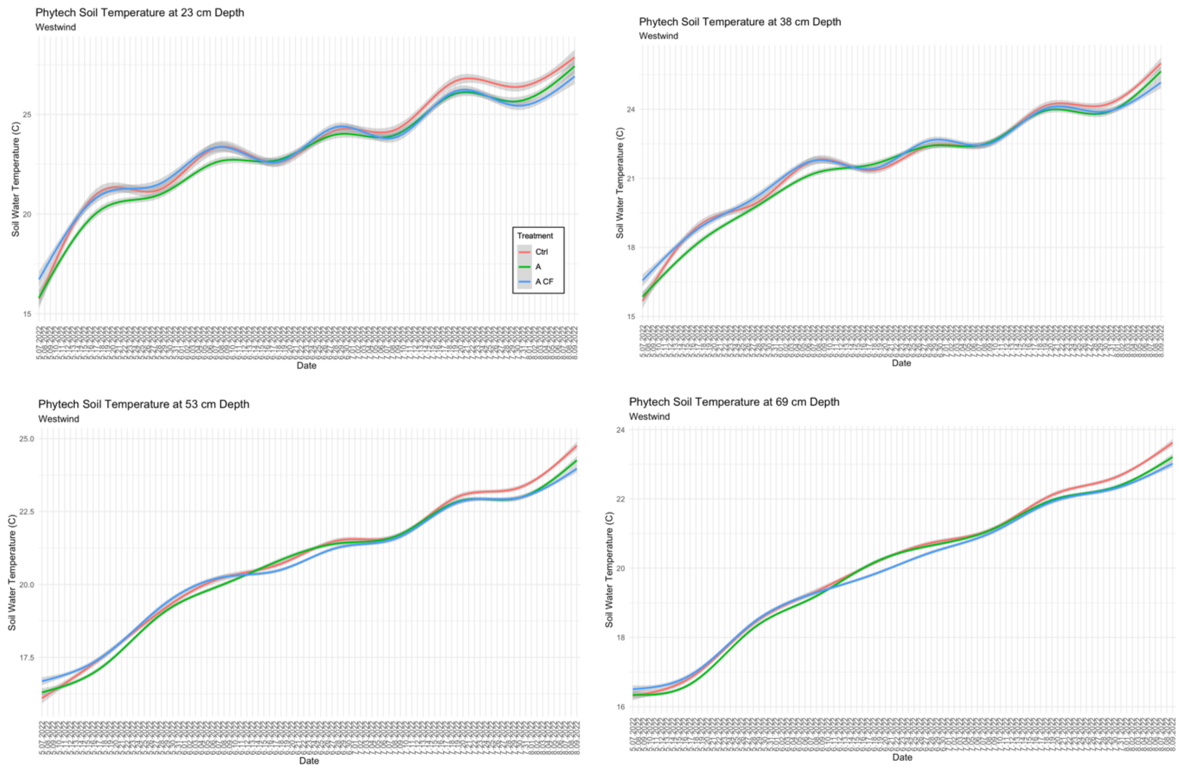
Supplementary Figure 3.3. Soil permittivity in the upper 0-10 cm (0-4 inches) of soil by the hour across all dates. Amended catch frame soil consistently demonstrated higher permittivity than control soil.



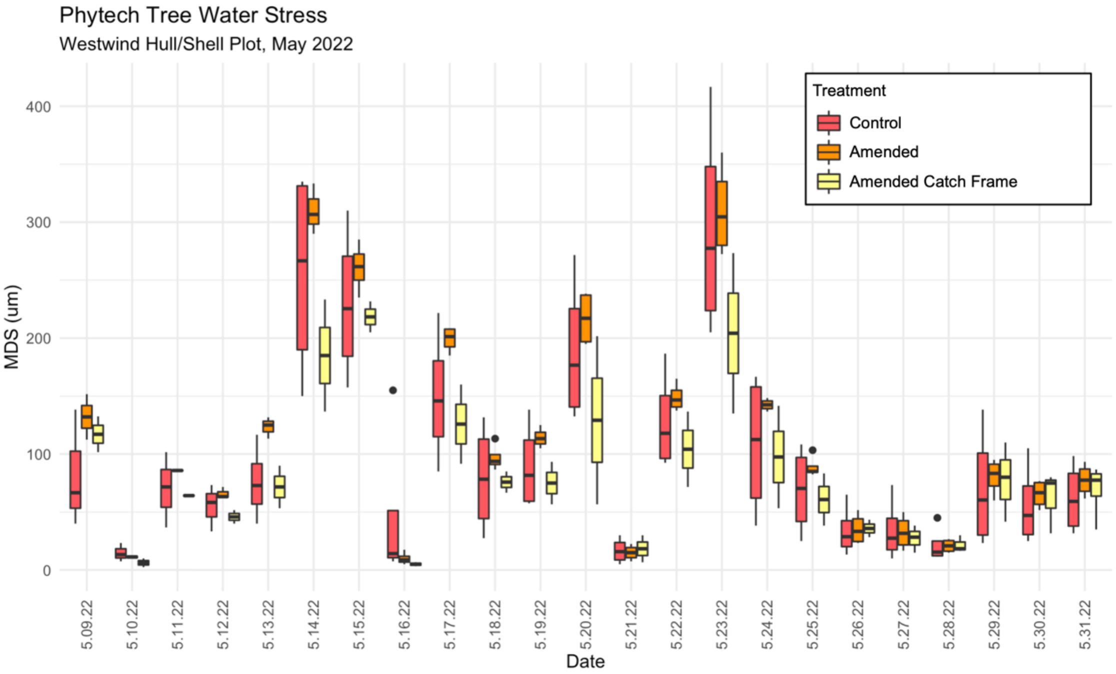
Supplementary Figures 3.4a and b. Phytech soil probe moisture and temperature across depths. Treatment 1 is the control, Treatment 3 is amended with hulls/shells, and Treatment 4 is amended with hulls/shells with catch frame harvest.

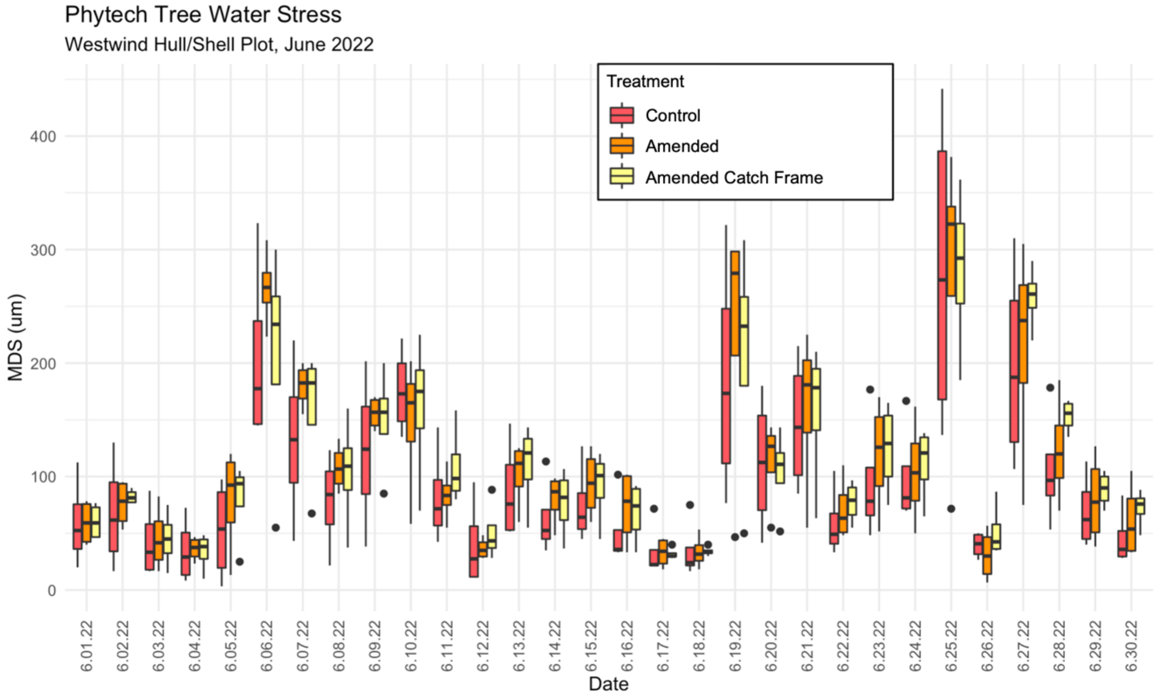


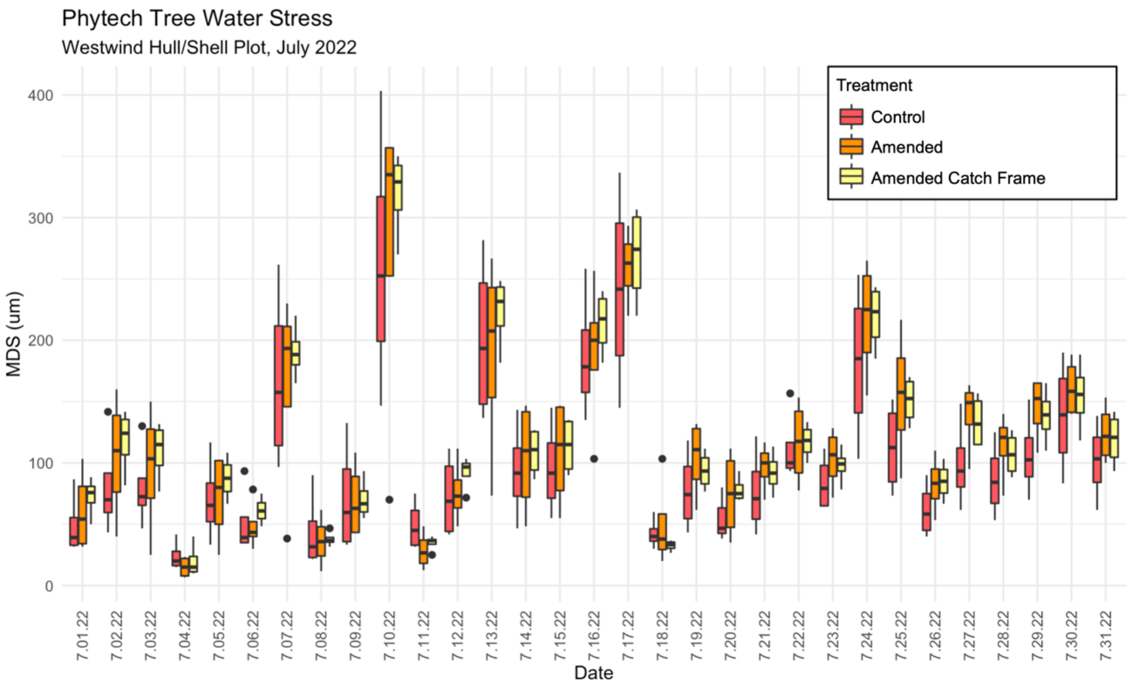
Supplementary Figures 3.5a-f. Phytech soil water content across depths from all days measured (Ctrl = control, A = amended, A CF = amended with catch frame harvest). Moisture measurement depths are 15 cm (6 inches), 31 cm (12 inches), 46 cm (18 inches), 61 cm (24 inches), 76 cm (30 inches), 91 cm (36 inches).



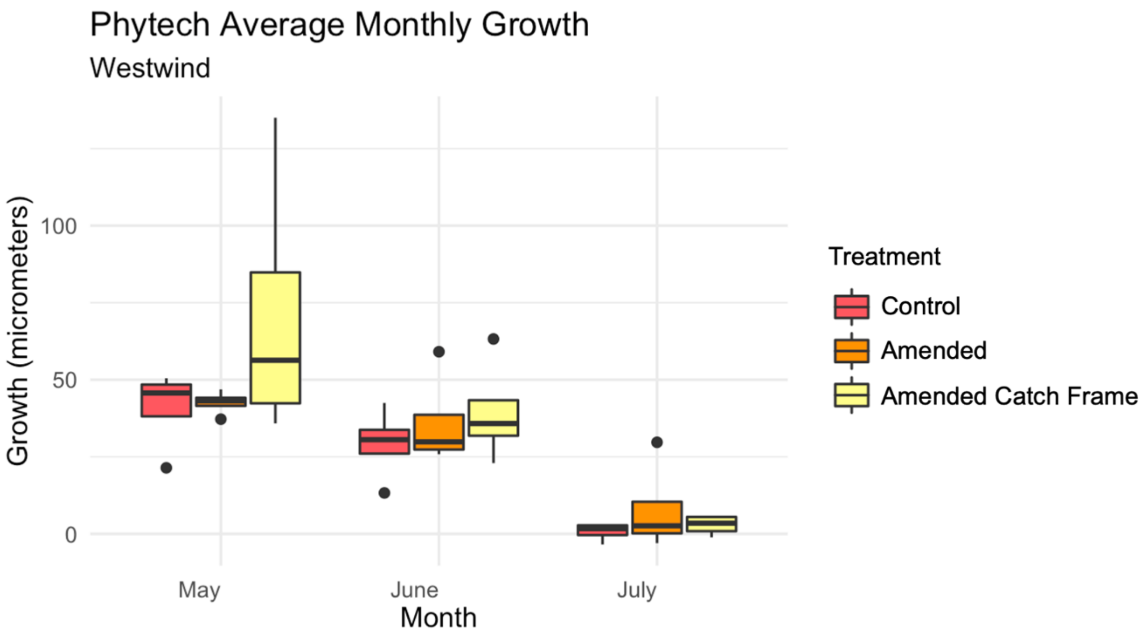
Supplementary Figures 3.6a-d. Phytech soil temperature across depths from all days measured (Ctrl = control, A = amended, A CF = amended with catch frame harvest). The lower average temperature of amended treatments became more apparent as temperatures rose in July and August. Temperature measurement depths are 23 cm (9 inches), 38 cm (15 inches), 53 cm (21 inches), and 69 cm (27 inches).


Phytech Tree Water Stress
Westwind Hull/Shell Plot, May 2022
MDS (um)
0
100
200
300
400
Date
5.09.22
5.10.22
5.11.22
5.12.22
5.13.22
5.14.22
5.15.22
5.16.22
5.17.22
5.18.22
5.19.22
5.20.22
5.21.22
5.22.22
5.23.22
5.24.22
5.25.22
5.26.22
5.27.22
5.28.22
5.29.22
5.30.22
5.31.22
Treatment
Control
Amended
Amended Catch Frame

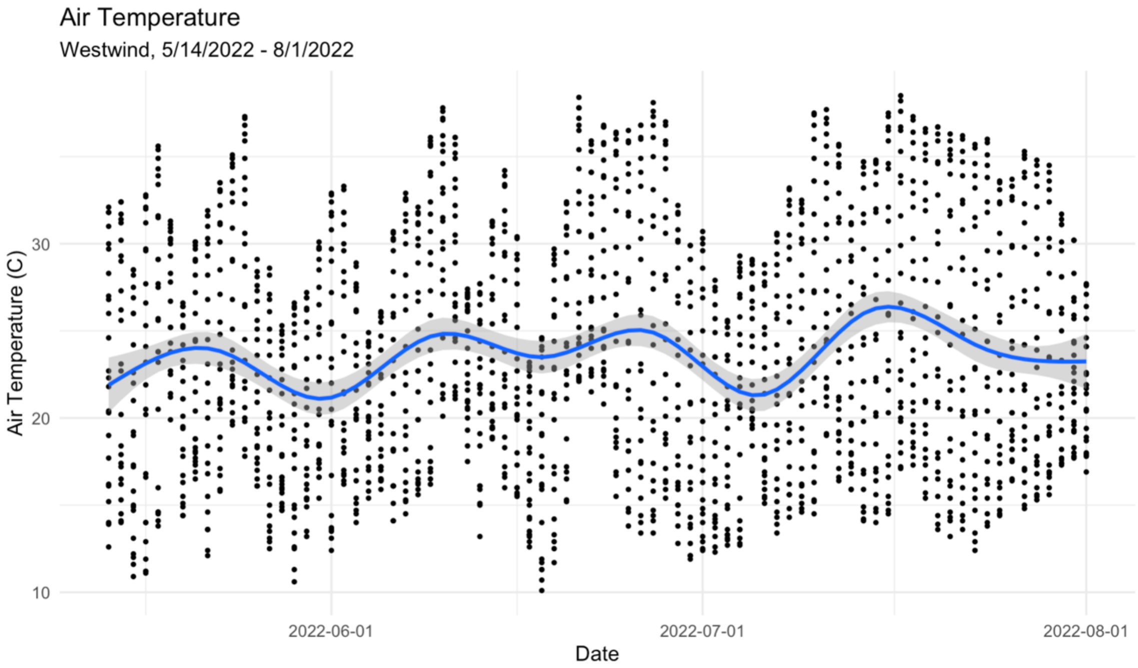

Phytech Tree Water Stress
Westwind Hull/Shell Plot, June 2022
MDS (um)
0
100
200
300
400
Date
6.01.22
6.02.22
6.03.22
6.04.22
6.05.22
6.06.22
6.07.22
6.08.22
6.09.22
6.10.22
6.11.22
6.12.22
6.13.22
6.14.22
6.15.22
6.16.22
6.17.22
6.18.22
6.19.22
6.20.22
6.21.22
6.22.22
6.23.22
6.24.22
6.25.22
6.26.22
6.27.22
6.28.22
6.29.22
6.30.22
Treatment
Control
Amended
Amended Catch Frame



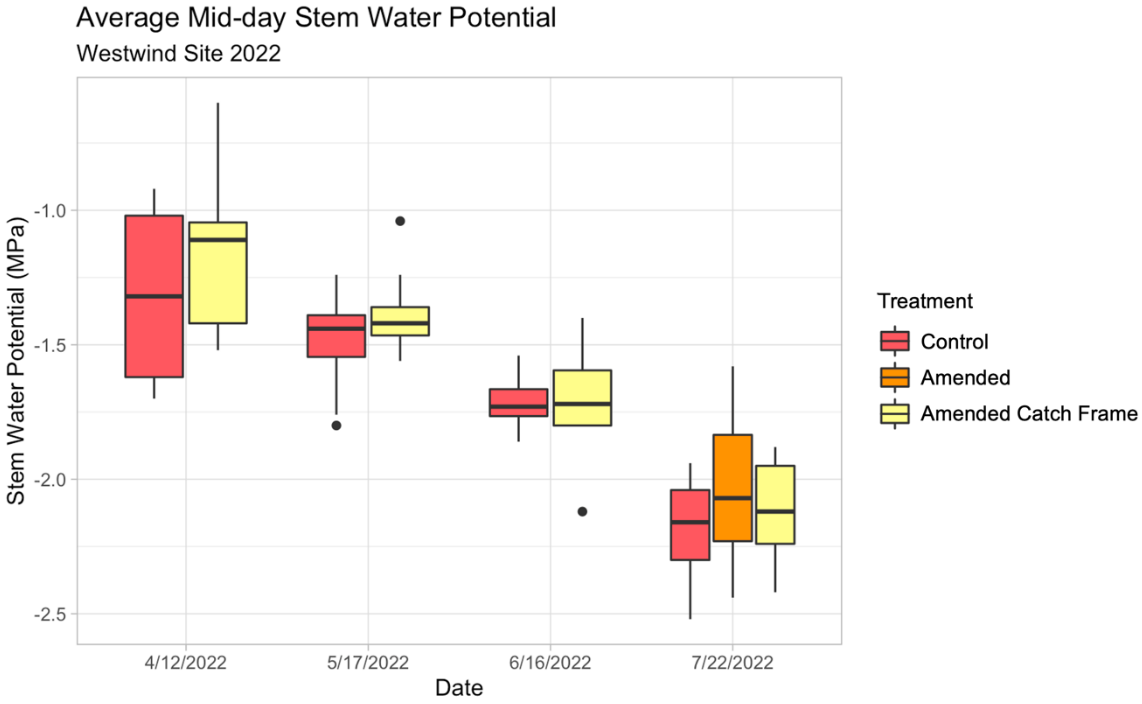
Supplementary Figure 3.7a-c. Mean daily shrinkage (MDS), Phytech's tree water stress metric, May, June, and July 2022. MDS represents the tree trunk's contraction during the day due to internal trunk tension. The greater the MDS (trunk contraction), the higher the tree water stress.



Supplementary Figure 3.8. Monthly average trunk growth rates. Note: data was missing for blocks 3 and 4 in May only.



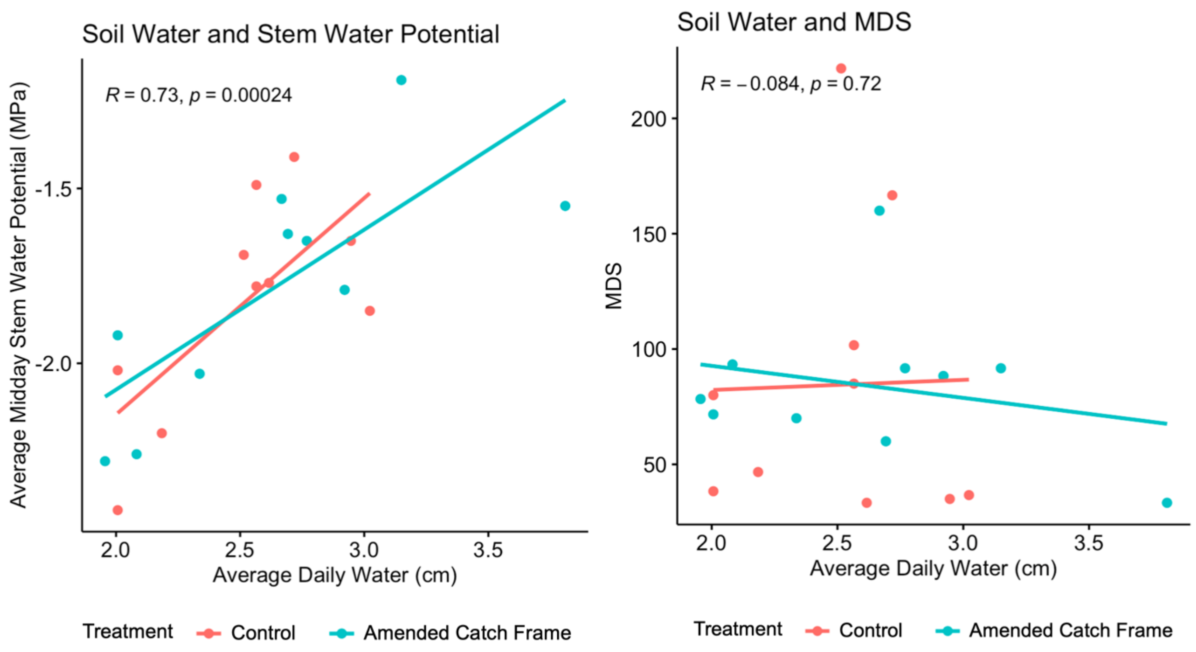
Supplementary Figure 3.9. Air temperature from 5/14/2022 to 8/1/2022 (CIMIS station #226, Woodland).



Supplementary Figure 3.10. Midday stem water potential in 2022 on 4/12/22 (subsample trees from last year, six days after irrigation), 5/17/22 (Phytech trees, one day after irrigation), 6/16/22 (Phytech trees, one day after irrigation), and 7/20/22 (Phytech trees, same day as irrigation). No significant differences between treatments were found on these days.

Supplementary Table 3.2. Stem water potential averages and baseline values, 2022.

| Treatment | Stem Water Potential (MPa) | | | |
|---|---|---|---|---|
| | 4/12/22 | 5/17/22 | 6/16/22 | 7/20/22 |
| Control | -1.31 a | -1.48 a | -1.72 a | -2.17 a |
| Amended | -- | -- | -- | -2.04 a |
| Amended Catch Frame | -1.16 a | -1.39 a | -1.70 a | -2.11 a |
| *Baseline* | *-0.57* | *-0.79* | *-0.80* | *-0.90* |



Supplementary Figures 3.11a and b. Pearson correlation between mid-day stem water potential and soil water and MDS values, respectively. This analysis indicated soil water in the upper 0-10 cm (0-4 inches) (Acclima data) was more closely related to stem water potential than MDS on 5/17/2022, 6/16/2022, and 7/20/2022.

Supplementary Table 3.3. Soil bulk density sampled on 9/13/2022 at Westwind and 10/7/2022 at Bullseye. No significant differences were found between treatments.

| Site | Treatment | Bulk Density (g dry soil cm$^{-3}$) | Moisture (%) at Time of Sampling |
|---|---|---|---|
| Westwind | Control | 1.27 | 12.2 |
| | Hull/shell Mix Amended | 1.18 | 13.0 |
| | Hull/shell Mix Amended with Catch Frame Harvest | 1.22 | 12.6 |
| Bullseye | Control | 1.27 | 21.2 |
| | Shell-based mix | 1.22 | 22.0 |
| | Compost | 1.27 | 22.0 |

Pictures

Top left: Acclima TDR probes (at 5 cm depth) connected to DataSnap solar datalogger. Top right: Phytech soil moisture probe. Bottom left: Phytech dendrometer attached to trunk. Bottom right: stem water potential bag around a leaf.

### 3.11 Literature Cited

Almond Board of California (2020). Almond Almanac. Modesto, California. Document #2020IR0296.

Andrews, E.M., Kassama, S., Smith, E.E., Khalsa, S.D.S., Brown, P.H. (2021). A review of potassium-rich crop residues used as organic matter amendments in orchard crop systems. MDPI Agriculture Special Issue, “Organic Management and Productivity of Tree Crops,” 11(7).

California Department of Water Resources (2022). Sustainable Groundwater Management Act (SGMA), copyright State of California, https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management

Costa, J.M., Ortuno, M.F., Chaves, M.M. (2007). Deficit irrigation as a strategy to save water: physiology and potential application to horticulture. Journal of Integrative Plant Biology, 49(10):1421-1434.

Cox, J., Van Zwieten, L., Ayres, M., & Morris, S. (2004). Macadamia husk compost improves soil health in sub-tropical horticulture. SuperSoil 2004: 3rd Australian New Zealand Soils Conference, University of Sydney, Australia.

Doll, D., Shackel, K. (2015). Drought Tip: Drought management for California almonds. University of California Agriculture and Natural Resources Publication 8515.

Doll, D. (2018). Summer Irrigation: considerations for deficit irrigation. The Almond Doctor.

Drechsler, K., Fulton, A., Kisekka, I. (2022). Crop coefficients and water use of young almond orchards. Irrigation Science, 40:379-395.

Dry, P.R., Loveys, B.R. (1999). Grapevine shoot growth and stomatal conductance are reduced when part of the root system is dried. Vitis 38(4):151-156.

Egea, G., Pagán, E., Baille, A., Domingo, R., Nortes, P.A., Pérez-Pastor, A. (2009a). Usefulness of establishing trunk diameter based reference lines for irrigation scheduling in almond trees. Irrigation Science 27, 431e441.

Egea, G., Dodd, I.C., Gonzalez-Real, M.M., Domingo, R., Baille, A. (2011). Partial rootzone drying improves almond tree leaf-level water use efficiency and afternoon water status compared with regulated deficit irrigation. Functional Plant Biology, 38:372-385.

Espadafor, M., Orgaz, F., Testi, L., Lorite, I.J., Gonzalez-Dugo, V., Fereres, E. (2017). Responses of transpiration and transpiration efficiency of almond trees to moderate water deficits. Scientia Horticulturae, 255, 6-14.

Farzi, R.; Gholami, M.; Baninasab, B.; Gheysari, M. (2017). Evaluation of different mulch materials for reducing soil surface evaporation in semi-arid region. Soil Use Management, 33, 120–128.

Fereres, E., Martinich, D.A., Aldrich, T.M., Castel, J.R., Holzapfel, E., Schulbach, H. (1982). Drip irrigation saves money in young almond orchards. California Agriculture, September-October 1982.

Forge, T., Neilsen, G., Neilsen, D., O’Gorman, D., Hogue, E., & Angers, D. (2015). Organic orchard soil management practices affect soil biology and organic matter. Acta Horticulturae, 1076, 77–84.

Fulton, A., Milliron, L. (2018). Using Baseline SWP for Precise Interpretation. Sacramento

Valley Orchard Source, University of California Agriculture and Natural Resources. https://www.sacvalleyorchards.com/manuals/stem-water-potential/using-baseline-swp-for-precise-interpretation/

Fulton, A. and Milliron, L. (2019). Advanced SWP Interpretation in Almond. Sacramento Valley Orchard Source, University of California Agriculture and Natural Resources.

Fulton, J., Norton, M., Shilling, F. (2019). Water-indexed benefits and impacts of California almonds. Ecological Indicators 96, 711-717.

Goldhamer, D.A., Viveros, M., Salinas, M. (2006). Regulated deficit irrigation in almonds: effects of variations in applied water and stress timing on yield and yield components. Irrigation Science, 24:101-114.

Goldhamer, D.A., Fereres, E. (2001b). Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrigation Science, 20:115-125.

Goldhamer, D.A., Fereres, E. (2017). Establishing an almond water production function for California using long-term yield response to variable irrigation. Irrigation Science, 35:168-179.

Goldhamer, D.A., Smith, T.E. (1995). Single-season drought irrigation strategies influence almond production. California Agriculture, January-February 1995.

Goldhamer, D.A., Viveros, M. (2000). Effects of preharvest irrigation cutoff durations and postharvest water deprivation on almond tree performance. Irrigation Science, 19:125-131.

Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G. (2018). The paradox of irrigation efficiency. Science 361, 6404:748-750.

Granatstein, D., Mullinix, K. (2008) Mulching Options for Northwest Organic and Conventional Orchards. HortScience, 43, 45–50.

Hannam, K.D., Neilsen, G.H., Forge, T.A., Neilsen, D., Losso, I., Jones, M.D., Nichol, C., Fentabil, M.M. (2016). Irrigation practices, nutrient applications, and mulches affect soil nutrient dynamics in a young Merlot (*Vitis vinifera* L.) vineyard. Canadian Journal of Soil Science, 96, 23–36.

Hernandez-Santana, V., Rodriguez-Dominguez, C.M., Fernandez, E., Diaz-Espejo, A. (2015) Role of leaf hydraulic conductance in the regulation of stomatal conductance in almond and olive in response to water stress. Tree Physiology, 36, 726-735.

Idowu, O.J., Sanogo, S., Brewer, C.E. (2017). Short-Term Impacts of Pecan Waste By-Products on Soil Quality in Texturally Different Arid Soils. Communications in Soil Science and Plant Analysis, 48, 1781–1791.

Iqbal, M., Ul-Hassan, A., Van Es, H.M. (2011). Influence of Residue Management and Tillage Systems on Carbon Sequestration and Nitrogen, Phosphorus, and Potassium Dynamics of Soil and Plant and Wheat Production in Semi-arid Region. Communications in Soil Science and Plant Analysis, 42, 528–547.

Jafari, M., Haghighi, J.A.P., Zare, H. (2012). Mulching Impact on Plant Growth and Production of Rainfed Fig Orchards under Drought Conditions; Journal of Food

Agriculture and Environment, 1, 428-433.

Janzen, H. H. (2006). The soil carbon dilemma: Shall we hoard it or use it? Soil Biology and Biochemistry, 38(3), 419–424.

Kang, S., Hu, X., Jerie, P., Zhang, J. (2003). The effects of partial rootzone drying on root, trunk sap flow and water balance in an irrigated pear (*Pyrus communis* L.) orchard. Journal of Hydrology, 280:192-206.

Karagoktas, M.; Uygur, V.; Aydog˘du, M.; Rastgeldi, I. (2014). The Effects of Pistachio Nut Hull Compost on Soil Fertility: A Comparative Study with Manure; Soil Science Society of Turkey & Federation of Eurasian Soil Science Societies: Side, Turkey.

Linstead, C. (2018). The contribution of improvements in irrigation efficiency to environmental flows. Frontiers in Environmental Science, 6:48.

Lipan, L., Martin-Palomo, M.J., Sanchez-Rodriguez, L., Cano-Lamadrid, M., Sendra, E., Hernandez, F., Burlo, F., Vazquez-Araujo, L., Andreu, L., Carbonell-Berrachina, A.A. (2019). Almond fruit quality can be improved by means of deficit irrigation. Agricultural Water Management, 217:236-242.

Lobel, M. R., Firth, D. J., & Johns, G. G. (1994). Effect of mulch, Ca, and Mg on growth, yield, and decline of macadamia. Tropical Agriculture, 71(3), 170–175.

Lu, X. (2020) A meta-analysis of the effects of crop residue return on crop yields and water use efficiency. PLoSONE, 15, e0231740.

Mall, N.K., Herman, J.D. (2019). Water shortage risks from perennial crop expansion in California's Central Valley. Environmental Research Letters, 14:104014.

Martin-Palomo, M.J., Andreu, L., Perez-Lopez, D., Centeno, A., Moriana, A., Corell, M. (2022). Trunk growth rate frequencies as water stress indicator in almond trees. Agricultural Water Management, 271, 107765.

McCutchan, and Shackel. (1992). Stem-water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). Journal of the American Society for Horticultural Science, 117:4.

Neilsen, G.H.; Hogue, E.J.; Forge, T.; Neilsen, D. (2002). Surface application of mulches and biosolids affect orchard soil properties after 7 years. Canadian Journal of Soil Science. .83, 131–137.

Neilsen, G.H.; Hogue, E.J.; Forge, T.; Neilsen, D. (2003). Mulches and biosolids affect vigor, yield and leaf nutrition of fertigated high density apple. HortScience, 38, 41–45.

Nortes, P.A., Perez-Pastor, A.P., Egea, G., Conejero, W., Domingo, R. (2005). Comparison of changes in stem diameter and water potential values for detecting water stress in young almond trees. Agricultural Water Management, 77:296-307.

Ortuno, M.F., Conejero, W., Moreno, F., Moriana, A., Intrigliolo, D.S., Biel, C., Mellisho, C.D., P´erez-Pastor, A., Domingo, R., Ruiz-S anchez, M.C., Casadesus, J., Bonany, J., Torrecillas, A. (2010). Could trunk diameter sensors be used in woody crops for irrigation scheduling? A review of current knowledge and future perspectives. Agricultural Water Management, 97, 1–11.

Overpeck, J.T., Udall, B. (2020). Climate change and the aridification of North America.

PNAS 117(22):11856-11858.

Ozenc, D.B., Ozenc, N. (2008). Short-Term Effects of Hazelnut Husk Compost and Organic Amendment Applications on Clay Loam Soil. Compost Science & Utilization, 16, 192–199.

Phogat, V., Skewes, M.A., Mahadevan, M., Cox, J.W. (2013). Evaluation of soil plant system response to pulse drip irrigation of an almond tree under sustained stress conditions. Agricultural Water Management, 118:1-11.

Prgomet, I., Pascual-Seva, N., Morais, M.C., Aires, A., Barreales, D., Ribeiro, A.C., Silva, A.P., Barros, A.I.R.N.A., Goncalves, B. (2020). Physiological and biochemical performance of almond trees under deficit irrigation. Scientia Horticulturae, 261, 108990.

Qin, W., Hu, C., Oenema, O. (2015). Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: A meta-analysis. Nature Scientific Reports. 5, 16210.

Rodriguez-Dominguez C.M., Buckley, T.N., Egea, G., de Cires, A., Hernandez-Santana V., Martorell, S., Diaz-Espejo A. (2016). Most stomatal closure in woody species under moderate drought can be explained by stomatal responses to leaf turgor. Plant, Cell, and Environment, 39:2014-2026.

Shackel, K.A. (2007). Water relations of woody perennial plant species. VIth International Terrior Congress – Bordeaux – Montpellier 2006. Journal International des Sciences de la Vigne et du Vin, 41, 121-129.

Shackel, K. (2011) A plant-based approach to deficit irrigation in trees and vines. HortScience, 46(2), 173-177.

Simonneau, T., Habib, R., Goutouly, J.P., Huguet, J.G. (1993). Diurnal changes in stem diameter depend upon variations in water content: direct evidence in peach trees. Journal of Experimental Botany. 44, 615–621.

Spinelli, G.M., Snyder, R.L., Sanden, B.L., Shackel, K.A. (2016). Water stress causes stomatal closure but does not reduce canopy evapotranspiration in almond. Agricultural Water Management, 168, 11-22.

Stewart, W.L., Fulton, A.E., Krueger, W.H., Lampinen, B.D., Shackel, K.A. (2011). Regulated deficit irrigation reduces water use of almonds without affecting yield. California Agriculture, 65(2).

Sumner, D.A., Grant, J.A., Caprile, J.L., Doll, D.A., Murdock, J. (2017). Sample costs to establish and orchard and produce walnuts: San Joaquin Valley – North. University of California Agriculture and Natural Resources Cooperative Extension. UC Davis Department of Agricultural and Resource Economics.

Sumner, D.A., Buchner, R.P., Niederholzer, F., Jarvis-Shean, K.S., Lightle, D.M., Symmes, E.J., Milliron, L., Stewart, D. (2019). Sample costs to establish an orchard and produce almonds Sacramento Valley. University of California Agriculture and Natural Resources Cooperative Extension. UC Davis Department of Agricultural and Resource Economics.

Sumner, D.A., Haviland, D.R., Fichtner, E.J., Sanden, B.L., Culumber, M., Viveros, M., Stewart, D. (2019). Sample costs to establish an orchard and produce almonds San Jaoquin Valley South. University of California Agriculture and Natural Resources Co operative Extension. UC Davis Department of Agricultural and Resource Economics.

Sumner, D.A., Zhuang, S., Fidelibus, M., Kurtural, S.K., Lund, K., Torres, G., Stewart, D. (2019). Sample costs to establish a vineyard and produce winegrapes – Southern San Joaquin Valley. University of California Agriculture and Natural Resources Cooperative Extension. UC Davis Department of Agricultural and Resource Economics.

Sumner, D.A., Baldwin, R., Battany, M., Beede, M., Brar, G., Culumber, M., Ferguson, L., Fichtner, E., Gordon, P., Hanson, B., Haviland, D., Hembree, K., Kallsen, C.E., Marino, G., Sanden, B., Michailides, T.J., Trouillas, F., Zaccaria, D., Harris, L., Stewart, D. (2020). Sample costs to establish and produce pistachios – San Joaquin Valley South. University of California Agriculture and Natural Resources Cooperative Extension. UC Davis Department of Agricultural and Resource Economics.

Sumner, D.A., Murdock, J., Goodrich, B. (2021). Sample costs to establish a vineyard and produce winegrapes – San Joaquin Valley North. University of California Agriculture and Natural Resources Cooperative Extension. UC Davis Department of Agricultural and Resource Economics.

Tejero, I.F.G., Moriana, A., Pleguezuelo, C.R.R., Zuazo, V.H.D., Egea, G. (2018). Sustainable deficit-irrigation management in almonds (*Prunus dulcis* L.): different strategies to assess the crop water status. Water Scarcity and Sustainable Agriculture in Semiarid Environment. Chapter 12, 271-298.

United States Department of Agriculture National Agricultural Statistics Service. (2021). Census of Agriculture for California. 2021 State Agriculture Overview. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=CALIFORNIA

United States Department of Agriculture National Agricultural Statistics Service. (2022). 2021 California Almond Objective Measurement Report. https://www.almonds.com/sites/default/files/2021-07/2021ObjectiveReport.pdf

Ward, F.A., Pulido-Velazquez, M. (2008). Water conservation in irrigation can increase water use. PNAS, Economic Sciences, 105(47):18215-18220.

# Chapter 4: Organic matter amendments and off-ground harvest in a California almond orchard promote microbial community functional group biomass in the soil and the organic layer

## 4.1 Background

Ecosystem-oriented agricultural management practices are needed in almond systems to rehabilitate degraded agricultural systems, promote agroecosystem services, and improve crop system sustainability (De Leijster et al. 2019, Fenster et al. 2021, Soto et al. 2021). The Almond Board of California has identified several almond crop system challenges and developed corresponding goals for improvements (ABC 2025 Goals). These goals include achieving zero waste by optimizing orchard biomass such as hulls and shells, reducing harvest dust, and reducing water use. In response to these goals, this research project investigates the practice of recycling almond hulls and shells as organic matter amendments combined with off-ground harvest. These combined treatments have the potential to improve soil-plant water dynamics, nutrient cycling, components of soil health, and crop performance. The term soil health typically refers to soil functionality, vitality, and sustainability (Janzen et al. 2021). The indicators or metrics of soil health are context-dependent and refer to different soil properties depending on soil management goals (Janzen et al. 2021). At this field site, specific chemical, physical, and biological components of soil health were chosen due to their relevance in assessing water and nutrient retention in the rootzone. Maintaining an undisturbed layer of hull/shell materials on the soil surface could help build an organic layer and provide annual organic inputs that build soil functionality.

While processors can sell a portion of hulls and shells as dairy feed, a substantial amount of remaining hull and shell materials need a convenient and sustainable destination each year. Almond hulls and shells contain potassium that can be released into the soil solution following water application, becoming available for plant uptake (Chapter 2). When surface-applied in the tree row, this organic matter amendment creates a barrier on the soil surface which can provide a mulching effect, maintaining soil water content (Chapter 3). The organic layer on orchard soils can buffer the soil against extreme conditions (e.g., temperature and moisture), promote orchard nutrient cycling, and provide a substrate for beneficial microbial communities (Andrews et al. 2021).

However, the typical harvest process in California almond orchards disturbs the soil, displacing organic matter and topsoil while generating dust. Most almond growers in California utilize an on-ground harvest approach: machinery shakes the tree trunks, the crop falls onto the ground, mechanical sweepers move the crop into windrows in the alley, the crop dries for several weeks, and then is mechanically picked up and transported to a processor. The sweeping step generates a substantial amount of dust and disturbs the topsoil over tree roots. This on-ground harvest approach necessitates bare orchard soil free of vegetation and organic debris at harvest. This limits the use of mulches, organic matter amendments, and other soil health building practices. In contrast, off-ground harvest equipment can be used to shake the crop into a catch frame that prevents the crop from contacting the soil over the tree roots, instead funneling the crop directly into a windrow in the alley. This can be useful for growers who have difficult terrain, such as rocky or cracked soils. Additionally, off-ground harvesting allows the grower to return irrigation sooner after trees are shaken since the crop is not in the irrigation zone. This harvest approach has potential as a soil health building practice in the tree row because it minimizes soil disturbance over tree roots, enabling the retention of organic matter provided through soil health building practices (e.g., mulches, cover crop biomass, compost, etc.). While on-ground harvest in tree crop systems limits the benefits provided by organic matter amendments and can lead to soil degradation, dust, prolonged herbicide reliance, and root damage, alternative harvest practices that reduce soil disturbance could help address these issues and improve soil and nutrient management (Granatstein et al. 2014, Galanti et al. 2019, Cox et al. 2004, Chen et al. 2021, Glover et al. 2000).

Prior findings related to soil fertility and water dynamics provide a backdrop to explore effects of hull/shell amendments on soil microbial responses. Chapter 2 illustrates that increases in soil XK can lead to higher leaf K within the first 1-3 years. However, no differences in leaf N status were found, indicating that any increases in microbial activity due to hull/shell amendments did not immobilize nitrogen enough to compete with plant N uptake. In the mid- to long-term, reduced soil disturbance and off ground harvest could potentially improve soil chemical and physical properties such as percent organic matter, CEC, and bulk density, though these changes would likely take several years to become significant. Chapter 3 demonstrated that the amended off-ground treatment increased water infiltration rate into the soil profile, maintained higher soil moisture, moderated soil temperature, and increased root biomass density in the upper soil layer. These benefits could help increase microbial biomass near the soil surface. Research is needed to assess how almond hull/shell amendments maintained with off ground harvest could alter microbial biomass, microbial community composition, carbon (C) substrate utilization, decomposition rates, and nutrient cycling in orchard soil and in the organic layer on the soil surface.

Prior research indicates that crop residue amendments such as almond shells have the potential to increase soil microbial biomass, alter the soil microbial community, and promote microbial enzyme production (Vida et al. 2016, Bonilla et al. 2012, Lopez et al. 2014, Yan et al. 2020, Neilsen et al. 2014). In the long-term, this nutshell amendment practice can create an organic layer on the soil surface (Lopez et al. 2014), build soil organic carbon (Idowu et al. 2017, Kasongo et al. 2010), and improve components of soil physical structure (Moyin-Jesu et al. 2007, Ozenc et al. 2008, Tahboub et al 2008). Previous research suggests almond hull/shell amendments promote microbial activity and biomass in the organic layer on the soil surface and the upper soil layer (Bonilla et al. 2012, Lopez et al. 2014). As several prior studies have found almond shell amendments in orchards may not lead to a highly specific soil communities of bacteria and other phyla, these amendments appear to promote a wide variety of microbial community groups (Bonilla et al. 2012, Vida et al. 2016). However, one study found almond shells did influence soil fungal community composition after two applications within 7 years prior to sampling by increasing the relative abundance of Ascomycota, which includes many species of saprophytes, leading to a high abundance of microbial groups which participate in biomass conversion plant litter degradation (Vida et al. 2016). Vida et al. 2016 found the microbial communities in almond shell amended soils had greater capacity for C degradation. Microbial degradation of almond shells could lead to a progressive release of simpler C compounds from lignin, increasing available C sources such as aromatic compounds, cellulose, and hemicellulose (Vida et al. 2016).

The goal of this research was to assess the effects of hull/shell mix amendments maintained with catch frame harvest equipment over time on soil health components related to decomposition, microbial community composition, C substrate utilization, and nutrient cycling. Changes within the hull/shell amendment organic layer on the soil surface and in the upper soil layer were evaluated to characterize shifts in response variables over time and associated implications for improving orchard soil health functions.

### 4.2 Research Questions

How does a mix of hulls and shells used as a surface-applied soil organic matter amendment affect major microbial functional group community composition and soil microbial carbon substrate utilization? What type of microbial community characterizes the hull/shell amendment organic layer maintained on the soil surface with off-ground harvest (reduced soil disturbance)? How rapidly do hull/shell amendments decompose and how does hull/shell amendment carbon:nitrogen (C:N) ratio shift over time? What are the implications for orchard soil health?

### 4.3 Hypotheses

Since microorganisms are typically the first organisms to respond to soil environmental changes, soil microbial biomass was hypothesized to be the first biological component of soil health to improve, likely increasing within the first year. After promoting high bacterial biomass in the first year, the soil microbial community was hypothesized to shift toward decomposers such as saprophytes and actinomycetes with a higher fungi:bacteria ratio after simple C compounds are metabolized and more complex C sources remain (Table 4.1). Increased overall microbial biomass and shifts community composition may lead to increased soil microbial activity and higher affinity for C substrate groups such as carbohydrates, however overall microbial diversity is unlikely to substantially change (Table 4.2). The hull/shell amendment was hypothesized to promote high microbial biomass and more specialized microbial functional groups which reflect a lower diversity index in the short term. Due to conducive moisture and temperature conditions and N fertilizer inputs in the tree row that likely support high microbial biomass and activity, hull/shell amendments likely decompose relatively quickly and decline in C:N within the first year.

Table 4.1. Hypotheses outline for major microbial community functional group response variables within the first year and a half following initial hull/shell application. See Supplementary Table 4.1 for explanations of functional significance of microbial group response variables.

| **Response Variable** | **Hypotheses for Amended Soil (vs. Control Soil)** | **Hypotheses for Amendment Layers Over Time** |
|---|---|---|
| Functional Group Diversity | No change. | Narrow initially. Increase over time as complex C substrates remain. |
| Total Microbial Biomass | Increase in the first year. | Very high. |
| Fungi:Bacteria | Gradual increase. | Favors bacteria initially, then fungi gradually. |
| Predator:Prey (Protozoa:Bacteria) | No change. | Gradual increase. |
| Gram(+):Gram(-) | Gradual increase. | Gradual increase. |
| Actinomycetes | Gradual increase | High, gradual increase. |
| Rhizobia | No change. | No change. |
| Arbuscular Mycorrhizae | No change. | No change. |

| | | |
|---|---|---|
| Saprophytes | Gradual increase. | High, gradual increase. |
| Saturated:Unsaturated | Gradual increase. | Gradual increase. |
| Monounsaturated:Polyunsaturated | Gradual increase. | Gradual increase. |

Table 4.2. Hypotheses outline for 2022 EcoPlate response variables which were informed by PLFA results from 2021.

| **Response Variable** | **Hypotheses for Amended Soil (vs. Control)** |
|---|---|
| Activity | Average well plate color development will be higher for amended catch frame soil compared to control soil. Activity will show the larger differences between treatments than diversity and similarity response variables. |
| Diversity | Considering diversity index from October 2021 provided by PLFA and prior studies, microbial community diversity may only be slightly higher for amended catch frame soil compared to control soil, likely not significantly different. |
| Similarity | PCA will likely indicate only slight directional differences between treatments. |

## 4.4 Site Description

Westwind Farms is a 61.5 hectare (152 acre) almond orchard located near Woodland, California. Every other row is Nonpareil variety on Bright Hybrid 5 rootstock. Alternating pollinizer row varieties are Butte, Carmel, and Monterey. All data was collected from Nonpareil rows only. Trees are spaced at 6.7 x 4.6 meters (22 x 15 ft) and rows are oriented north-south. The experimental plot is located on the southwest area of the orchard and consists of the first 40 trees south of the central lateral alley. While amendments were applied to entire rows, only the northern most 40 trees in each row were used for harvest data. The soil type within this experimental plot is San Ysidro loam (NRCS database). Irrigation is applied by micro-sprinklers. At the start of the experiment before treatments were applied, at 0-10 cm depth soil average pH was 7.4, average percent organic matter was 2.3%, and average CEC was 20 meq 100 $g^{-1}$ soil. Annual fertilizer applications at this site are reported in Chapter 2, Supplementary. Each fall, the grower applied 4.4 metric tons ha$^{-1}$ (2 US tons ac$^{-1}$) compost across the entire orchard as a best management practice. This occurred on 11/11/2020 around one month after hull/shell amendment application, and again on 10/8/2021 four days after hull/shell amendment application. A cover crop mix was seeded in 2020 in the alley and allowed to set seed.

### 4.5 Experimental Design

At Westwind Farms, a control (bare soil) treatment was compared with a treatment consisting of hull/shell amendments that were maintained over two years with catch frame (off-ground) harvest equipment. Treatments were applied to individual rows of trees and replicated across four blocks in a randomized complete block design. Each plot consisted of one tree row. On 10/7/2020, 18 tons ha$^{-1}$ (8 US tons ac$^{-1}$) of hull/shell mix with 6.6% moisture were applied at approximately 17 dry tons ha$^{-1}$ (7.5 dry US tons ac$^{-1}$) broadcasted by a compost spreader across the tree row and alley. On 10/4/2021, 18 tons ha$^{-1}$ (8 US tons ac$^{-1}$) hull/shell mix were applied with 2.1% moisture at approximately 17.5 dry tons ha$^{-1}$ (7.8 dry US tons ac$^{-1}$) total concentrating the amendment over tree roots only. In 2020 the mix was 32% hulls and 68% shells, and in 2021 the mix was 53% hulls and 47% shells. A catch frame harvester was utilized in August 2021 to maintain the amendment layer.

Results from the Westwind field site are the central focus of this chapter. However, at second field site, Bullseye Farms, separate research questions and hypotheses (see Chapter 2) were explored through a different set of treatments across four blocks in a randomized complete block design: control, fresh shells, and composted shells. Soil samples for microbial community composition from this field trial will be discussed briefly to evaluate how almond hull and shell based organic matter amendments affected microbial community shifts in a different orchard context. A third field site with separate research objectives, Crown Nut Company, received hull/shell amendment applications in randomized complete block design across four blocks and was similarly sampled at one time point for microbial community composition. At all sites, all amendment and soil samples were collected within the irrigation wetted zone in the tree row. All identities of grower companies are shared with permission.

### 4.6 Methods and Analyses

Amendment Nutrient Methods. Samples from the initial applied amendments were taken from each amended treatment row on application dates. After weighing for dry net mass remaining across time points, the contents of litter bag amendment samples were used for nutrient analysis. Amendment samples were oven-dried, pulverized, and sent to the UC Davis Analytical Lab to be analyzed for nutrient concentrations: carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, boron, zinc, manganese, iron, and copper. As carbon and nitrogen are highlighted in this Chapter due to their relevance for microbial research questions, other nutrients can be found in Chapter 2.

Decomposition Methods. Following the October 2020 application, litter bags (size 0.79 mm, 1/32 inch mesh) containing amendments were installed on the soil surface to measure decomposition of amendments by mass loss over time in the amended catch frame harvest treatment (see Methods section Chapter 2). Mesh litter bags were installed immediately following hull/shell amendment application on 10/7/2020. Bags were collected on 11/6/20

(Time 1, Day 30), 12/6/20 (Time 2, Day 60), 2/4/21 (Time 3, Day 120), 3/6/21 (Time 4, Day 150), 6/6/21 (Time 5, Day 240), 7/29/21 (Time 6, right before harvest on Day 293), 10/7/21 (Time 7, Day 365). Litter bags were oven-dried, contents were weighed dry, and dry weights were used to calculate percent net mass remaining at each time point as a metric of decomposition (Figure 4.1, Supplementary Table 4.2).

In addition, the cohort layered screen technique was used to assess longer term decomposition rates and net mass fluctuations in the litter layer formed by hull/shell amendments and maintained by catch-frame harvest (Binkley et al. 2002, Karlberg et al. 2008, Krishna & Mohan, 2017). On 9/29/2021, prior to amendment application, seven 3 mm nylon mesh squares 1 $m^2$ in diameter (Memphis Net & Twine) were pinned to the soil surface with landscape stables in the amended catch frame treatments. This slightly larger mesh size was chosen for the cohort layered screen technique to optimize access by all organisms including macrofauna, while reducing potential excessive loss of litter particles (Hoover et al. 2008). Prior to the second amendment application in October 2021, flat mesh squares were installed over the first amendment layer to keep each application of hulls and shells separated to measure changes in decomposition and microbial community composition within new and old organic layers.

Soil Methods. Immediately prior to amendment application, soil samples were taken from each treatment row to assess soil fertility, which included: nitrate-N, Olsen-P, exchangeable K, exchangeable Na, exchangeable Ca, exchangeable Mg, CEC, percent organic matter (via Loss on Ignition), and pH (results reported in Chapter 2). These samples were taken at 0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm depths. Three subsamples were taken for each treatment row, dried and ground separately by a soil pulverizer. Each of the three subsamples per treatment row from 0-10 cm depth were aggregated for analysis through the University of California Davis Analytical Lab. At select time points, soil total nitrogen (TN) and total organic carbon (TOC) were analyzed via oxidation by flash combustion. Bulk density measurements were taken using a metal ring and mallet, dried, weighed, calculated, and expressed as g soil $cm^{-3}$ as reported in Chapter 3. Soil samples for root biomass were taken using 10 cm x 3.8 cm soil cores in triplicate within each plot (methods reported in Chapter 3).

Microbial Methods. Microbial methods were chosen to provide an integrated picture of broad group community functional composition and microbial physiological capacity associated with decomposition and the carbon cycle. Phospholipid fatty acid (PLFA) analysis was used to assess microbial community functional groups in the spring and fall. This method provides a representation of living soil microbial biomass and allows the identification of the presence or absence of functional groups of interest. Since soils tend to vary widely, PLFA is useful for comparing between management conditions at a given site.

Samples analyzed via Phospholipid Fatty Acid (PLFA) analysis were taken on 4/6/2021, 10/14/2021, and 5/11/2022. Three subsamples were taken per plot and aggregated into one bag per plot prior to analysis. Samples were taken from the control and amended catch frame treatments within the sprinkler zone, placed in Ziplock plastic bags, packaged on ice in a Styrofoam cooler, and sent to Ward Labs (Kearney, NE) for analysis. On 4/6/2021, eight soil samples (four from control plots and four from amended catch frame plots) and one preliminary aggregated sample from the amendment layer were submitted. On 10/14/2021, sixteen samples were submitted for PLFA: four from control soil, four from the amended catch frame soil, four from the original 1-year-old fall 2020 amendment layer, and four from the new 1-week old amendment layer which had been kept separate by a mesh layer. After collecting both amendment samples from the mesh square area, the soil surface was brushed to remove any remaining organic matter and three soil samples in the top 0-10 cm were aggregated in a plastic bag. This sampling approach on 10/14/2021 was replicated again on 5/11/2022 for sixteen samples at each time point.

Community-level physiological profiling to compare communities was conducted using Biolog EcoPlate microplate assays, which estimate microbial community function by measuring the capacity to degrade different C sources (Garland and Mills, 1991). Each EcoPlate contains 31 C sources replicated in triplicate within a plate. Carbon sources belong to six major groups: amino acids, carbohydrates, carboxylic acids, phenolic acids, polymers, and amines. Microbial communities provide a distinct metabolic reaction or “fingerprint” which allows functionally relevant community characterization. The community-level physiological profile is assessed for similarity (pattern development), activity (rate of color change in each well), and diversity (richness of well response) (Garland 1997, Weber and Legge 2010, Biolog EcoPlate Instruction Manual).

EcoPlate samples were collected on 6/21/2022 from the control and amended catch frame soils only at 0-10 cm, with three subsamples per treatment-block combination which were kept separate (not aggregated). Fresh soils were sieved to 4 mm, diluted with sodium pyrophosphate and shaken, allowed to settle, and shaken and diluted again. The solution was pipetted into Biolog plates and absorbance (optical density) was read at 590 and 750nm at 12-hour increments for 108 hours total. Readings at hour 108 were utilized for analysis as values plateaued at this time and mold was found on the samples after this sampling time. Activity is measured via the density or rate of average well color development (AWCD). Diversity describes the richness and evenness of responses among wells and can be quantified via calculated indices such as McIntosh, Shannon-Wiener, and Simpson diversity indices. Similarity between soils indicates pattern development or relative rate of utilization among wells and can be measured using multivariate analysis, the most common approach for EcoPlates being Principal Components Analysis (PCA).

Tree Sampling, Water Dynamics, and Yield. Methods for trunk circumferences, tree leaf nutrient status, tree water stress, and yield are reported in Chapter 2. Soil probes were used to measure soil moisture and temperature as described in Chapter 3.

Data analysis. All data was analyzed in R (version 4.1.2, 2021 The R Foundation for Statistical Computing, RStudio 2022.07.1 build 554). The package ggplot2 was used for data visualization. Linear mixed effects models were used with treatments as fixed effects and blocks as random effects using lmer() command from the lmerTest package. When individual subsamples were kept separate prior to analysis, plot was included as a random variable nested within block (e.g. EcoPlate response variables, root biomass). The assumptions of normality and homogeneity of variances were assessed with Normal Quantile-Quantile and Scale-Location plots. All analysis of variance (ANOVA) tests utilized $\alpha=0.05$. When

ANOVA indicated significant differences, Compact Letter Display groupings were generated using the estimated marginal means for multiple pairwise comparisons via Tukey test (multcomp package).

Pearson correlation was used to assess correlations between net dry mass remaining and C, as well as AWCD and substrate richness and McIntosh Index. Using the ggbiplot and devtools packages in R, Principal Components Analysis (PCA) was performed as a dimensionality-reduction method to summarize patterns, transforming data while preserving trends. PCA biplots were used to visualize relationships between microbial functional groups and directional shifts separating different treatments or substrates, which were represented with different colors. Using the vegan package, Canonical Correspondence Analysis (CCA) was utilized to model a matrix of microbial community data (PLFA) constrained by environmental characteristics (soil fertility) to evaluate how environmental variables are related to microbial community composition (Oksanen et al. 2017, Schmidt et al. 2018). CCA is a constrained ordination technique that is used to identify environmental gradients that drive shifts in ecological community composition.

## 4.7 Results

### 4.7.1. Amendment Nutrients and Decomposition

The average initial hull/shell amendment C:N ratio was approximately 53:1 in 2020 and 51:1 in 2021. The hull/shell applications provided approximately 7487-7846 kg $ha^{-1}$ (6680-7000 lb $ac^{-1}$) carbon and 143-155 (128-138 lb $ac^{-1}$) nitrogen in addition to other nutrients (Chapter 2). After one year, the average net dry mass remaining was approximately 45% of the initial dry mass (Figure 4.1). After two years, on 10/13/2022 average dry net mass remaining of the original fall 2020 applied amendment was 13.2% of the original dry mass applied. This low net mass remaining value indicates most of the initial hull/shell amendment layer decomposed within 2 years after initial application.

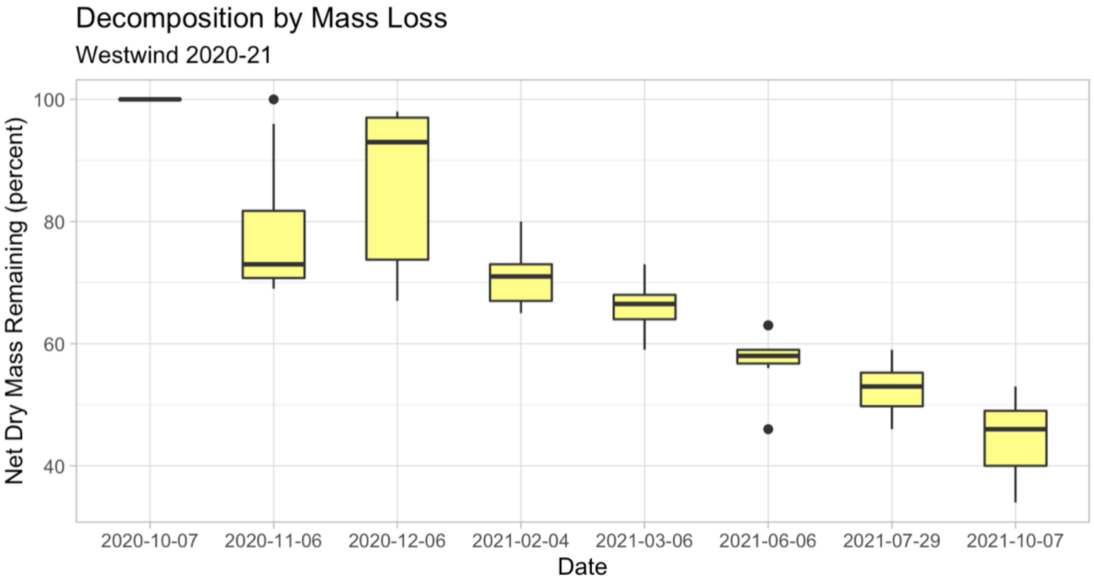
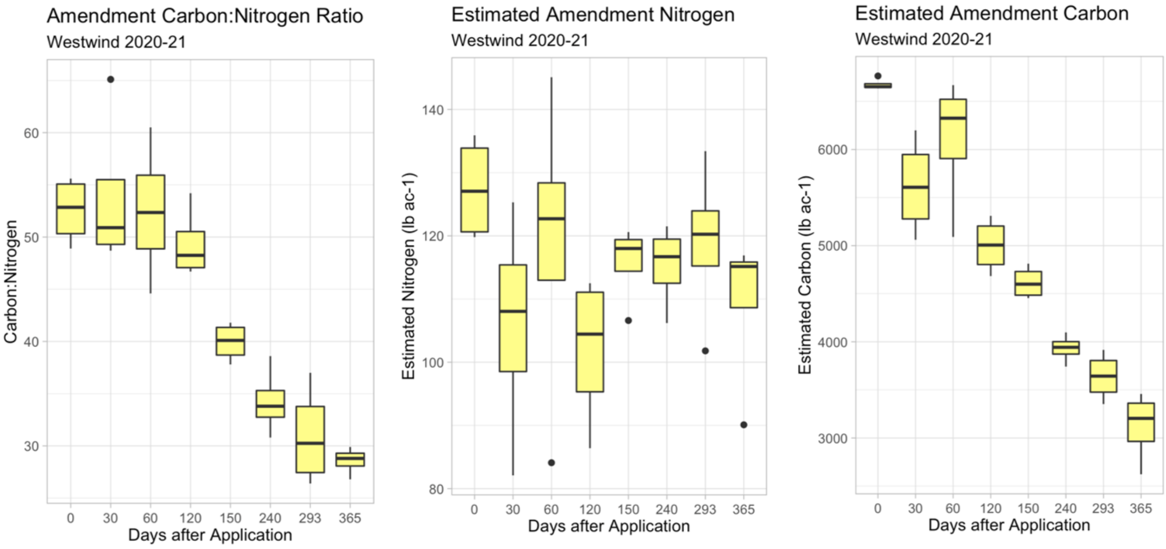


Figure 4.1. Decomposition by mass loss over time expressed as net dry mass remaining (percent), Westwind. The increase at 12/6/20 can be attributed to compost application 4.4 metric tons ha$^{-1}$ (2 US tons ac$^{-1}$) on 11/11/2020. On Day 365, average net dry mass remaining was approximately 45%.

Nutrient analysis of litter bag samples indicated amendment C:N ratio decreased over time particularly after 120 days in the spring following fall application (Figure 4.2a). Dry weights and nutrient concentrations were utilized to estimate nitrogen and carbon contained within the hull/shell amendment material at each time point (Figure 4.2b and c). Estimated carbon in the hull/shell amendment layer generally followed a similar stepwise decline as the C:N ratio over the year. While net mass remaining and carbon both increased slightly at 12/6/2020 due to an application of 4.4 metric tons ha$^{-1}$ (2 US tons ac$^{-1}$), the overall decline in net mass remaining indicated decomposition occurred at a steady rate comparable to the decline in amendment carbon. While some N fluctuation occurred, N decreased somewhat but remained relatively similar over the course of the year. While amendment C was steadily metabolized, N applied through compost (11/11/2020) and fertigation throughout the growing season likely influenced amendment layer N levels which were maintained at approximately 114-144 kg ha$^{-1}$ (102-128 lb ac$^{-1}$), likely supporting microbial biomass. From October 2020 to October 2021 during the decomposition process, decreases in amendment C and dry mass were closely correlated (Figure 4.3).



Figures 4.2a-c. Carbon:nitrogen ratio, estimated carbon, and estimated nitrogen in amendment layers by dry mass over time.

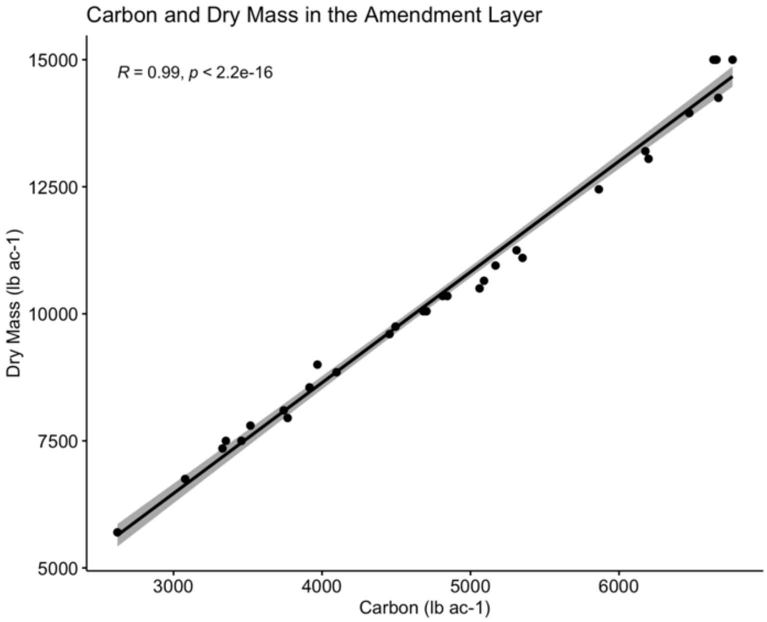


Figure 4.3. Carbon and net dry mass were strongly correlated throughout the year following amendment application, 10/7/2020 to 10/7/2021.

4.7.2. Microbial functional group community composition and activity

Soil samples for PLFA analysis were taken on 4/6/2021, 10/14/2021, and 5/11/2022. On 4/6/2020, no microbial community groups were significantly different between the control and the amended soils (Supplementary Table 4.3). However, the amended soil had slightly lower functional group diversity than control soil indicating that more specialized soil microbes may have been present, though not significant. The amended soil contained slightly higher total microbial biomass, arbuscular mycorrhizal biomass, and undifferentiated biomass. At this time, one composite hull/shell amendment organic litter layer sample was taken as a preliminary assessment of amendment layer microbial groups. This hull/shell layer had approximately triple the average total microbial biomass of both control and amended soils, and higher fungi, bacteria, and protozoan biomass (Supplementary Table 4.3). The hull/shell layer had a relatively lower average diversity index and higher fungi:bacteria ratio. Total rainfall/irrigation was 8.9 inches since hull/shell application on 10/7/2020.

On 10/14/2021, compared to the control soil, the amended catch frame soil contained significantly higher average total biomass, total bacterial percent and biomass, gram(-) percent and biomass, actinomycete biomass, and a lower diversity index and gram(+):gram(-) ratio (Supplementary Table 4.4). Fungal biomass, gram(-), gram(+), arbuscular mycorrhizal, protozoan, and undifferentiated biomass were slightly higher in amended catch frame soil, though nonsignificant. The amended catch frame soil had slightly lower average fungi:bacteria ratio. After one year, the microbially-active amendment layer appeared to gradually be affecting the soil microbial community underneath it starting with bacteria. Considering how these soil microbial shifts might be related to changing soil fertility variables, CCA showed the control and amended catch frame soil microbial groups clustered separately, with soil XK and pH changing along the axis separating the two treatment clusters (Figure 4.4). This indicates changes in microbial community composition may be related to soil XK and pH, while somewhat related to TN, TOC, and CEC but not $NO_3$ at this time. No significant differences were found using ANOVA with the CCA. At this sampling time, total rainfall/irrigation from 10/7/2020 until 10/14/2021 was approximately 44 inches.

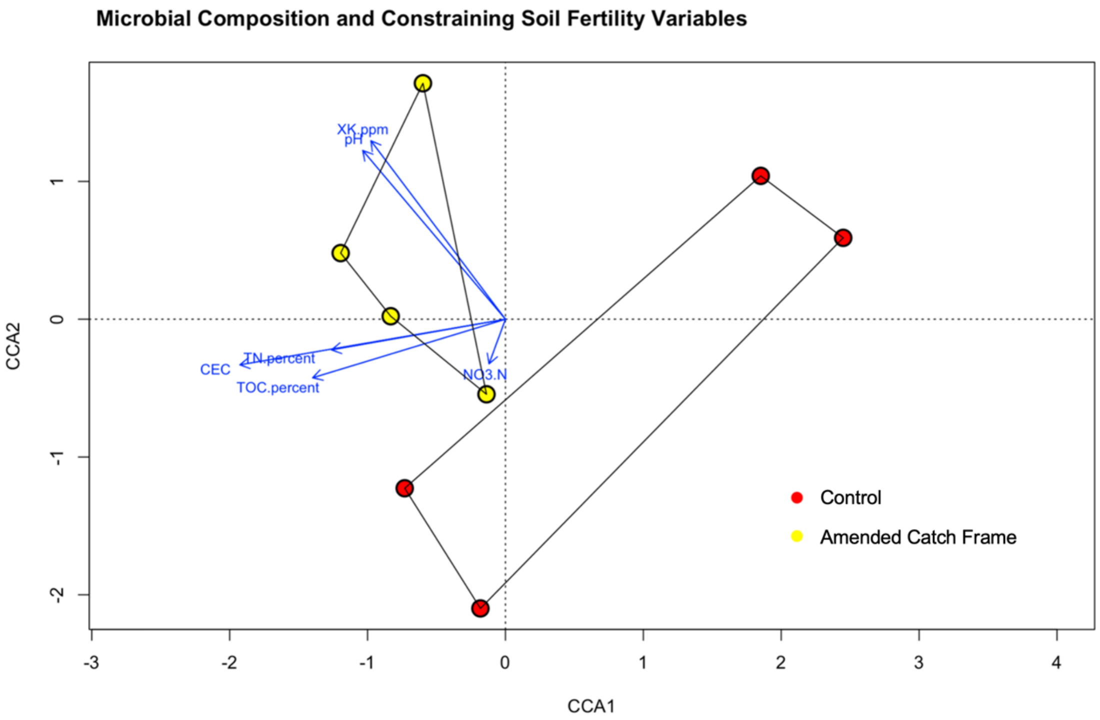
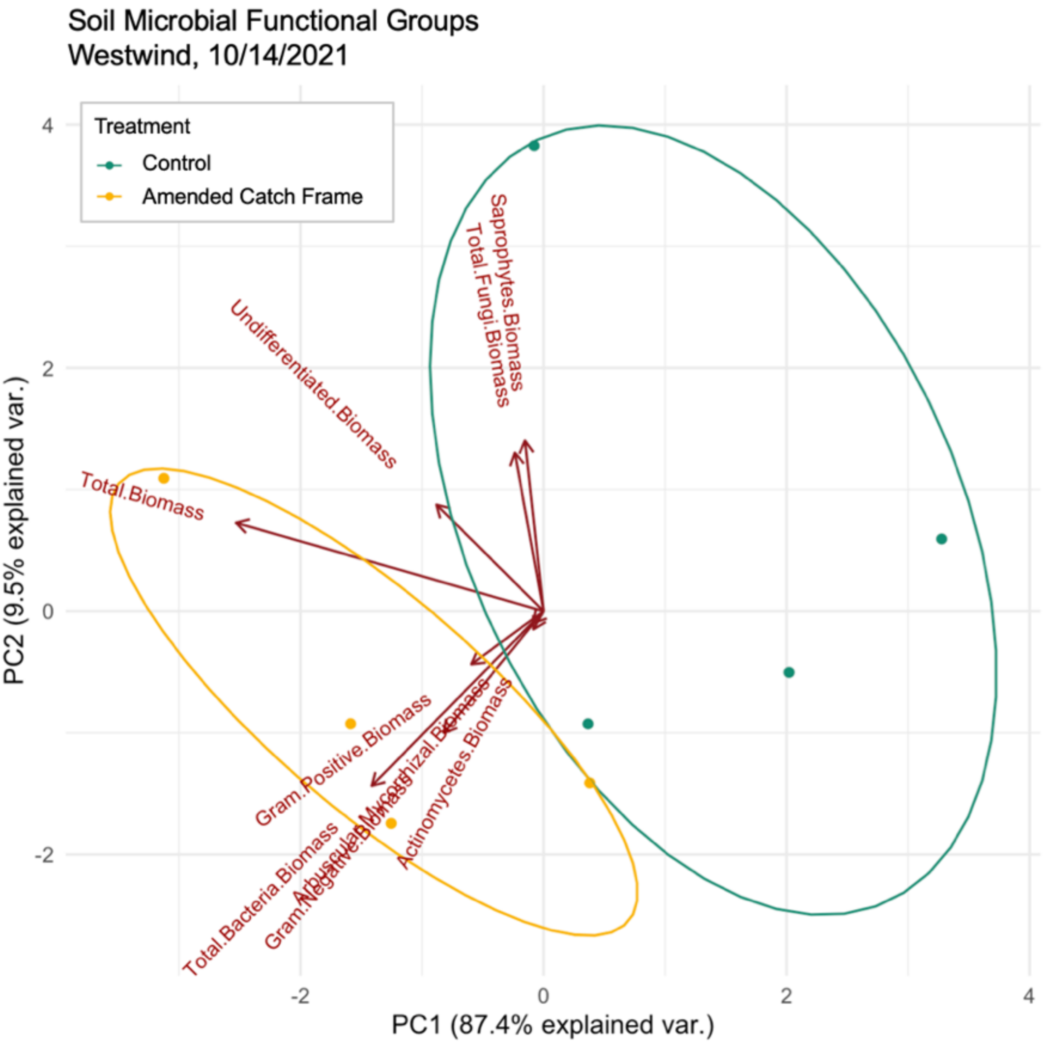


Figure 4.4. Canonical correspondence plot using components of soil fertility shown by blue arrow vectors that provide environmental context for diverging clusters of microbial community group biomass data, represented by the clustered colored points for each treatment, Fall 2021.

On 10/14/2021, compared to the newly applied one-week-old amendment layer, the original one-year-old hull/shell organic layer contained double the total microbial biomass and higher average bacterial, fungal, actinomycete, gram (+) and (–) bacterial, saprophytic, and protozoan biomass, though none were statistically significant (Supplementary Table 4.5). The 1-year-old amendment layer had a slightly higher fungi:bacteria ratio than the new hull/shell amendment. Both hull/shell amendment layers appeared to begin supporting microbial life across higher trophic levels at this time.

On 5/11/2022, the amended catch frame soil had significantly higher average fungi:bacteria ratio, total biomass, total bacteria, total fungi, gram(-), gram(+), saprophyte, and arbuscular mycorrhizal biomass compared to control soil (Supplementary Table 4.6). Several of these functional groups showed significantly higher percent composition as well. The control soil had a significantly higher percent undifferentiated microbes, but not biomass. Notably, total fungi, saprophyte, and mycorrhizal biomass were approximately doubled in the amended catch frame soil compared to the control. These functional groups play well-established roles in decomposition and help explain the substantial decrease in net dry mass remaining observed between fall 2021 and fall 2022. The saturated:unsaturated ratio was significantly lower for the amended catch frame soil than the control soil, suggesting a more stable bacterial community (Supplementary Table 4.1). While many significant increases were found in microbial biomass across different functional groups, diversity indices between the two soils were similar at this time. This indicates the substantial increases in biomass of many microbial groups did not lead to a unique microbial diversity index compared to the control in the second spring.

PCA was used to assess community-wide shifts in control and amended catch frame soils using microbial biomass in fall 2021 and spring 2022 (Figures 4.5a and b). After one year, increased bacterial biomass, both gram(+) and gram(-), was the most evident difference characterizing amended catch frame soils. These vectors appeared to be correlated with actinomycete biomass and arbuscular mycorrhizal biomass, and to a lesser degree, total biomass. However, in spring 2022 after a year and a half, the control and amended catch frame soil clusters were more clearly separated. The vectors separating the amended catch frame soil cluster from the control then included saprophytes, fungi, and actinomycete vectors, in addition to bacteria, gram(+) and gram(-), and total biomass. While higher bacterial biomass set the amended catch frame soil apart from the control soil after 1 year, after 1.5 years and a second amendment application, decomposer functional groups joined bacterial groups.



Soil Microbial Functional Groups
Westwind, 10/14/2021

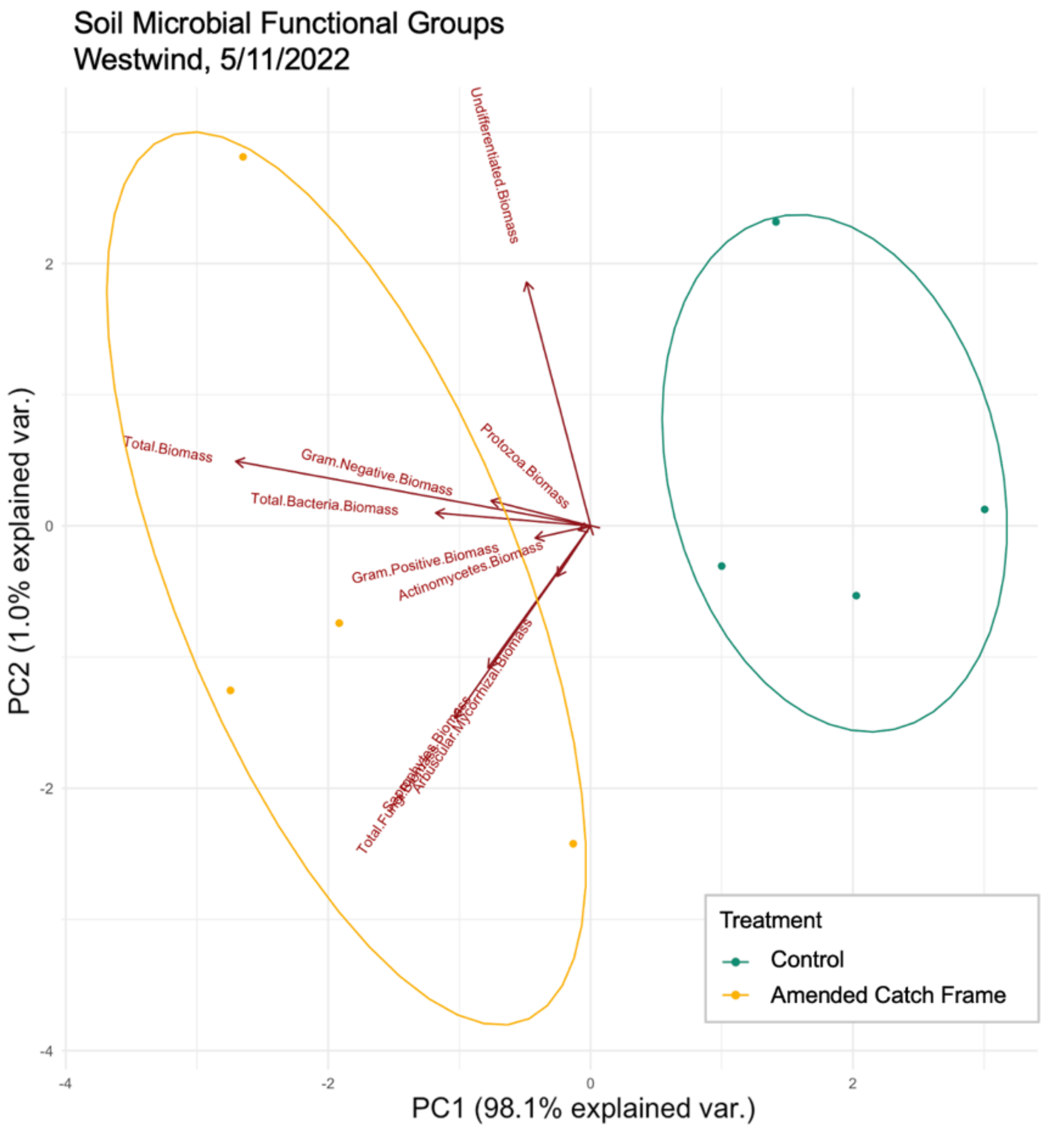


Figure 4.5a and b. Principal components analysis biplot comparing community composition of control and amended soils on 10/14/2021 and 5/11/2022.

On 5/11/2021, the half-year-old organic layer had approximately double the total bacteria and undifferentiated biomass, more than double the gram(-), and more than triple protozoan biomass than the 1.5-year-old organic layer, all of which were significantly different (Supplementary Table 4.7). However, the 1.5-year-old organic layer had a higher diversity index and contained significantly higher actinomycete and arbuscular mycorrhizal biomass than the half-year-old amendment layer. This suggests the newer hull/shell organic layer favored a community of bacteria and undifferentiated microbes that can metabolize carbon compounds from fresh hull/shell amendments and their associated predators, while the older amendment layer favored higher diversity which included decomposer and symbiotic functional groups. In addition, the older organic layer contained a significantly higher gram(+):gram(-) ratio and percentage of gram(+) bacteria, which are more dependent on complex C compounds. PCA at this spring 2022 sampling time illustrated the two amendment layers clustered separately, with the older amendment layer cluster changing along the axis driven by vectors such as arbuscular mycorrhizae, actinomycetes, and diversity index (Figure 4.6). Meanwhile, the new half-year amendment layer was distinguished by total bacteria, gram(-), undifferentiated, protozoa, and rhizobia vectors.

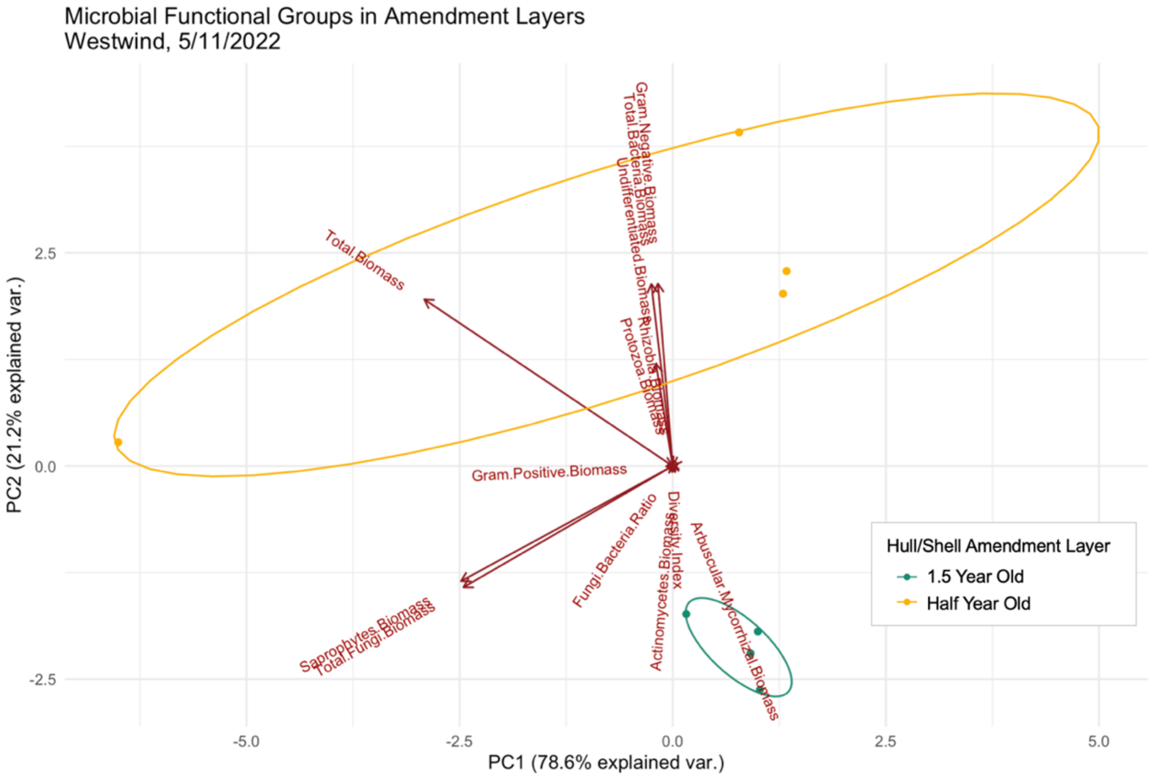


Figure 4.6. Principal components analysis biplot of microbial functional group biomass in the two hull/shell amendment organic layers sampled on 5/11/2021. The 1.5-year-old amendment layer was applied in fall 2020 and the half-year-old layer was applied in fall 2021.

In the spring of 2022, arbuscular mycorrhizal biomass was significantly higher in the amended catch frame soil compared to the control soil, and significantly higher in the old amendment layer applied fall 2020 compared to the new amendment layer (Figures 4.7a and b). These unexpected increases in arbuscular mycorrhizal biomass in the amended soil and hull/shell amendment layers suggest the maintained hull/shell layer promotes plant symbionts that are known to provide plant benefits such as improved nutrient and water capture. Arbuscular mycorrhizal biomass appears to become concentrated in the old decaying amendment layer in contact with the soil surface, as this layer contained more than triple the average arbuscular mycorrhizal biomass than the control soil at the spring 2022 time point.

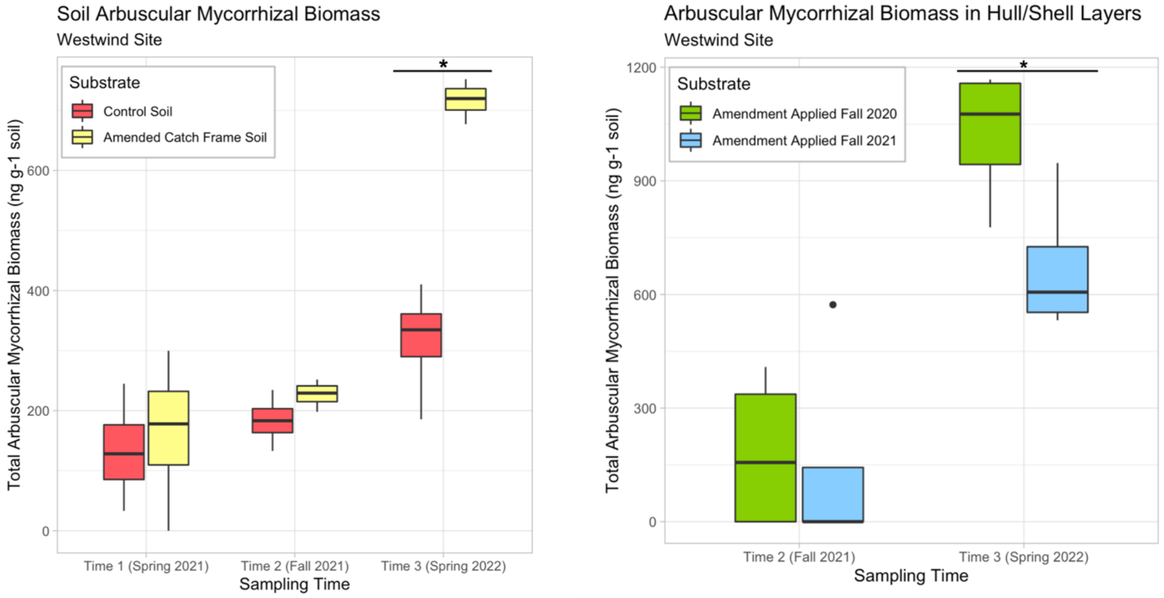


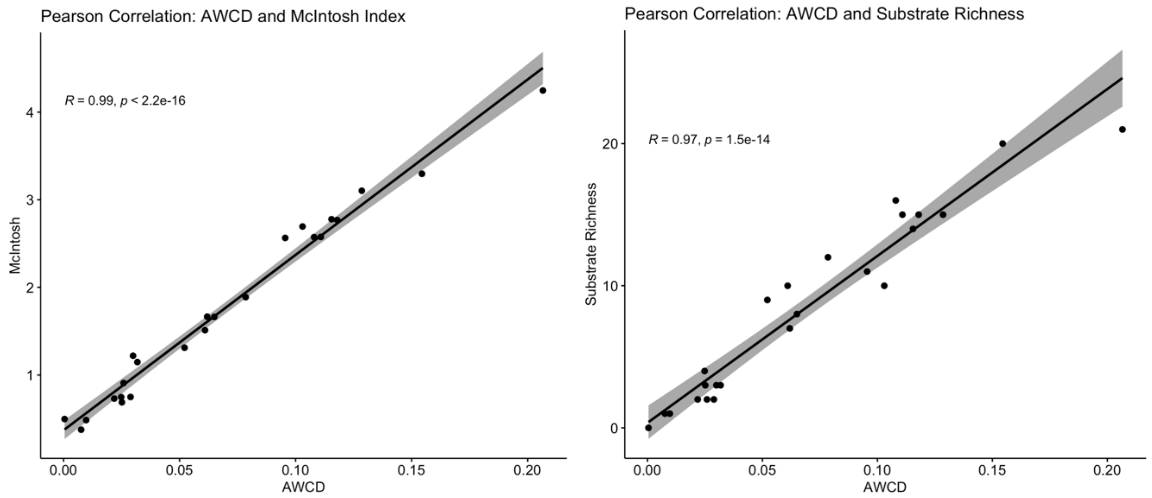
Figure 4.7a and b. Total arbuscular mycorrhizal biomass across all substrates over time. Asterisks indicate significant differences between substrates within a given sampling time in each panel. Note the slight difference in y-axis scales.

While EcoPlate response variables displayed no significant differences between treatments, the amended catch frame soil had slightly higher Average Well Color Development, McIntosh Index, and Substrate Richness, and slightly lower Shannon-Wiener Index and

Simpson Index (Table 4.3). McIntosh Index is a measure of heterogeneity of the sample expressed in geometric terms. The Shannon-Wiener Index and the Simpson Index estimate diversity using both richness (number of species) and evenness (relative abundance). However, data for the Simpson Index and Shannon-Wiener Index were not normally distributed and treatments had unequal variances which transformation could not correct, therefore they were excluded from further analysis. Microbial activity (AWCD) was positively correlated with McIntosh Index and Substrate Richness (Pearson correlation, Figures 4.8a and b). Supplementary Figures 4.1 and 4.2 illustrate microbial activity for individual and major C sources for both treatments. PCA indicated the EcoPlate response variables in the control soil cluster overlapped with amended catch frame soil cluster, and AWCD and McIntosh index were correlated (Figure 4.9). Including total fungi, total bacteria, and PLFA diversity index in PCA with EcoPlate response variables confirmed the small observed differences in EcoPlate activity and diversity between treatments had negligible influences compared to these major soil microbial community compositional groups (Figure 4.10). Amended catch frame soil total bacteria and fungi vectors drove the shift away from the control soil, while diversity indices and microbial activity in response to EcoPlate C substrates did not influence this treatment cluster separation.

Table 4.3. EcoPlate response variable means for the control and amended catch frame soils. No significant differences were found between treatments. AWCD, substrate richness, and McIntosh index were slightly higher for the amended catch frame soils.

| Treatment | AWCD | Substrate Richness | McIntosh Index | Shannon-Wiener Index | Simpson Index |
|---|---|---|---|---|---|
| Control | 0.180 | 7.83 | 1.55 | 2.72 | 0.891 |
| Amended Catch Frame | 0.236 | 9.17 | 1.96 | 2.49 | 0.839 |



Figures 4.8a and b. Average Well Color Development (activity), the main EcoPlate response variable of interest, correlated with McIntosh Index and Substrate Richness.

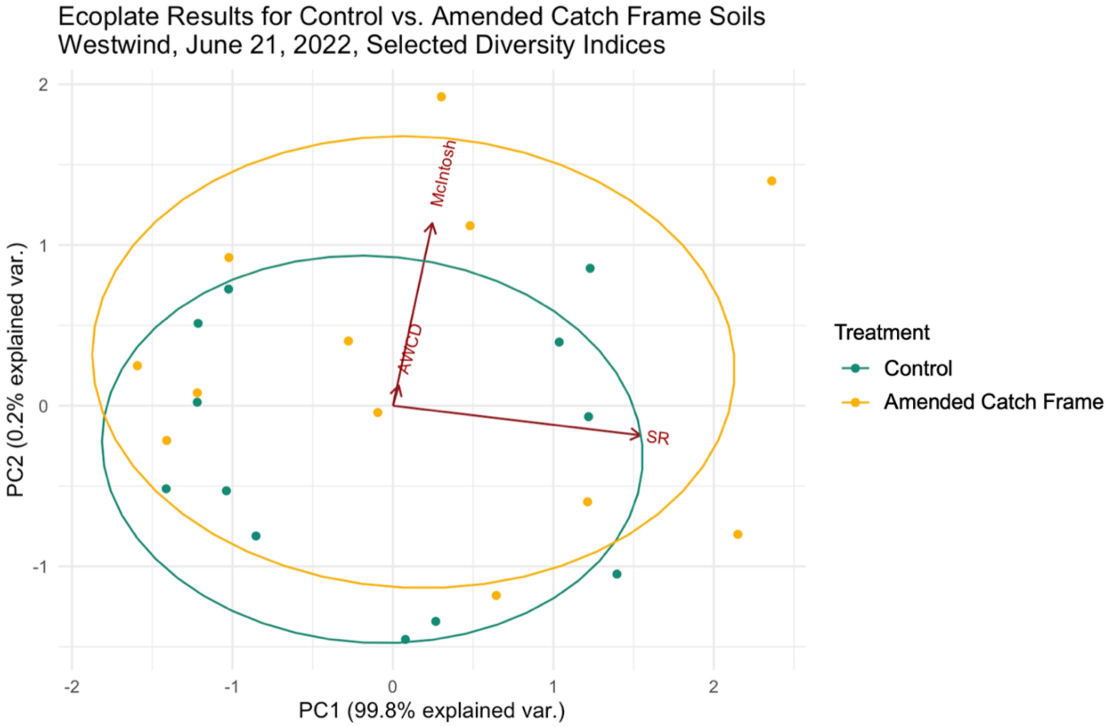


Figure 4.9. Principal components analysis biplot for EcoPlate data using activity (AWCD, average well plate color development), McIntosh diversity index, and Substrate Richness (SR). These three EcoPlate response variables were normally distributed and variances were homogeneous, however Shannon-Wiener and Simpson indices did not fulfill these assumptions even after log transformation and were therefore excluded from PCA. The control and amended catch frame soil clusters overlap. Activity and McIntosh index are correlated along the axis that slightly separates the amended catch frame soil from control soil.

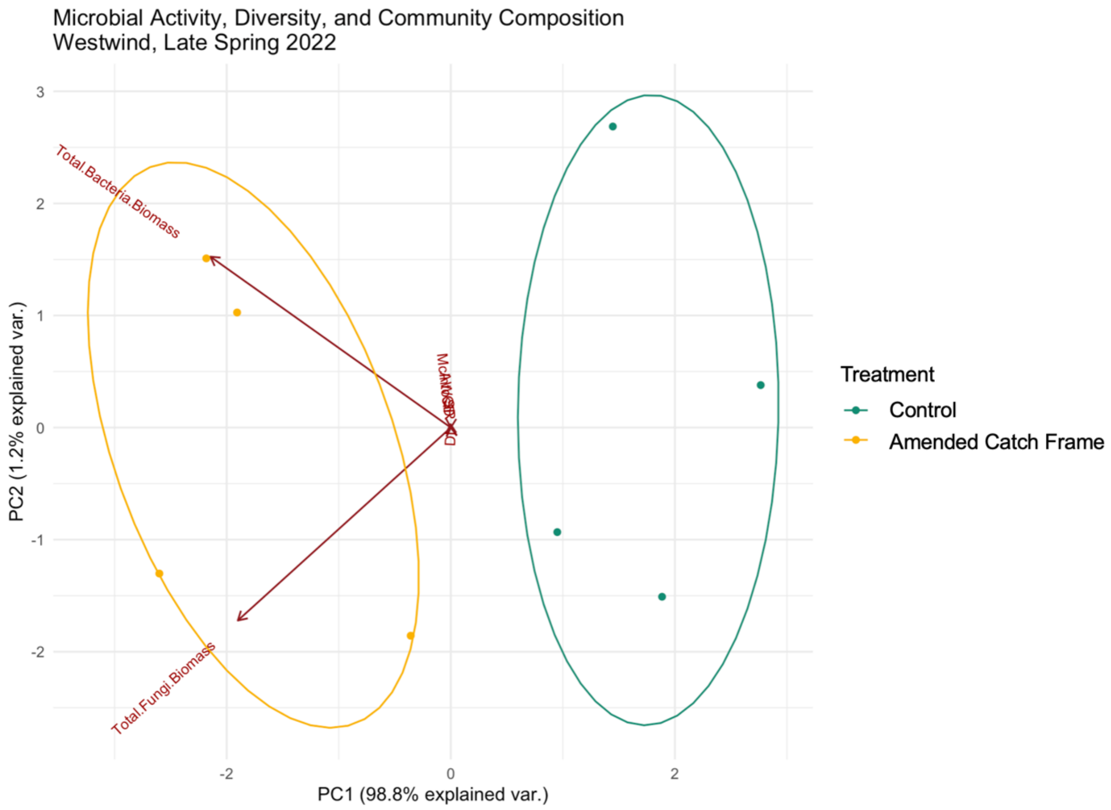


Figure 4.10. Principal components analysis biplot of microbial activity (AWCD from EcoPlate data), diversity indices (diversity index from PLFA data, McIntosh Index and Substrate Richness from EcoPlate data) and total fungi and total bacteria (PLFA). Amended catch frame soil total bacteria and total fungi vectors both contribute to the shift away from the control soil, while diversity indices and microbial activity in response to EcoPlate carbon substrates are vectors that do not drive this treatment cluster separation.

PLFA results from the two other field trials (trials described in Chapter 2) provide broad comparisons for general shifts in microbial community composition under hull/shell amendments at different orchards. At Bullseye Farms, soil samples were collected on 7/6/2022 in the upper 0-10 cm and submitted for PLFA analysis to compare the bare control soil, soil amended with fresh shells/hulls (predominately shells), and soil amended with a shell/hull/manure-based compost. Compared to the control soil, the shell/hull-amended soil had significantly higher total microbial biomass, total bacteria, actinomycete, gram(-), gram(+), saprophytic, arbuscular mycorrhizal biomass, while the compost-amended soil shared intermediate significance groupings between the control and shell soil (Supplementary Table 4.8). Percent bacteria, fungi, gram(-), arbuscular mycorrhizae, undifferentiated followed the same significance trend, as did gram(+):gram(-) ratio and saturated:unsaturated ratio. However, diversity indices and fungi:bacteria ratios were similar among treatments. PCA utilizing microbial biomass data indicated the control soil microbial functional groups clustered separately from those of the fresh shell/hull treatment, while the compost treatment clustered between the other two treatments (Figure 4.11). These results suggest the fresh shell/hull treatment led to significantly higher levels of many microbial functional groups in the upper soil layer than the control soil after 1.5 years and two fall applications, and the compost provided some benefit as well. However, at Crown no significant differences were found between hull, mix, and shell treatments when soil samples were taken on 6/9/2022, approximately 10 months after the amendments were displaced by harvest and without re-application in the fall of 2021 (Supplementary Figure 4.3).

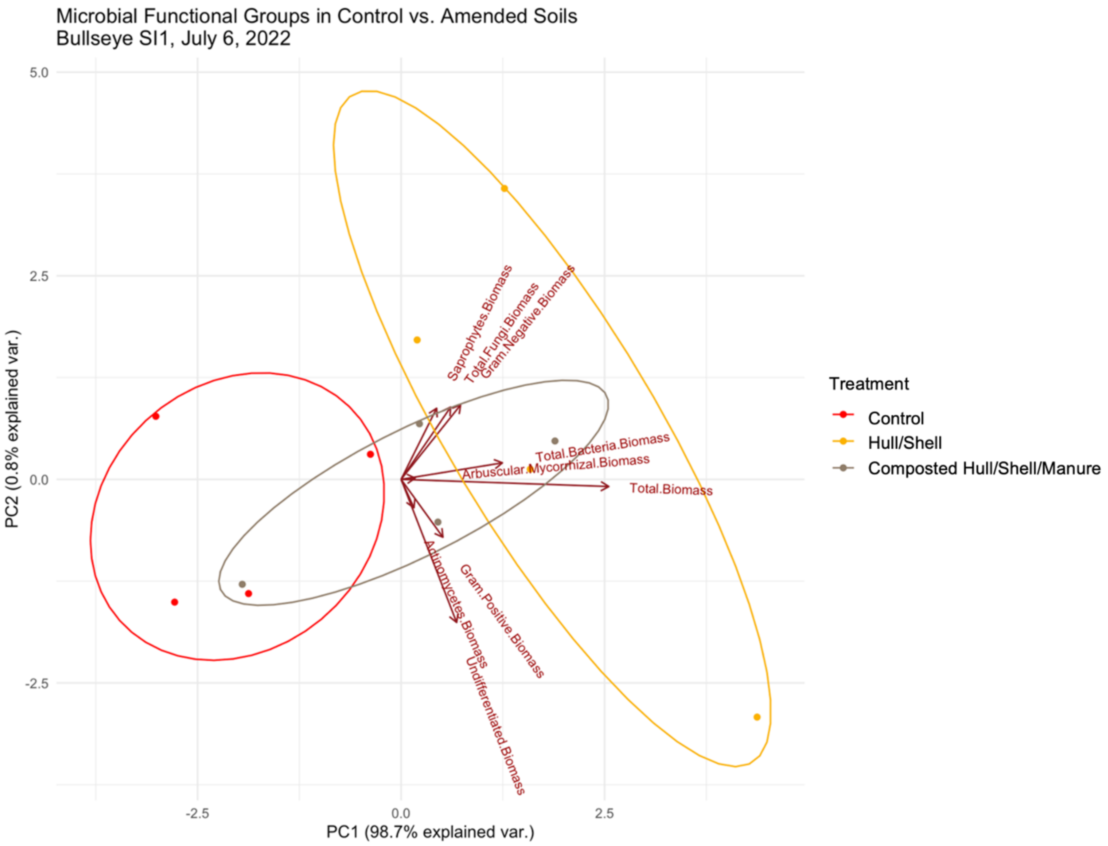


Figure 4.11. Principal components analysis biplot with Bullseye soil from control, fresh hull/shell amendments, and composted hull/shell/manure treatments, sampled on 7/6/2022.

### 4.7.3. Soil fertility, soil XK, bulk density, root biomass

Annual fall soil fertility results from the upper 0-10 cm soil indicated soil XK in 2021 was the only response variable that was significantly different between treatments (Chapter 2). No differences in any soil fertility variables were found at lower depths at this time. As reported in Chapter 2, average soil XK at 0-10 cm was higher in the amended soil compared to the control soil from 10/23/2020 through 9/22/2021, with significant differences at five of the nine sampling time points following application. No significant differences in nitrate-N, TN, or TOC were found between the control and the amended catch frame treatments in fall 2020, spring 2021, or fall 2021. However, average nitrate-N, TN, and TOC were slightly higher in the amended catch frame soil than the control soil on 9/22/2021, though not significant (Table 4.4, Supplementary Figure 4.4, Chapter 2). Root biomass in the upper 0-10 cm soil was significantly higher in amended catch frame soil compared to the control on 5/17/2022 but only slightly higher in amended soil compared to the control on 6/21/2022 (Chapter 3). In fall 2022 at Westwind and Bullseye, bulk density was slightly lower hull/shell amended soils compared to control soils, although nonsignificant (Chapter 3).

Table 4.4. Total soil nitrogen and total soil organic carbon over time in the upper 0-10 cm soil, Westwind. No significant differences were found between treatments within each time point and soil metric.

| Treatment | 9/16/2020 | | 5/6/2021 | | 9/22/2021 | |
|---|---|---|---|---|---|---|
| | TN (%) | TOC (%) | TN (%) | TOC (%) | TN (%) | TOC (%) |
| Control | 0.119 | 1.20 | 0.093 | 0.90 | 0.097 | 0.91 |
| Amended Catch Frame | 0.101 | 1.00 | 0.097 | 0.87 | 0.113 | 1.08 |

### 4.7.4. Tree Responses, Water Dynamics, Yield, and Harvest

As reported in Chapter 2, July leaf K in 2021 and 2022 was significantly higher and leaf Mg was significantly lower in the amended catch frame trees compared to control trees, although both nutrient averages were within the suggested sufficiency ranges. No differences in trunk circumferences or yield were found between treatments (Chapter 2). As reported in Chapter 3, the amended catch frame soil maintained higher average soil water and moderated daily soil temperature in the top 0-10 cm soil. This indicates observed significant differences in response variables including microbial biomass and community composition, root biomass, tree water stress, and tree K and Mg status did not significantly impact yield at the Westwind site. In 2022, the catch frame harvest equipment significantly reduced the total trash percent in yield samples, demonstrating that this harvest approach preserved the organic layer and led to cleaner yield leaving the orchard at harvest.

## 4.8 Discussion

### 4.8.1. Amendment Nutrients and Decomposition

After the fall 2020 application, the C:N ratio and estimated carbon in the amendment layer declined steadily over the following year, while estimated nitrogen levels remained more similar over time likely due to N inputs from fertigation and compost. While this suggests that applied N was likely retained in the amendment layer in microbial biomass, any N immobilization in the microbial pool did not impact tree leaf N status (Chapter 2). As C was metabolized and N was maintained, amendment C:N ratio declined from approximately 53:1 to 29:1 after one year. Decomposition rate was closely correlated with carbon loss from the amendment layer and microbial biomass was high, indicating the hull/shell layer provided a substrate that supported microbial life and decomposition. Considering decomposition is not a simple one-way process, mass loss patterns are a net result of breakdown of plant material and transformations of chemical components to new materials (Prescott and Vesterdal 2021). Decomposition assessed via litter bags is referred to as net mass remaining or net residue mass remaining because some of the remaining mass is likely microbial biomass and transformation products in addition to plant residues (Prescott and Vesterdal 2021). While litter bags excluded leaf litter and other organic debris, the mesh squares separating hull/shell layers naturally included annual residues from leaf litter and other organic debris. In this orchard system, approximately net mass remaining was approximately 45% after one year and approximately 13% after two years, indicating a high degree of decomposition occurred within the first two years.

### 4.8.2. Microbial Community Composition

Six months after the first hull/shell application, the amendment hull/shell organic layer contained high microbial biomass relative to all soil samples, with higher average fungal, bacterial, and protozoan biomass. The simple C compounds in hull/shell materials likely contributed to the high level of gram(-) bacteria and low gram(+):gram(-) ratio. In addition, the amendment contained relatively higher saprophyte and arbuscular mycorrhizal biomass and had a higher fungi:bacteria ratio than both treatment soils. However, high microbial biomass in the amendment layer did not translate to any significant differences in the amended soil beneath it compared to control soil after only six months.

After one year, the amended catch frame soil had significantly higher total microbial biomass, bacterial biomass (particularly gram(-) and actinomycetes), and a lower functional group diversity than the control soil. Several other microbial groups were slightly higher than control soil, though not significant. At this time, K and pH appeared to be the only soil fertility variables potentially related to the observed shifts in soil microbial community composition. The original one-year-old organic layer contained double the total microbial biomass and higher fungi:bacteria than the fresh one-week-old amendment layer, though not significantly different. Compared to soils, on average both amendment layers had a relatively lower diversity index, higher fungi:bacteria, higher total microbial biomass, saprophyte, and protozoan biomass.

After a year and a half in spring 2022, the amended soil maintained by catch frame had significantly higher total biomass, bacterial, fungal, gram(-), gram(+), saprophyte, arbuscular mycorrhizal biomass, and fungi:bacteria than control soil. While the amended catch frame treatment enabled higher levels of microbial biomass from many different microbial community functional groups, it did not significantly influence soil diversity index. The new 6-month-old amendment layer had significantly higher total bacterial biomass, gram(-), undifferentiated, and protozoan biomass than the older 1.5-year-old amendment layer. The old amendment layer had significantly higher diversity index, gram(+):gram(-) ratio, actinomycete, and arbuscular mycorrhizal biomass. The old amendment layer had double the fungi:bacteria ratio of the new layer, though not significantly different. From fall 2021 to spring 2022, the older amendment layer increased in diversity index, actinomycete, and arbuscular mycorrhizal biomass. Saprophyte levels approximately doubled in the old amendment layer and tripled in the new amendment layer but remained statistically similar.

Overall, the soil microbial community in the amended catch frame treatment increased in bacterial biomass by one year after fall application, and in both bacterial and fungal biomass by 1.5 years. Significant increases in amended catch frame soil saprophyte and arbuscular mycorrhizal biomass indicate this treatment promotes decomposers which drive C transformation processes as well as plant symbionts which can enhance root nutrient and water uptake. Compared to the soils, amendment layers were generally characterized by lower diversity indices, higher fungi:bacteria, higher total microbial biomass, saprophyte, and gram(-) biomass. The surface-applied hull/shell layer supports robust microbial growth in the short-term after one week (Supplementary Table 4.4) and over time within the first year and a half (Supplementary Table 4.6). As the original hull/shell layer aged, it favored increased levels of most functional groups and a higher diversity index. In addition, elevated levels of many functional groups in the half-year-old amendment layer in spring 2022 compared to the half-year-old amendment layer in spring 2021 suggest the older amendment layer likely plays a role in promoting biomass in the new layer above it.

These changes in microbial community composition promote ecosystem functions that can promote tree nutrient and water uptake. Decomposer groups such as saprophytes and actinomycetes transform hull/shell carbon and could contribute to more stable forms of soil carbon if treatments are maintained in the long-term. Saprophytes drive nutrient cycling and provide a “powerful cocktail” of lignocellulolytic enzymes that can deconstruct complex C compounds (Crowther et al. 2012). Increased soil arbuscular mycorrhizae indicate this practice promotes symbiotic fungal associations that assist in nutrient and water capture by roots via hyphae. The amendment layer can support protozoa over time, which suggests maintaining this amendment layer could promote higher trophic levels in the organic layer food web. The significantly higher fungi:bacteria in the amended catch frame soil indicates this microbial community may be more resilient to environmental stressors after 1.5 years. Fostering an organic layer on the soil surface over time promotes microbial biomass and functional groups that provide multiple ecosystem services related to nutrient cycling.

Soil organic matter is the heterogeneous, decaying debris of biota that live on and in the soil; it is not only a carbon pool, but a dynamic flow of C atoms through a variety of streams that drive biological processes (Janzen 2006). However, organic matter is most biologically useful when it decays; to transform the C in organic plant residues into more stable soil carbon pools, some fraction of the initial plant C is lost through microbial respiration (Janzen 2006). Thus, land management can help optimize the balance of C respired and C relocated to more stable soil pools (Janzen 2006). Decomposition of plant residues by soil microbial communities and their associated physiology/enzymes occurs along a continuum of soil microbial, physical, and chemical processes that generate a diversity of both inorganic and organic compounds (Lehmann et al. 2015, Gross et al. 2019). These C transformations are driven by biological activity in plant residues and influenced by factors such as existing SOM levels and microbial community composition, rainfall, irrigation, temperature, and soil management.

High C:N ratio crop residue amendments provide C inputs that can gradually build SOM particularly if soil disturbance is low. In the present study, decomposition occurred relatively quickly under high moisture (within the irrigation zone) in this warm climate which supported increases in many microbial functional groups in both the amendment layers and soil beneath. After one year, considering the hull/shell amendment net mass remaining was less than half of initial dry weight and no substantial increase in SOC had occurred, respiration was likely high during the first year, although it was not measured in the current study. However, increases in root biomass under the hull/shell amendment could lead to increases in root C inputs which may gradually influence soil C in the future. Increased soil fungal biomass and fungi:bacteria after 1.5 years could set the stage for more C-efficient microbial communities in future years, however more time is needed to assess long-term soil microbial community shifts and associated effects on C transformations and destinations.

The significant increases in arbuscular mycorrhizal fungal (AMF) biomass in both soil and hull/shell layers at two separate field trials was an unanticipated treatment response that may be attributed to a combination of factors. Mycorrhizal fungi are known to form associations with over 80% of terrestrial plant species and are ubiquitous in many soils (Wei et al. 2019), including California almond orchards (Vasilikiotis et al. 2020). Mycorrhizae assist plants in nutrient uptake and in responding to both abiotic and biotic stressors (Chalker-Scott 2017). The undisturbed hull/shell amendment likely encouraged unexpectedly high soil mycorrhizal biomass through improved soil aeration, available moisture, moderated temperature, and increased root biomass to colonize. In addition, prior studies suggest that mycorrhizae can respond to mulch and fresh residues with high C:N ratio, stimulating decomposition (Wei et al. 2019) and in some cases increasing colonization rate due to improved soil moisture retention (Cook et al. 2009). Arbuscular mycorrhizal fungi have been shown to increase decomposition and nitrogen capture from complex organic material which can increase hyphal growth (Hodge et al. 2001).

In spring 2022 the highest levels of AMF biomass in the old amendment layer support the growing body of evidence that AMF can promote decomposition of fresh residues with high C:N ratio (Talbot et al. 2008, Wei et al. 2019). In addition to their well-known plant mutualism functions, AMF likely play important roles in decomposition and C cycling in their search for nutrients despite lacking the genetic capacity to act as saprotrophs (Talbot et al.

2008, Frey 2019). While AMF do not directly gain energy or C from organic matter, they may scavenge nutrients from organic matter via several potential mechanisms including stimulating rhizosphere microbial activity through exudates (“priming”) and competing with free-living saprotrophs for nutrients (the Gadgil effect) (Frey 2019, Talbot et al. 2008). Literature indicates that AMF appear to stimulate fresh residue decomposition in the short-term with the presence of available nitrogen, in the long-term AMF tend to promote organic C retention in aggregates (Wei et al. 2019). Further long-term studies are needed to assess how AMF may influence C cycling under hull/shell amendments.

Complementary PLFA data from Bullseye Farms indicated the shell/hull-amended soil displayed significantly higher total microbial biomass, total bacteria, actinomycetes, gram(-), gram(+), saprophytic, arbuscular mycorrhizal biomass than the control soil. The compost-amended soil response variables generally fell between the control and shell/hull soil. This indicates that the beneficial effects of fresh hull/shell amendments on soil microbial functional communities can be found across orchards with different soil types, fertilizer, and irrigation management, etc. and outweigh mature compost in terms of soil microbial community benefits. While the C compounds in composted hull/shell materials had already been largely metabolized during the composting process, fresh hull/shell materials likely provided a wider array of accessible carbon compounds that support microbial growth. However, results from the Crown site suggest that increases in soil microbial biomass may not occur at all orchards, and/or that effects may fade over time without repeated annual applications.

### 4.8.3. Microbial Activity and Diversity Indices

Soil samples taken in June 2022 indicated average microbial activity (AWCD), McIntosh Index for microbial diversity, and substrate richness were all slightly higher in the amended catch frame soil compared to the control soil, though no differences were statistically significant. Activity was strongly correlated with the McIntosh Index and substrate richness. When these three EcoPlate response variables were integrated with major microbial functional groups in PCA, total fungi and bacteria drove separation of amended catch frame soil away from the control soil, while diversity indices and microbial activity had negligible effects on treatment cluster separation. Overall, all diversity indices suggested that control and amended catch frame soils did not differ substantially. Both treatments showed similar responses in activity to the C substrates provided by EcoPlates. Considering microbial biomass of many different functional groups increased substantially while diversity and activity remained similar, the amendment appears to support many functional groups relatively indiscriminately 1.5 years after application.

Prior studies similarly indicate almond hull/shell amendments support microbial activity in the amendment layer and can increase soil microbial biomass without substantial shifts in diversity or richness. Almond shells have been shown to maintain high levels of biological activity in the mulch layer (Lopez et al. 2014). Bonilla et al. 2012 found that almond shell amendments can increase soil heterotrophic bacterial biomass and influence bacterial community composition, although this effect is limited to the upper soil layer and is influenced by site-specific orchard conditions. These authors found that almond shells led to separate PCA clusters influenced by vectors such as C and N but did not impact soil bacterial richness

(Bonilla et al. 2012). In addition, prior research indicates almond hulls and shells can be a useful tool in soil pathogen suppression in avocado orchards and when combined with bio-solarization processes (Vida et al. 2016, Fernandez-Bayo et al. 2020). Future research could further investigate the effects of hull/shell amendments on decomposers, plant symbionts including mycorrhizae, pathogen suppression, and associated effects on plant function.

### 4.8.4. Soil Fertility, Bulk Density, Root Biomass, and Harvest

Considering shifts in soil fertility, soil XK was the only soil fertility response variable significantly different in the top 0-10 cm after one year. At this time, soil TN and TOC were slightly higher in the amended catch frame soil compared to the control soil, though not significantly different. This suggests more time is likely required to assess potential increases in TN and TOC in amended catch frame soil. Soil N and C responses would likely be different if the hull/shell amendment had been incorporated into the soil rather than applied on the surface. Prior laboratory studies found coffee husks and pulp can increase SOC and TN (Kasongo et al. 2011) and pecan husks can increase permanganate oxidizable C (labile soil C) (Idowu et al. 2017). While crop residues provide C inputs that can gradually build soil organic matter, decomposition processes involved in C cycling can be influenced by many contextual variables such as irrigation, rainfall, temperature, fertilizer, existing SOM levels, soil type, and microbial community composition (Andrews et al. 2021). High microbial biomass found in the hull/shell amendment layer on the soil surface suggests relatively high demand for both N and C to support metabolism which may help explain the minimal changes in soil N and C in the present study. Similarly, the slight but nonsignificant decreases in soil bulk density under fresh hull/shell amendments compared to control soil suggest that extended time periods are likely needed to assess long-term changes in soil physical structure as well.

The amended catch frame treatment led to a significant increase in the total root biomass in the top 0-10 cm soil in the spring after the second annual amendment application, indicating this treatment created favorable conditions for root proliferation. Increased root development can increase microbial activity, rhizodeposition, and plant uptake of water and nutrients. In prior studies, root growth has previously been shown to increase under almond shell mulch (Jafari et al. 2012), macadamia husk mulch (Lobel et al. 1994), and bark mulches (Forge et al. 2015, Granatstein et al. 2008). Roots provide labile C substrate inputs into the surrounding soil that stimulate SOM decomposition; this phenomenon is commonly referred to as the rhizosphere priming effect (Dijkstra et al. 2009). Rhizosphere priming is an important mechanism in the global C cycle and can help transfer inactive SOM N into active microbial pools (Dijkstra et al. 2009). While AMF have been shown to be common in California almond orchards, organically managed orchards display higher AMF root colonization rates compared with conventionally managed orchards due to the presence of vegetation rather than organic inputs (Vasilikiotis et al. 2020). In the present study, the increase in almond root biomass, available water, and moderated temperature likely contributed to the increased AMF biomass in the amended catch frame treatment. However, high AMF biomass levels were found in the hull/shell amendment layer as well, suggesting that these obligate symbionts extended hyphal networks into this organic layer, thus expanding the range of associated root nutrient and water capture.

Future studies could investigate whether hull/shell amendments catch frame harvest could alter other components of soil health in the long-term including soil fertility variables such as CEC, SOM, and pH, root-derived C substrate production, and associated effects on soil physical variable such as aggregate stability, water retention, and bulk density. Additionally, further research is needed to better understand whether soil AMF biomass increased because of higher root colonization rates, increased root biomass for colonization, or both. Future studies could evaluate metrics of microbial activity such as respiration, enzyme production, and the effects of altered soil water and temperature.

The catch frame harvester was utilized as a form of off ground harvest to effectively preserve the organic hull/shell layer on the soil surface over time. Considering crop system effects more broadly, removing the sweeping step at almond harvest provides one strategy to work toward the Almond Board of California's goal to reduce dust production at harvest. This goal is critical, as agricultural dust exposure among young California farmworkers has been shown to increase the risk of respiratory illnesses (Schenker et al. 2009, Greskevitch et al. 2008). In addition, off ground harvest can enable growers to deliver a cleaner crop to processing facilities which may charge growers for certain types of "trash" which can damage processing machinery. This practice could help reduce total costs associated with harvest and orchard management, as removing the sweeping step could save approximately $72 per acre in California almond orchards (Sumner et al. 2019). Off ground harvest can allow growers to reduce the frequency of mowing, herbicide and miticide sprays, which would save money, reduce machinery passes, pesticide applications, and could potentially help reduce risk of the development of pesticide resistance. Taken together, off ground harvest offers a strategy for promoting an organic layer on the soil surface in the tree row while reducing human, environmental, and financial costs associated with the sweeping step of on ground harvest.

## 4.9 Conclusion

The hull/shell amendment decomposed relatively quickly on the soil surface, declining in C:N, C, and net dry mass remaining while generally retaining N over time. Microbial analyses indicate the hull/shell amendment maintained with catch frame harvest increased soil microbial biomass in the upper 0-10 cm soil to favor higher levels of many beneficial microbial functional groups compared to bare soil. This began with increases in total biomass and bacterial biomass after one year. Then after 1.5 years, soil microbial biomass had significantly increased under the hull/shell amendment for many functional groups: total biomass, bacteria, fungi, gram(+) bacteria, gram(-) bacteria, saprophytes, and arbuscular mycorrhizal fungi. While soil microbial diversity was lower in the amended catch frame soil after one year, by the following spring diversity was similar between treatments. At this time, microbial physiological profiling suggested only slight increases in soil microbial activity, McIntosh index, and substrate richness in amended catch frame soil compared to control soil. These soil microbial results illustrate that the hull/shell amendment maintained with catch frame harvest supports the living component of orchard soil health. After one year, this treatment favored higher soil bacteria and lower diversity, while after a year and a half it substantially increased biomass of many functional groups and diversity became similar to control soil.

The hull/shell amendment layers supported higher average total biomass, saprophyte biomass, gram(-) biomass, fungi:bacteria, and lower diversity than soils. The use of a catch frame harvester enabled the amendment layer to remain intact and develop high levels of microbial biomass over time representing many broad functional groups that support ecosystem multifunctionality after 1.5 years, including several decomposer groups and arbuscular mycorrhizal fungi. Results indicate the hull/shell amendment provides a substrate that promotes mycorrhizal growth and hyphal exploration in addition to significantly increasing mycorrhizal biomass in the soil beneath it. Further research is needed to evaluate the effects of hull/shell amendment layers on microbial community member abundance, functioning, and associated ecosystem services. Overall, hull/shell amendments maintained with off ground harvest offer a new strategy for creating and maintaining a biological active organic layer on the almond orchard soil surface using recycled crop biomass while reducing soil disturbance.

## 4.10 Supplementary Materials

Supplementary Table 4.1. Explanations of functional significance of PLFA response variables in relation to hull/shell amendments and reduced soil disturbance (Ward Laboratories).

| **Response Variable** | **Significance and Functions** |
|---|---|
| Functional group diversity index (DI) | Does treatment increase or decrease diversity? Indicates a broad/narrow range of microbe traits that influence functioning. The more diverse the carbon sources provided by the treatment, the more likely to increase DI. |
| Total microbial biomass | Does the treatment create conditions and resources that lead to more microbes? Indicates to what degree soil can support microbial life and biomass production. Treatments that supply carbon (and nitrogen) are more likely to increase total microbial biomass. |
| Fungi : bacteria | Bacteria tend to dominate systems with lower organic residues, dry conditions, or after soil disturbances. Fungal-dominated communities tend to be more resilient to environmental stressors. Fungi tend to be considered good soil health indicators. Lower disturbance and increased organic residues tend to promote fungi. |
| Predator : prey | This represents protozoa:bacteria. As protozoa feed on bacteria, they release nutrients, especially nitrogen. The higher the ratio, the more active the community where base level nutrients are great enough to support higher trophic levels. |
| Gram (+) : gram (-) | Higher gram(+) levels are common when the bacterial community is stressed or coming out of dormancy. Since they can form spores, they survive better under environmental stressors such as drought or extreme temperatures. Higher gram(-) levels may be due to anaerobic conditions or other stressors. The soil bacterial community tends to become more balanced (1.0-2.0 ratio) as soil conditions become more favorable during the growing season. Gram(+) bacteria have many-layered thick cell walls, while gram(-) have thinner cell walls. This ratio can help indicate relative carbon availability for soil bacteria: gram(-) are more dependent on simple C compounds from plants, while gram(+) are more dependent on complex C compounds in organic soils. |
| Actinomycetes (bacteria) | Gram(+) bacteria that cycle organic matter and decompose complex mixtures of polymers such as cellulose and hemicellulose. They resemble fungi because they have long branching filaments (smaller than fungi), but they are bacteria. Some can fix nitrogen on legumes. |
| Rhizobia (bacteria) | Gram(-) bacteria that form root nodules on legumes and fix nitrogen. |
| Arbuscular mycorrhizae (fungi) | Plant symbiont that enhances nutrient and water uptake and can increase plant stress tolerance. |
| Saprophytes (fungi) | Decomposers that drive nutrient cycling, availability, and $CO_2$ flux. They provide a “powerful cocktail” of lignocellulolytic enzymes that can |

| | |
|---|---|
| | deconstruct complex C compounds (Crowther et al. 2012). They transfer nutrients through hyphae. |
| Protozoa | The presence of protozoa indicate sufficient base level nutrients to support higher trophic levels beyond bacteria. |
| Undifferentiated | Most soil microbes still await identification. |
| Saturated : unsaturated | Reflects how bacteria may be altering their membranes under environmental stressors to maintain optimal fluidity and waste transport, so higher saturated fatty acids may indicate a more well-adapted community to present environmental conditions (temperature and moisture). A higher ratio means a healthier and more stable bacterial community. |
| Monounsaturated : polyunsaturated | Higher ratio indicates less stress. Lower ratio indicates higher levels of prolonged stress due to conditions such as temperature, moisture, pH, or nutrient availability (starvation). |

Supplementary Table 4.2. Decomposition by mass loss over time expressed as average dry weight (g) and average percent net dry mass remaining using litter bag data.

| | 10/7/20 | 11/6/20 | 12/6/20 | 2/4/21 | 3/6/21 | 6/6/21 | 7/29/21 | 10/7/21 |
|---|---|---|---|---|---|---|---|---|
| Dry weight (g) | 67.0 | 52.5 | 58.1 | 47.5 | 44.3 | 38.6 | 35.4 | 30.0 |
| % Net Dry Mass Remaining | 100% | 78.4% | 86.8% | 70.9% | 66.2% | 57.6% | 52.9% | 44.8% |

Supplementary Table 4.3. Average microbial biomass from samples taken on 4/6/2020 from the upper 0-10 cm soil and the amendment layer. No significant differences were found between control soil and amended catch frame soil (response variables are not statistically compared with the organic amendment layer). Biomass response variables are reported in ng biomass g$^{-1}$ soil.

| Response Variable | Control Soil | | Amended Catch Frame Soil | | Aggregate Sample of Organic Layer |
|---|---|---|---|---|---|
| | Mean | Std. Dev. | Mean | Std. Dev. | |
| Total Biomass | 3104.1 | 1645.4 | 3156.5 | 1223.4 | 10749.58 |
| Total Bacteria Biomass | 1264.1 | 710.9 | 1228.4 | 602.6 | 5917.04 |
| Total Fungi Biomass | 320.3 | 235.9 | 303.3 | 213.2 | 4014.75 |
| Actinomycete Biomass | 154.4 | 100.1 | 157.9 | 107.5 | 198.26 |
| Gram Negative Biomass | 601.6 | 388.5 | 527.6 | 267.2 | 4112.16 |
| Gram Positive Biomass | 662.4 | 334.4 | 700.7 | 397.0 | 1804.88 |
| Saprophyte Biomass | 186.7 | 167.9 | 139.3 | 91.7 | 3692.20 |
| Arbuscular Mycorrhizal Biomass | 133.6 | 89.1 | 163.9 | 126.1 | 322.56 |
| Protozoan Biomass | 53.6 | 89.4 | 16.4 | 20.2 | 100.57 |
| Rhizobia Biomass | 25.2 | 40.8 | 5.9 | 7.6 | 21.66 |
| Undifferentiated Biomass | 1466.1 | 678.6 | 1608.5 | 514.0 | 717.23 |
| Functional Group Diversity Index | 1.47 | 0.16 | 1.39 | 0.15 | 1.27 |

| | | | | | |
|---|---|---|---|---|---|
| Fungi:Bacteria | 0.22 | 0.07 | 0.23 | 0.14 | 0.68 |
| Gram(+):Gram(-) | 1.28 | 0.37 | 1.36 | 0.66 | 0.44 |
| Predator:Prey | 0.059 | 0.061 | 0.021 | 0.003 | 0.017 |
| Saturated:Unsaturated | 2.19 | 1.05 | 2.38 | 1.03 | 0.94 |

Supplementary Table 4.4. PLFA response variables from soil samples collected 10/14/2020 from the upper 0-10 cm soil. Letter groupings represent comparisons between the control and amended soil within each response variable at this time point. Biomass is expressed as ng biomass $g^{-1}$ soil. NA indicates treatments were not analyzed due to high presence of zeros in data for the given response variable.

| Response Variable | Treatment | Mean | Std. Dev. | Std. Error | CLD Groups |
|---|---|---|---|---|---|
| Total Biomass | Control | 4683.8 | 782.4 | 391.21 | **b** |
| Total Biomass | Amended Catch Frame | 5908.0 | 735.6 | 367.79 | **a** |
| Diversity Index | Control | 1.43 | 0.04 | 0.02 | **a** |
| Diversity Index | Amended Catch Frame | 1.39 | 0.02 | 0.01 | **b** |
| Bacteria Percent | Control | 40.3 | 4.51 | 2.25 | **a** |
| Bacteria Percent | Amended Catch Frame | 47.6 | 2.36 | 1.18 | **b** |
| Total Bacteria Biomass | Control | 1883.3 | 361.0 | 180.48 | **a** |
| Total Bacteria Biomass | Amended Catch Frame | 2801.9 | 259.1 | 129.52 | **b** |
| Actinomycetes Percent | Control | 6.87 | 1.20 | 0.60 | a |
| Actinomycetes Percent | Amended Catch Frame | 6.27 | 0.41 | 0.21 | a |
| Actinomycetes Biomass | Control | 315.9 | 37.4 | 18.69 | **b** |
| Actinomycetes Biomass | Amended Catch Frame | 368.4 | 29.9 | 14.93 | **a** |
| Gram Negative Percent | Control | 23.0 | 1.85 | 0.93 | **b** |
| Gram Negative Percent | Amended Catch Frame | 29.2 | 3.11 | 1.56 | **a** |
| Gram Negative Biomass | Control | 1071.9 | 173.8 | 86.9 | **b** |
| Gram Negative Biomass | Amended Catch Frame | 1705.6 | 53.8 | 26.9 | **a** |
| Rhizobia Percent | Control | 0.00 | 0.00 | 0.00 | NA |
| Rhizobia Percent | Amended Catch Frame | 0.00 | 0.00 | 0.00 | NA |
| Rhizobia Biomass | Control | 0.00 | 0.00 | 0.00 | NA |
| Rhizobia Biomass | Amended Catch Frame | 0.00 | 0.00 | 0.00 | NA |
| Total Fungi Percent | Control | 19.7 | 5.33 | 2.67 | a |
| Total Fungi Percent | Amended Catch Frame | 16.2 | 1.1 | 0.5 | a |
| Total Fungi Biomass | Control | 921.5 | 313.1 | 156.7 | a |
| Total Fungi Biomass | Amended Catch Frame | 952.9 | 112.7 | 56.4 | a |
| Arbuscular Mycorrhizal Percent | Control | 3.91 | 0.54 | 0.27 | a |
| Arbuscular Mycorrhizal Percent | Amended Catch Frame | 3.87 | 0.44 | 0.22 | a |
| Arbuscular Mycorrhizal Biomass | Control | 183.5 | 42.2 | 21.1 | a |
| Arbuscular Mycorrhizal Biomass | Amended Catch Frame | 227.1 | 23.2 | 11.6 | a |
| Saprophytic Percent | Control | 15.8 | 5.82 | 2.91 | a |

| | | | | | |
|---|---|---|---|---|---|
| Saprophytic Percent | Amended Catch Frame | 12.3 | 1.29 | 0.64 | a |
| Saprophytes Biomass | Control | 738.0 | 316.6 | 158.3 | a |
| Saprophytes Biomass | Amended Catch Frame | 725.8 | 115.7 | 57.8 | a |
| Protozoan Percent | Control | 0.00 | 0.00 | 0.00 | a |
| Protozoan Percent | Amended Catch Frame | 0.09 | 0.18 | 0.09 | a |
| Protozoa Biomass | Control | 0.00 | 0.00 | 0.00 | NA |
| Protozoa Biomass | Amended Catch Frame | 4.53 | 9.05 | 4.53 | NA |
| Gram Positive Biomass | Control | 811.4 | 207.2 | 103.6 | a |
| Gram Positive Biomass | Amended Catch Frame | 1096.3 | 217.6 | 108.8 | a |
| Gram Positive Percent | Control | 17.30 | 3.38 | 1.69 | a |
| Gram Positive Percent | Amended Catch Frame | 18.4 | 1.85 | 0.93 | a |
| Undifferentiated Percent | Control | 40.1 | 2.19 | 1.10 | a |
| Undifferentiated Percent | Amended Catch Frame | 36.2 | 2.36 | 1.18 | a |
| Undifferentiated Biomass | Control | 1879.1 | 334.5 | 167.3 | a |
| Undifferentiated Biomass | Amended Catch Frame | 2148.7 | 408.6 | 204.3 | a |
| Fungi:Bacteria Ratio | Control | 0.50 | 0.19 | 0.09 | a |
| Fungi:Bacteria Ratio | Amended Catch Frame | 0.34 | 0.03 | 0.02 | a |
| Predator to Prey Ratio | Control | 0.00 | 0.00 | 0.00 | NA |
| Predator to Prey Ratio | Amended Catch Frame | 0.00 | 0.00 | 0.00 | NA |
| Gram(+): Gram(-) | Control | 0.75 | 0.13 | 0.07 | **a** |
| Gram(+): Gram(-) | Amended Catch Frame | 0.64 | 0.12 | 0.06 | **b** |
| Saturated:Unsaturated | Control | 1.16 | 0.21 | 0.10 | a |
| Saturated:Unsaturated | Amended Catch Frame | 1.01 | 0.14 | 0.07 | a |
| Monounsaturated:Polyunsaturated | Control | 6.13 | 4.00 | 2.00 | a |
| Monounsaturated:Polyunsaturated | Amended Catch Frame | 8.72 | 2.39 | 1.19 | a |

Supplementary Table 4.5. PLFA response variables in the new 1-week-old hull/shell amendment layer compared to the old 1-year-old hull/shell amendment organic layer, 10/14/2021. No significant differences were found between layers, although averages tended to be higher in the older amendment layer. Biomass is expressed as ng biomass g$^{-1}$ soil.

| Response Variable | Treatment | Mean | Std. Dev. | Std. Error |
|---|---|---|---|---|
| Total Biomass | Organic 1 Week Old | 8273.7 | 13017.2 | 6508.6 |
| Total Biomass | Organic 1 Year Old | 16372.7 | 19182.9 | 9591.5 |
| Diversity Index | Organic 1 Week Old | 0.85 | 0.18 | 0.09 |
| Diversity Index | Organic 1 Year Old | 0.80 | 0.31 | 0.16 |
| Bacteria Percent | Organic 1 Week Old | 23.00 | 13.28 | 6.64 |
| Bacteria Percent | Organic 1 Year Old | 24.35 | 22.67 | 11.34 |
| Total Bacteria Biomass | Organic 1 Week Old | 2743.9 | 5012.8 | 2506.4 |
| Total Bacteria Biomass | Organic 1 Year Old | 6910.1 | 9384.0 | 4692.0 |
| Actinomycetes Percent | Organic 1 Week Old | 0.58 | 0.47 | 0.23 |

| | | | | |
|---|---|---|---|---|
| Actinomycetes Percent | Organic 1 Year Old | 0.47 | 0.48 | 0.24 |
| Actinomycetes Biomass | Organic 1 Week Old | 48.4 | 76.4 | 38.2 |
| Actinomycetes Biomass | Organic 1 Year Old | 92.7 | 100.3 | 50.1 |
| Gram Negative Percent | Organic 1 Week Old | 19.7 | 13.9 | 6.9 |
| Gram Negative Percent | Organic 1 Year Old | 20.9 | 21.5 | 10.7 |
| Gram Negative Biomass | Organic 1 Week Old | 2359.2 | 4385.4 | 2192.7 |
| Gram Negative Biomass | Organic 1 Year Old | 6277.0 | 8835.3 | 4417.6 |
| Rhizobia Percent | Organic 1 Week Old | 0.00 | 0.00 | 0.00 |
| Rhizobia Percent | Organic 1 Year Old | 0.08 | 0.15 | 0.08 |
| Rhizobia Biomass | Organic 1 Week Old | 0.00 | 0.00 | 0.00 |
| Rhizobia Biomass | Organic 1 Year Old | 3.26 | 6.51 | 3.26 |
| Total Fungi Percent | Organic 1 Week Old | 24.0 | 10.48 | 5.24 |
| Total Fungi Percent | Organic 1 Year Old | 23.4 | 7.18 | 3.59 |
| Total Fungi Biomass | Organic 1 Week Old | 2772.1 | 4653.2 | 2326.6 |
| Total Fungi Biomass | Organic 1 Year Old | 4092.4 | 4380.1 | 2190.0 |
| Arbuscular Mycorrhizal Percent | Organic 1 Week Old | 0.52 | 1.04 | 0.52 |
| Arbuscular Mycorrhizal Percent | Organic 1 Year Old | 0.76 | 1.09 | 0.54 |
| Arbuscular Mycorrhizal Biomass | Organic 1 Week Old | 143.3 | 286.5 | 143.3 |
| Arbuscular Mycorrhizal Biomass | Organic 1 Year Old | 180.3 | 211.9 | 105.9 |
| Saprophytic Percent | Organic 1 Week Old | 23.46 | 9.78 | 4.89 |
| Saprophytic Percent | Organic 1 Year Old | 22.64 | 6.20 | 3.10 |
| Saprophytes Biomass | Organic 1 Week Old | 2628.9 | 4368.4 | 2184.2 |
| Saprophytes Biomass | Organic 1 Year Old | 3912.1 | 4199.3 | 2099.7 |
| Protozoan Percent | Organic 1 Week Old | 0.08 | 0.16 | 0.08 |
| Protozoan Percent | Organic 1 Year Old | 0.19 | 0.15 | 0.08 |
| Protozoa Biomass | Organic 1 Week Old | 21.9 | 0.43 | 0.22 |
| Protozoa Biomass | Organic 1 Year Old | 32.9 | 3.1 | 1.5 |
| Gram Positive Biomass | Organic 1 Week Old | 384.7 | 63.2 | 31.6 |
| Gram Positive Biomass | Organic 1 Year Old | 633.2 | 63.6 | 31.8 |
| Gram Positive Percent | Organic 1 Week Old | 3.3 | 2.00 | 1.00 |
| Gram Positive Percent | Organic 1 Year Old | 3.5 | 2.28 | 1.14 |
| Undifferentiated Percent | Organic 1 Week Old | 53.0 | 17.2 | 8.6 |
| Undifferentiated Percent | Organic 1 Year Old | 52.1 | 27.9 | 14.0 |
| Undifferentiated Biomass | Organic 1 Week Old | 2735.7 | 3381.4 | 1690.7 |
| Undifferentiated Biomass | Organic 1 Year Old | 5337.3 | 5607.2 | 2803.6 |
| Fungi:Bacteria Ratio | Organic 1 Week Old | 1.44 | 1.10 | 0.55 |
| Fungi:Bacteria Ratio | Organic 1 Year Old | 3.57 | 4.60 | 2.30 |
| Predator to Prey Ratio | Organic 1 Week Old | 0.00 | 0.00 | 0.00 |
| Predator to Prey Ratio | Organic 1 Year Old | 0.01 | 0.02 | 0.01 |
| Gram Positive to Gram Negative Ratio | Organic 1 Week Old | 0.34 | 0.40 | 0.20 |
| Gram Positive to Gram Negative Ratio | Organic 1 Year Old | 0.55 | 0.51 | 0.25 |

|  |  |  |  |  |
|---|---|---|---|---|
| Saturated to Unsaturated Ratio | Organic 1 Week Old | 1.32 | 0.68 | 0.34 |
| Saturated to Unsaturated Ratio | Organic 1 Year Old | 1.92 | 1.87 | 0.94 |
| Monounsaturated to Polyunsaturated Ratio | Organic 1 Week Old | 1.57 | 1.20 | 0.60 |
| Monounsaturated to Polyunsaturated Ratio | Organic 1 Year Old | 1.12 | 1.14 | 0.57 |

Supplementary Table 4.6. PLFA response variables in the control vs. amended catch frame soil on 5/11/2022 from the upper 0-10 cm soil. Letter groupings indicate significant differences between treatments for each response variable. Biomass response variables are reported in ng biomass g$^{-1}$ soil. NA indicates treatments were not analyzed due to high presence of zeros in data for the given response variable.

| Response Variable | Treatment | Mean | Std. Dev. | Std. Error | CLD Groups |
|---|---|---|---|---|---|
| Total Biomass | Control | 8595.1 | 917.1 | 458.6 | **b** |
| Total Biomass | Amended Catch Frame | 12394.7 | 1294.3 | 647.1 | **a** |
| Diversity Index | Control | 1.46 | 0.05 | 0.02 | a |
| Diversity Index | Amended Catch Frame | 1.47 | 0.02 | 0.01 | a |
| Bacteria Percent | Control | 41.6 | 0.93 | 0.46 | a |
| Bacteria Percent | Amended Catch Frame | 42.5 | 0.73 | 0.37 | a |
| Total Bacteria Biomass | Control | 3578.2 | 3578.2 | 386.4 | **b** |
| Total Bacteria Biomass | Amended Catch Frame | 5265.2 | 5265.2 | 527.2 | **a** |
| Actinomycetes Percent | Control | 6.45 | 1.05 | 0.52 | a |
| Actinomycetes Percent | Amended Catch Frame | 5.40 | 0.64 | 0.32 | a |
| Actinomycetes Biomass | Control | 558.0 | 134.8 | 67.4 | a |
| Actinomycetes Biomass | Amended Catch Frame | 666.6 | 83.7 | 41.9 | a |
| Gram Negative Percent | Control | 24.6 | 2.6 | 1.3 | a |
| Gram Negative Percent | Amended Catch Frame | 26.0 | 0.5 | 0.3 | a |
| Gram Negative Biomass | Control | 2111.5 | 296.3 | 148.1 | **a** |
| Gram Negative Biomass | Amended Catch Frame | 3221.6 | 330.3 | 165.2 | **b** |
| Rhizobia Percent | Control | 0 | 0 | 0 | NA |
| Rhizobia Percent | Amended Catch Frame | 0 | 0 | 0 | NA |
| Rhizobia Biomass | Control | 0 | 0 | 0 | NA |
| Rhizobia Biomass | Amended Catch Frame | 0 | 0 | 0 | NA |
| Total Fungi Percent | Control | 17.1 | 2.6 | 1.3 | **b** |
| Total Fungi Percent | Amended Catch Frame | 24.3 | 1.21 | 0.6 | **a** |
| Total Fungi Biomass | Control | 1483.3 | 355.8 | 177.9 | **b** |
| Total Fungi Biomass | Amended Catch Frame | 3014.9 | 380.3 | 190.1 | **a** |
| Arbuscular Mycorrhizal Percent | Control | 3.63 | 0.81 | 0.40 | **b** |
| Arbuscular Mycorrhizal Percent | Amended Catch Frame | 5.82 | 0.41 | 0.20 | **a** |
| Arbuscular Mycorrhizal Biomass | Control | 316.4 | 94.4 | 47.2 | **b** |
| Arbuscular Mycorrhizal Biomass | Amended Catch Frame | 717.2 | 32.1 | 16.0 | **a** |
| Saprophytic Percent | Control | 13.5 | 1.9 | 0.9 | **b** |

| | | | | | |
|---|---|---|---|---|---|
| Saprophytic Percent | Amended Catch Frame | 18.5 | 1.4 | 0.7 | **a** |
| Saprophytes Biomass | Control | 1166.9 | 263.7 | 131.8 | **b** |
| Saprophytes Biomass | Amended Catch Frame | 2297.7 | 356.2 | 178.1 | **a** |
| Protozoan Percent | Control | 0.67 | 0.17 | 0.09 | a |
| Protozoan Percent | Amended Catch Frame | 0.47 | 0.09 | 0.05 | a |
| Protozoa Biomass | Control | 57.9 | 16.8 | 8.4 | a |
| Protozoa Biomass | Amended Catch Frame | 58.1 | 10.3 | 5.13 | a |
| Gram Positive Biomass | Control | 1466.7 | 277.7 | 138.8 | **b** |
| Gram Positive Biomass | Amended Catch Frame | 2043.6 | 218.5 | 109.2 | **a** |
| Gram Positive Percent | Control | 17.0 | 2.18 | 1.09 | a |
| Gram Positive Percent | Amended Catch Frame | 16.5 | 0.76 | 0.38 | a |
| Undifferentiated Percent | Control | 40.6 | 2.2 | 1.1 | **a** |
| Undifferentiated Percent | Amended Catch Frame | 32.7 | 1.5 | 0.7 | **b** |
| Undifferentiated Biomass | Control | 3475.7 | 219.4 | 109.7 | a |
| Undifferentiated Biomass | Amended Catch Frame | 4056.6 | 469.1 | 234.6 | a |
| Fungi:Bacteria Ratio | Control | 0.41 | 0.07 | 0.04 | **b** |
| Fungi:Bacteria Ratio | Amended Catch Frame | 0.57 | 0.02 | 0.01 | **a** |
| Predator to Prey Ratio | Control | 0.02 | 0.004 | 0.002 | a |
| Predator to Prey Ratio | Amended Catch Frame | 0.01 | 0.002 | 0.001 | a |
| Gram(+): Gram(-) | Control | 0.71 | 0.17 | 0.08 | a |
| Gram(+): Gram(-) | Amended Catch Frame | 0.63 | 0.04 | 0.02 | a |
| Saturated:Unsaturated | Control | 1.02 | 0.1 | 0.05 | **a** |
| Saturated:Unsaturated | Amended Catch Frame | 0.76 | 0.04 | 0.02 | **b** |
| Monounsaturated:Polyunsaturated | Control | 2.82 | 0.34 | 0.17 | **b** |
| Monounsaturated:Polyunsaturated | Amended | 3.93 | 0.40 | 0.20 | **a** |

Supplementary Table 4.7. PLFA response variables in the two organic hull/shell amendment layers on 5/11/2022. Letter groupings indicate significant differences. Biomass response variables are reported in ng biomass $g^{-1}$ soil. NA indicates treatments were not analyzed due to high presence of zeros in data for the given response variable.

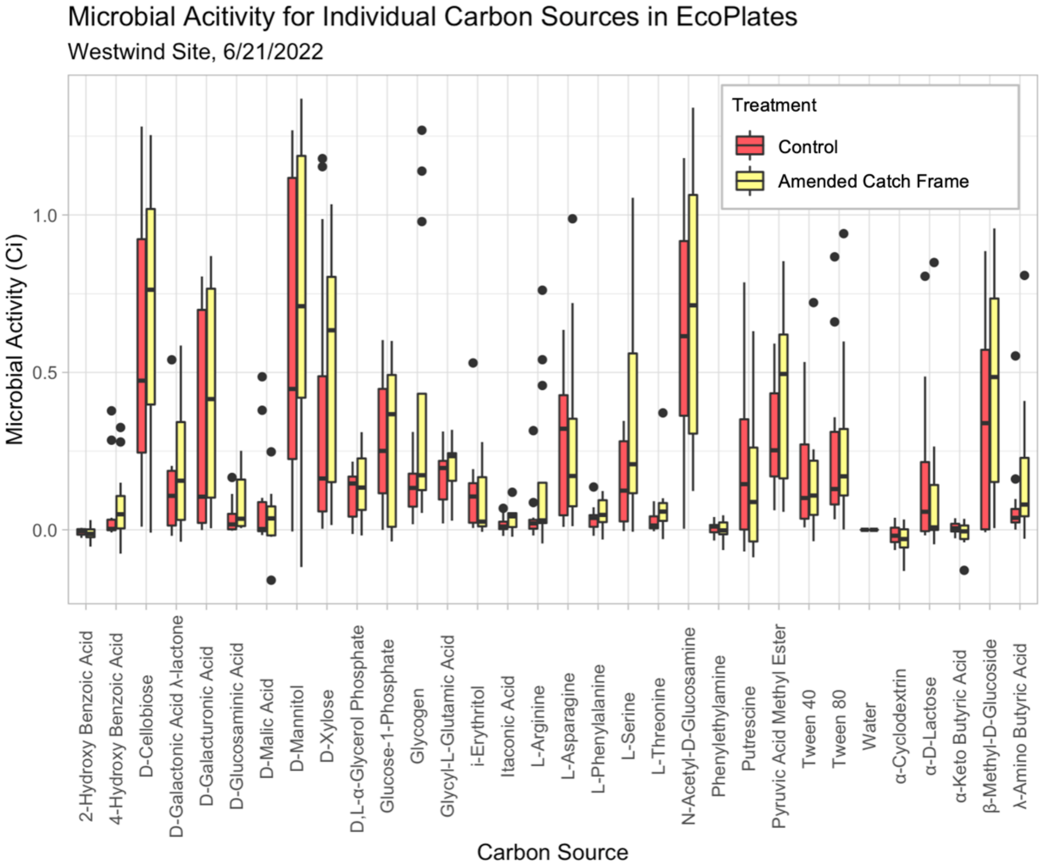
| Response Variable | Treatment | Mean | Std. Dev. | Std. Error | CLD Groups |
|---|---|---|---|---|---|
| Total Biomass | Organic Layer 1.5 Year | 21507.5 | 2315.8 | 1157.9 | a |
| Total Biomass | Organic Layer Half Year | 34981.8 | 14027.0 | 7013.5 | a |
| Diversity Index | Organic Layer 1.5 Year | 1.29 | 0.04 | 0.02 | **a** |
| Diversity Index | Organic Layer Half Year | 0.79 | 0.11 | 0.05 | **b** |
| Bacteria Percent | Organic Layer 1.5 Year | 37.0 | 1.77 | 0.89 | a |
| Bacteria Percent | Organic Layer Half Year | 50.7 | 16.3 | 8.1 | a |
| Total Bacteria Biomass | Organic Layer 1.5 Year | 7948.8 | 818.9 | 409.4 | **b** |
| Total Bacteria Biomass | Organic Layer Half Year | 16100.9 | 2030.7 | 1015.3 | **a** |
| Actinomycetes Percent | Organic Layer 1.5 Year | 2.79 | 0.28 | 0.14 | **a** |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Actinomycetes Percent | Organic Layer Half Year | 0.99 | 0.17 | 0.08 | **b** |
| Actinomycetes Biomass | Organic Layer 1.5 Year | 601.9 | 100.8 | 50.4 | **a** |
| Actinomycetes Biomass | Organic Layer Half Year | 336.4 | 104.9 | 52.4 | **b** |
| Gram Negative Percent | Organic Layer 1.5 Year | 26.1 | 1.12 | 0.56 | a |
| Gram Negative Percent | Organic Layer Half Year | 43.2 | 15.1 | 7.56 | a |
| Gram Negative Biomass | Organic Layer 1.5 Year | 5596.5 | 490.9 | 245.5 | **b** |
| Gram Negative Biomass | Organic Layer Half Year | 13618.4 | 2277.7 | 1138.8 | **a** |
| Rhizobia Percent | Organic Layer 1.5 Year | 0 | 0 | 0 | NA |
| Rhizobia Percent | Organic Layer Half Year | 0.36 | 0.37 | 0.19 | NA |
| Rhizobia Biomass | Organic Layer 1.5 Year | 0 | 0 | 0 | NA |
| Rhizobia Biomass | Organic Layer Half Year | 120.9 | 94.8 | 47.4 | NA |
| Total Fungi Percent | Organic Layer 1.5 Year | 37.0 | 2.8 | 1.38 | a |
| Total Fungi Percent | Organic Layer Half Year | 15.9 | 25.9 | 12.9 | a |
| Total Fungi Biomass | Organic Layer 1.5 Year | 7973.4 | 1173.7 | 586.9 | a |
| Total Fungi Biomass | Organic Layer Half Year | 8256.6 | 14851.0 | 7425.5 | a |
| Arbuscular Mycorrhizal Percent | Organic Layer 1.5 Year | 4.75 | 0.62 | 0.31 | **a** |
| Arbuscular Mycorrhizal Percent | Organic Layer Half Year | 2.18 | 1.07 | 0.54 | **b** |
| Arbuscular Mycorrhizal Biomass | Organic Layer 1.5 Year | 1024.5 | 181.7 | 90.8 | **a** |
| Arbuscular Mycorrhizal Biomass | Organic Layer Half Year | 672.8 | 190.0 | 95.0 | **b** |
| Saprophytic Percent | Organic Layer 1.5 Year | 32.27 | 3.3 | 1.67 | a |
| Saprophytic Percent | Organic Layer Half Year | 13.7 | 26.7 | 13.4 | a |
| Saprophytes Biomass | Organic Layer 1.5 Year | 6948.9 | 1129.4 | 564.7 | a |
| Saprophytes Biomass | Organic Layer Half Year | 7583.8 | 14944.1 | 7472.0 | a |
| Protozoan Percent | Organic Layer 1.5 Year | 0.32 | 0.03 | 0.01 | a |
| Protozoan Percent | Organic Layer Half Year | 0.78 | 0.44 | 0.22 | a |
| Protozoa Biomass | Organic Layer 1.5 Year | 69.3 | 7.48 | 3.74 | **b** |
| Protozoa Biomass | Organic Layer Half Year | 253.3 | 111.2 | 55.6 | **a** |
| Gram Positive Biomass | Organic Layer 1.5 Year | 2352.3 | 344.5 | 172.2 | a |
| Gram Positive Biomass | Organic Layer Half Year | 2482.6 | 423.9 | 212.0 | a |
| Gram Positive Percent | Organic Layer 1.5 Year | 10.9 | 0.94 | 0.47 | **a** |
| Gram Positive Percent | Organic Layer Half Year | 7.5 | 1.52 | 0.76 | **b** |
| Undifferentiated Percent | Organic Layer 1.5 Year | 25.7 | 1.0 | 0.50 | a |
| Undifferentiated Percent | Organic Layer Half Year | 32.6 | 9.9 | 4.9 | a |
| Undifferentiated Biomass | Organic Layer 1.5 Year | 5516.0 | 583.4 | 291.7 | **b** |
| Undifferentiated Biomass | Organic Layer Half Year | 10370.9 | 771.8 | 385.9 | **a** |
| Fungi:Bacteria Ratio | Organic Layer 1.5 Year | 1.01 | 0.12 | 0.06 | a |
| Fungi:Bacteria Ratio | Organic Layer Half Year | 0.55 | 1.00 | 0.50 | a |
| Predator to Prey Ratio | Organic Layer 1.5 Year | 0.009 | 0.0007 | 0.0003 | a |
| Predator to Prey Ratio | Organic Layer Half Year | 0.016 | 0.007 | 0.003 | a |
| Gram(+): Gram(-) | Organic Layer 1.5 Year | 0.42 | 0.03 | 0.02 | **a** |
| Gram(+): Gram(-) | Organic Layer Half Year | 0.19 | 0.06 | 0.03 | **b** |

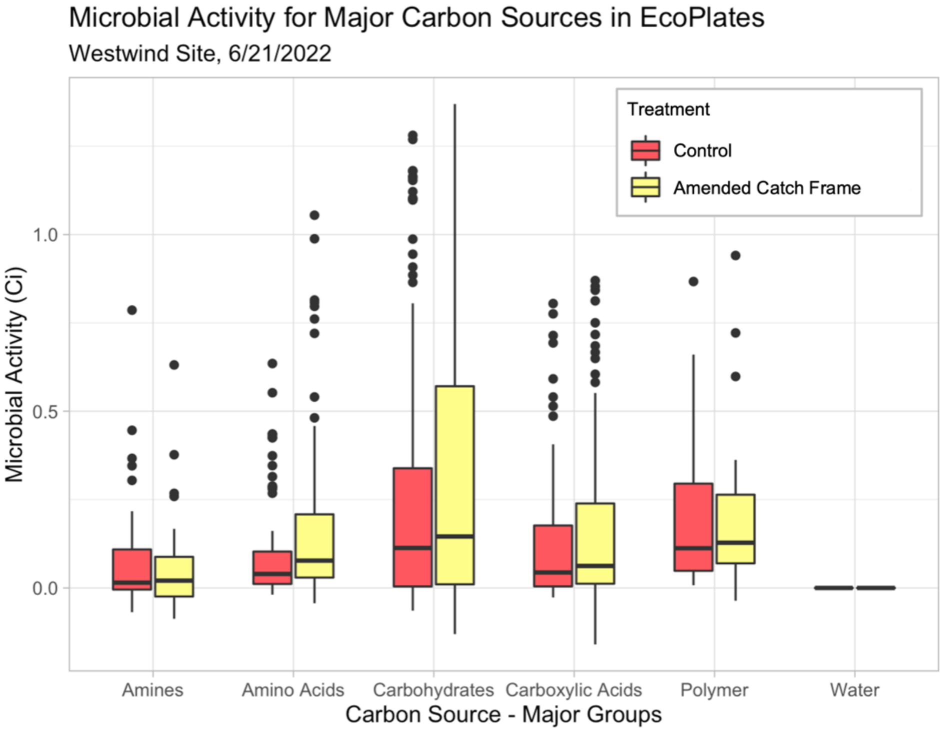
| | | | | | |
|---|---|---|---|---|---|
| Saturated:Unsaturated | Organic Layer 1.5 Year | 0.44 | 0.04 | 0.02 | a |
| Saturated:Unsaturated | Organic Layer Half Year | 0.56 | 0.21 | 0.11 | a |
| Monounsaturated:Polyunsaturated | Organic Layer 1.5 Year | 1.1 | 0.17 | 0.09 | a |
| Monounsaturated:Polyunsaturated | Organic Layer Half Year | 24.8 | 18.1 | 9.05 | a |

Supplementary Table 4.8. PLFA response variables from Bullseye soil samples taken on 7/6/2022, from the upper 0-10 cm soil. Letter groupings indicate significant differences between treatments for each response variable. Biomass response variables are reported in ng biomass $g^{-1}$ soil. NA indicates treatments were not analyzed due to high presence of zeros in data for the given response variable.

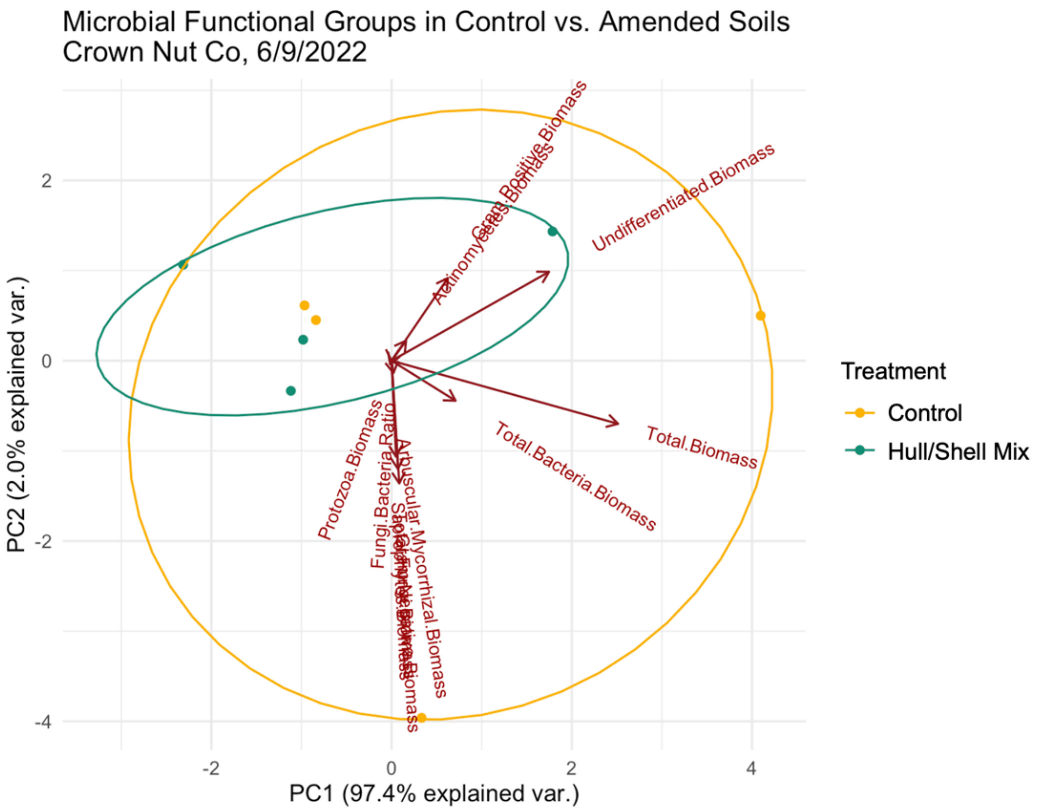
| Response Variable | Treatment Mean | | |
|---|---|---|---|
| | Control | Shells | Compost |
| Total Biomass | 4649.4 b | 7868.7 a | 6439.9 ab |
| Total Bacteria Biomass | 1762.6 b | 3371.3 a | 2687.8 ab |
| Bacterial Percent | 37.6 b | 42.8 a | 41.5 ab |
| Total Fungi Biomass | 524.7 a | 1327.5 a | 945.3 ab |
| Total Fungi Percent | 10.9 b | 16.8 a | 14.2 ab |
| Actinomycete Biomass | 400.3 b | 597.0 a | 486.5 ab |
| Actinomycete Percent | 8.7 a | 7.6 a | 7.7 a |
| Gram Negative Biomass | 655.5 b | 1634.0 a | 1229.9 ab |
| Gram Negative Percent | 13.8 b | 20.8 a | 18.6 ab |
| Gram Positive Biomass | 1097.1 b | 1737.3 a | 1457.9 ab |
| Gram Positive Percent | 23.8 a | 22.0 a | 22.9 a |
| Saprophyte Biomass | 406.5 b | 993.2 a | 683.1 ab |
| Saprophyte Percent | 8.4 b | 12.6 a | 10.3 ab |
| Arbuscular Mycorrhizal Biomass | 118.1 b | 334.3 a | 262.2 ab |
| Arbuscular Mycorrhizal Percent | 2.4 b | 4.2 a | 3.9 ab |
| Rhizobia Biomass | 0 NA | 40.0 NA | 0 NA |
| Rhizobia Percent | 0 NA | 0.54 NA | 0 NA |
| Protozoan Biomass | 5.1 NA | 63.6 NA | 0 NA |
| Protozoan Percent | 0.13 NA | 0.86 NA | 0 NA |
| Undifferentiated Biomass | 2357.2 a | 3105.3 a | 2806.8 a |
| Undifferentiated Percent | 51.4 a | 39.5 b | 44.3 ab |
| Functional Group Diversity Index | 1.48 a | 1.55 a | 1.49 a |
| Fungi:Bacteria | 0.29 a | 0.39 a | 0.34 a |
| Gram(+):Gram(-) | 1.8 a | 1.1 b | 1.3 ab |
| Saturated:Unsaturated | 1.53 a | 1.10 b | 1.22 ab |



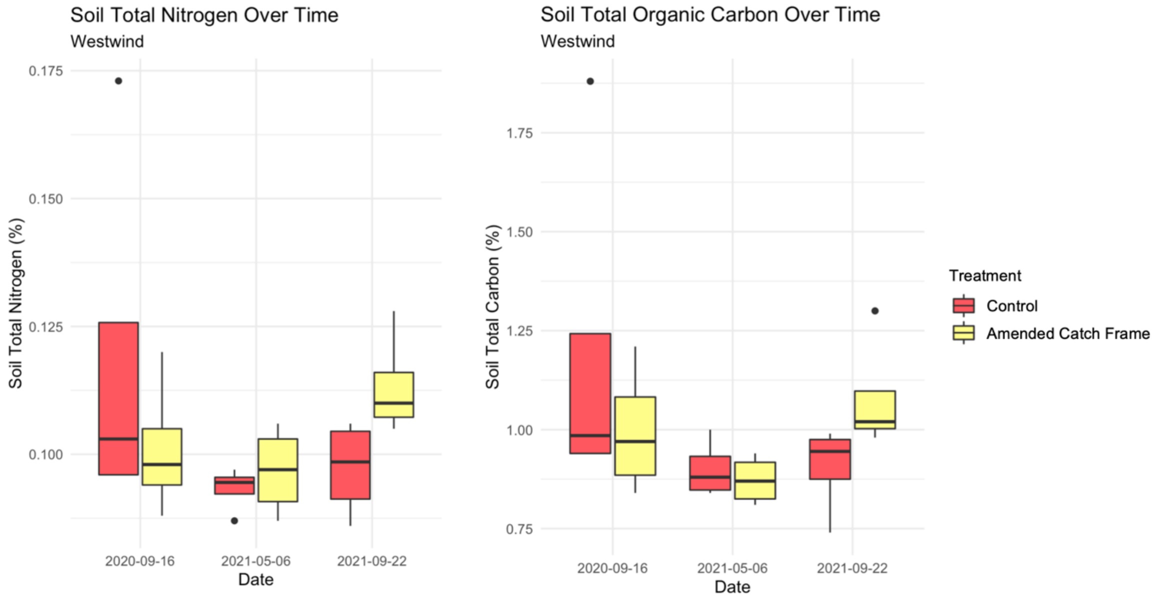
Supplementary Figure 4.1. Microbial activity for individual carbon sources from the upper 0-10cm soil.



Supplementary Figure 4.2. Microbial activity for major carbon source groups from the upper 0-10cm soil.

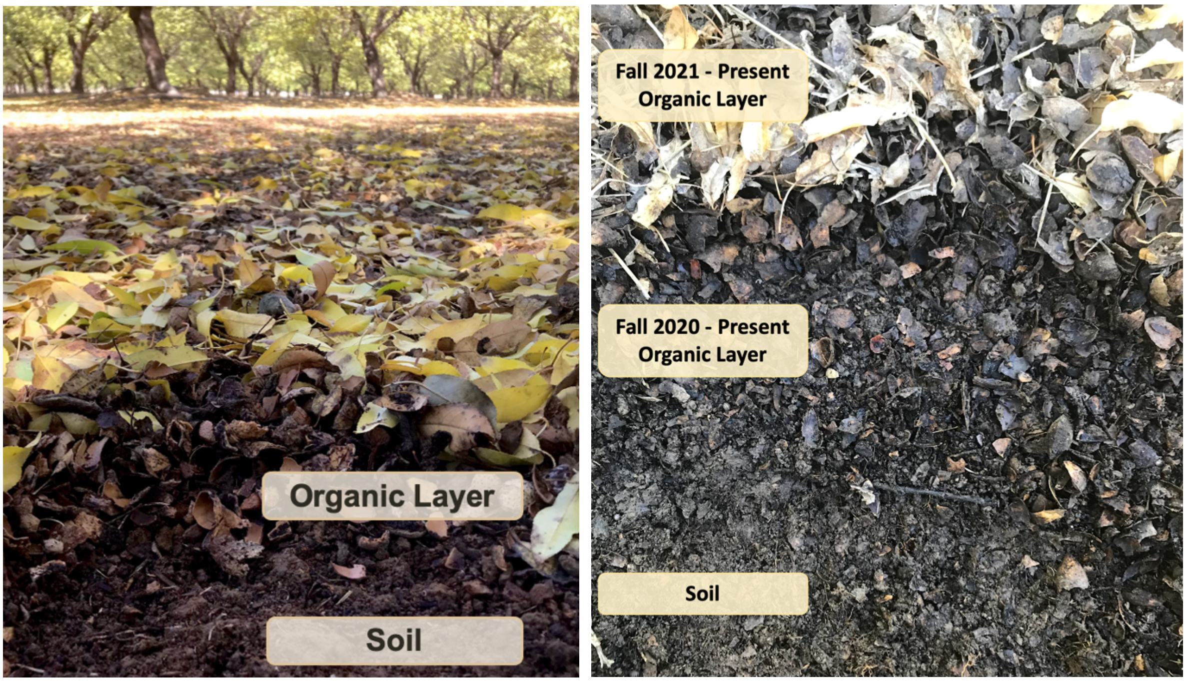


Supplementary Figure 4.3. Principal components analysis biplot for Crown Nut Co control soil vs. hull/shell mix-amended soils in the upper 0-10 cm on 6/9/2022. Soils had been bare without amendments since harvest (on-ground across the entire orchard) in August the year prior, approximately 10 months. No significant differences were found between any PLFA response variables. Any possible impacts on the soil microbial community that may or may not have occurred were not observable at this time after on-ground harvest displaced the amendment layer.



Supplementary Figures 4.4a and b . Total soil nitrogen (TN) and total soil organic carbon (TOC) over time in the upper 0-10 cm soil. TN and TOC were slightly higher in the amended catch frame soil one year after amendment application and prior to the second application fall 2021.

<u>Pictures</u>



Left: on 11/24/2020, freshly applied hull/shell amendment, compost, and leaf litter on top of the soil surface. Right: on 9/13/2022, 1-year-old organic layer from fall 2021 and 2-year-old amendment layer from fall 2020 on top of the soil surface. The organic layers consist of hull/shell amendments, compost, and organic debris such as leaf litter, mowed cover crops, twigs, etc.

Unidentified basidiocarps appeared in the hull/shell amendment treatments at Crown Nut Co in the spring on 5/10/2020 (right) and 5/25/2020 (left). While potassium was the main focus at the Crown Nut Co field site, these fungi inspired the preliminary PLFA analysis for microbial community composition in the hull/shell amendment layer (in addition to the soil) on 4/6/2021 at the Westwind field site where soil health and microbial community composition was the research focus.

## 4.11 Literature Cited

Almeida, D.O., Filho, O.K., Almeida, H.C., Gebler, L., Felipe, A.F. (2011). Soil microbial biomass under mulch types in an integrated apple orchard from Southern Brazil. Sci. Agric. (Piracicaba, Braz.) 68(2):21-222.

Almond Board of California. (2019). Almond Orchard 2025 Goals. Modesto, California. https://www.almonds.com/sites/default/files/2020-05/GoalsRoadmap_2019_web.pdf

Biolog (2022). EcoPlate Microbial Community Analysis Instruction Manual. https://www.biolog.com/wp-content/uploads/2020/04/00A-012-rD-EcoPlate-IFU.pdf

Binkley, D. (2002). Ten-year decomposition in a loblolly pine forest. Canadian Journal of Forest Research, 32, 2231–2235.

Bonilla, N., Cazorla, F. M., Martínez-Alonso, M., Hermoso, J. M., González-Fernández, J. J., Gaju, N., Landa, B. B., & de Vicente, A. (2012). Organic amendments and land management affect bacterial community composition, diversity and biomass in avocado crop soils. Plant and Soil, 357(1), 215–226.

Chalker-Scott, L. A gardener's primer to mycorrhizae: understanding how they work and learning how to protect them. Washington State University Extension, FS269E.

Chen, C., Khir, R., Shen, Y., Wu, X., Zhang, R., Cao, X., Niederholzer, F., & Pan, Z. (2021). Energy consumption and product quality of off-ground harvested almonds under hot air column drying. LWT Food Science and Technology, 138, 110768.

Crowther, T.W., Boddy, L., Jones, T.H. (2012). Functional and ecological consequences of saprotrophic fungus-grazer interactions. International Society for Microbial Ecology Journal, 6:1993-2001.

Cook, K.L, Wallender, W.W., Bledsoe, C.S., Pasternack, G., Upadhyaya, S.K. (2011). Effects of native plant species, mycorrhizal inoculum, and mulch on restoration of reservoir sediment following dam removal, Elwha River, Olympic Peninsula, Washington. Restoration Ecology, 19(2):251-260.

Cox, J., Van Zwieten, L., Ayres, M., & Morris, S. (2004). Macadamia husk compost improves soil health in sub-tropical horticulture. SuperSoil 2004: 3rd Australian New Zealand Soils Conference, University of Sydney, Australia.

De Leijster, V., Santos, M.J., Wassen, M.J., Ramos-Font, M.E., Robles, A.B., Diaz, M., Staal, M., Verweij, P.A. (2019). Agroecological management improves ecosystem services in almond orchards within one year. Ecosystem Services, 38:100948.

Dijkstra, F.A., Bader, N.E., Johnson, D.W., Cheng, W. (2009). Does accelerated soil organic matter decomposition in the presence of plants increase plant N availability? Soil Biology and Biogeochemistry, 42:1080-1087.

Fenster, T.L.D., Oikawa, P.Y., Lundgren, J.G. (2021). Regenerative Almond Production Systems Improve Soil Health, Biodiversity, and Profit. Front. Sustain. Food Syst. 5:664359.

Fernandez-Bayo, J. D., Shea, E. A., Parr, A. E., Achmon, Y., Stapleton, J. J., VanderGheynst, J. S., Hodson, A. K., & Simmons, C. W. (2020). Almond processing residues as a source of organic acid biopesticides during biosolarization. Waste Management, 101, 74–82.

Frey, S.D. (2019). Mycorrhizal Fungi as Mediators of Soil Organic Matter Dynamics. Annual Review of Ecology, Evolution, and Systematics, 50(1), 237-259.

Galanti, R., Cho, A., Ahmad, A., & Radovich, T. (2019). Soil Amendments and Soil Profiling Impact on Macadamia Growth and Yield Performance. HortScience, 54(3), 519–527.

Garland, J.L. (1997). Analysis and interpretation of community-level physiological profiles in microbial ecology. FEMS Microbiology Ecology 24:289-300.

Glover, J. D., Reganold, J. P., & Andrews, P. K. (2000). Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington State. Agriculture, Ecosystems & Environment, 80(1), 29–45.

Granatstein, D., Andrews, P., & Groff, A. (2014). Productivity, economics, and fruit and soil quality of weed management systems in commercial organic orchards in Washington State, USA. Organic Agriculture, 4(3), 197–207.

Gross, C. D., & Harrison, R. B. (2019). The Case for Digging Deeper: Soil Organic Carbon Storage, Dynamics, and Controls in Our Changing World. Soil Systems, 3(2).

Greskevitch, M., Kullman, G., Bang, K.M., Mazurek, J.M. (2008) Respiratory disease in agricultural workers: mortality and morbidity statistics. Journal of Agromedicine, 12(3): 5-10.

Idowu, O. J., Sanogo, S., & Brewer, C. E. (2017). Short-Term Impacts of Pecan Waste By-Products on Soil Quality in Texturally Different Arid Soils. Communications in Soil Science and Plant Analysis, 48(15), 1781–1791.

Janzen, H. H. (2006). The soil carbon dilemma: Shall we hoard it or use it? Soil Biology and Biochemistry, 38(3), 419–424.

Janzen, H.H., Janzen, D.W., Gregorich, E.G. (2021). The ‘soil health’ metaphor: illuminating or illusory? Soil Biology and Biochemistry, 159:108167.

Hodge, A., Campbell, C.D., Fitter, A. (2001). An arbuscular mycorrhizal fungus accelerates decomposition and acquires nitrogen directly from organic material. Nature, 413: 297-299.

Hoover, C.M., Karlberg, N.J., Scott, N.A., Giardina, C.P. (2008). Chapter 8 Methods for estimating litter decomposition. Field measurements for forest carbon monitoring: a landscape-scale approach. New York, NY: Springer Science + Business Media: 103-11.

Karlberg, N. J., Scott, N. A., & Giardina, C. P. (2008). Chapter 8 Methods for estimating litter decomposition. In Hoover, Coeli M., ed. Field measurements for forest carbon monitoring: A landscape-scale approach. New York, NY: Springer Science + Business Media: 103-111.

Kasongo, R. K., Verdoodt, A., Kanyankagote, P., Baert, G., & Ranst, E. V. (2011). Coffee waste as an alternative fertilizer with soil improving properties for sandy soils in humid tropical environments. Soil Use and Management, 27(1), 94–102.

Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. Nature, 528(7580), 60–68.

López, R., Burgos, P., Hermoso, J. M., Hormaza, J. I., & González-Fernández, J. J. (2014).

Long term changes in soil properties and enzyme activities after almond shell mulching in avocado organic production. Soil and Tillage Research, 143, 155–163.

Moyin-Jesu, E. I. (2007). Use of plant residues for improving soil fertility, pod nutrients, root growth and pod weight of okra (*Abelmoschus esculentum* L). Bioresource Technology, 98(11), 2057–2064.

Neilsen, G., Forge, T., Angers, D., Neilsen, D., & Hogue, E. (2014). Suitable orchard floor management strategies in organic apple orchards that augment soil organic matter and maintain tree performance. Plant and Soil, 378(1), 325–335.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R., et al. Vegan: community ecology package. R package version 2.6-4, Cited 10/24/2022.

Ozenc, D.B.; Ozenc, N. (2008). Short-Term Effects of Hazelnut Husk Compost and Organic Amendment Applications on Clay Loam Soil. Compost Science and Utilization, 16, 192–199.

Krishna, M. P., & Mohan, M. (2017). Litter decomposition in forest ecosystems: A review. Energy, Ecology and Environment, 2(4), 236–249.

Prescott, C. E., & Vesterdal, L. (2021). Decomposition and transformations along the continuum from litter to soil organic matter in forest soils. Forest Ecology and Management, 498, 119522.

Schenker, M.B., Pinkerton, K.E., Mitchell, D., Vallyathan, V., Elvine-Kreis, B., Green, F.H.Y. (2009). Pneumoconiosis from agricultural dust exposure among young California farmworkers. Environmental Health Perspectives, 117(6):988-994.

Schmidt, R., Gravuer, K., Bossange, A.V., Mitchell, J., Scow, K. (2018) Long-term use of cover crops and no-till shift soil microbial community life strategies in agricultural soil. PLoS ONE, 13(2), e0192953.

Soto, R.L., Martinez-Mena, M., Padilla, M.C., de Vente, J. (2021). Restoring soil quality of woody agroecosystems in Mediterranean drylands through regenerative agriculture. Agriculture, Ecosystems and Environment, 306:107191.

Sumner, D.A., Buchner, R.P., Niederholzer, F., Jarvis-Shean, K.S., Lightle, D.M., Symmes, E.J., Milliron, L., Stewart, D. (2019). Sample costs to establish an orchard and produce almonds Sacramento Valley. University of California Agriculture and Natural Resources Cooperative Extension. UC Davis Department of Agricultural and Resource Economics.

Talbot, J.M., Allison, S.D., Treseder, K.K. (2008). Decomposers in disguise: mycorrhizal fungi as regulators of soil C dynamics in ecosystems under global change. Functional Ecology, 22:955-963.

Tahboub, M. B., Lindemann, W. C., & Murray, L. (2007). Nutrient Availability in Soil Amended with Pecan Wood Chips. HortScience HORTS, 42(2), 339–343.

United States Department of Agriculture, National Agricultural Statistics Service (2021). 2021 California Almond Objective Measurement Report. Pacific Region.

Vasilikiotis, C., Li, M., Schmidt, J.E., Azimi, A., Garciz, J., Volder, A., Lampinen, B., Gaudin, A.C.M. (2020). Orchard management practices affect arbuscular mycorrhizal fungal root colonization of almond. Biological Agriculture & Horticulture.

Vida, C., Bonilla, N., de Vicente, A., & Cazorla, F. M. (2016). Microbial profiling of a suppressiveness-induced agricultural soil amended with composted almond shells. Frontiers in Microbiology, 7, 4.

Weber, K.P., Legge, R.L. (2010). Community-level physiological profiling. Chapter 16 in Bioremediation: methods and protocols, edited by Stephen P. Cummings. Humana Press.

Wei, L., Ding, J., Yan, W., Vosatka, M., Lu, C., Li, Y., Cai, B., Xu, J., Liu, C. (2019). The role of arbuscular mycorrhiza fungi in the decomposition of fresh residue and soil organic carbon: a mini-review. Soil Biology and Biogeochemistry 83:511-517.

Yan, S., Song, J., Fan, J., Yan, C., Dong, S., Ma, C., & Gong, Z. (2020). Changes in soil organic carbon fractions and microbial community under rice straw return in Northeast China. Global Ecology and Conservation, 22, e00962.

## Conclusion

In summary, almond hulls and shells used as organic matter amendments can enhance potassium cycling, improve soil-plant water dynamics, and increase microbial life on and in the soil. Hulls and shells provided solubilized K which increased soil available K and tree K status to varying degrees depending on orchard site. This surface-applied amendment created a barrier on the soil surface which maintained higher soil water content near the soil surface and improved soil-plant water dynamics. Pairing this practice with off ground harvest ensured the amendment layer remained undisturbed, maximizing the benefits provided by hulls and shells and establishing a microbially active organic layer on the soil surface. This organic layer was colonized by many beneficial microbial functional groups such as saprophytes which led to relatively high decomposition. Increases in root biomass under this preserved amendment layer and arbuscular mycorrhizae in the soil and hull/shell layers merit further study. Future research could investigate additional ecosystem services, such as potential suppression of weeds, plant pathogens, and insect pests overwintering in the soil. Further long-term studies are needed to better understand how almond hull/shell amendments affect soil and plant processes across different soil types, management practices, and at different application rates over time. Overall, recycling almond hull/shell materials as organic matter amendments in nearby orchards offers a sustainable outlet for hull/shell biomass waste materials accumulating in California almond processing facilities.

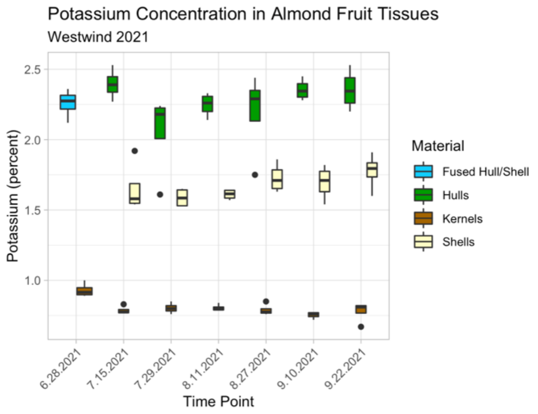
**Supplementary: Almond fruit nutrient concentration fluctuations**

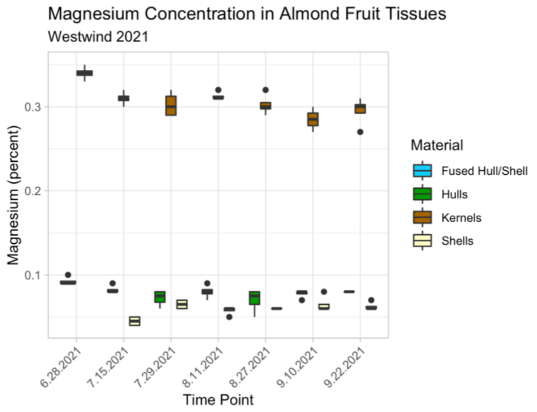
Questions remain regarding the factors that influence K concentrations in hull and shell amendment materials. As shown in Chapter 2, the three trials utilized hulls that ranged from approximately 2.0-2.7% K, hull/shell mixes at 1.9-2.9% K, and shells at 1.54-1.84% K. These ranges could make it challenging to precisely predict K applied through these materials. Contextual factors likely impacting K concentration include fertilizer and water management practices at the orchard of origin, soil type, variety, and harvest timing. Almond hulls and shells used as amendments originate from massive piles at processing facilities where it is difficult to determine orchard of origin.

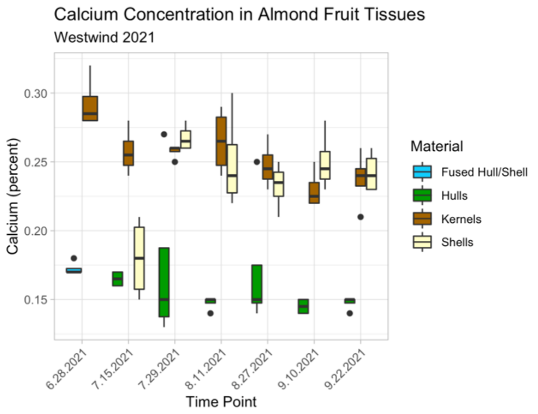
However, understanding nutrient accumulation/remobilization dynamics to and from fruit organs over time could provide valuable information about K concentration fluctuations in hull and shell materials at different harvest dates. Prior research has been conducted to assess nutrient partitioning in California almond trees, although data was only provided through July while harvest typically happens throughout August and early September (Muhammad et al. 2015, Muhammad et al. 2020). Unpublished data from four field sites was provided from Dr. Sebastian Saa's (Associate Director, ABC) doctoral research at UC Davis to investigate this further and is used with permission. All samples are from Nonpareil trees. This data is from an observational study following a grid sampling design of the same trees over time (further details found in Saa et al. 2014).

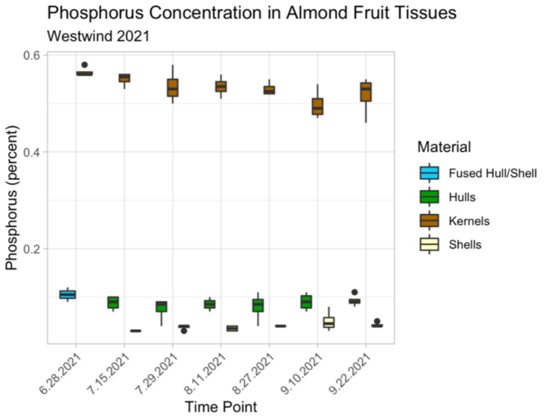
At Westwind from late June to late September in 2021, hull and shell K and P concentrations in developing fruit remained relatively consistent over time, while average Mg and

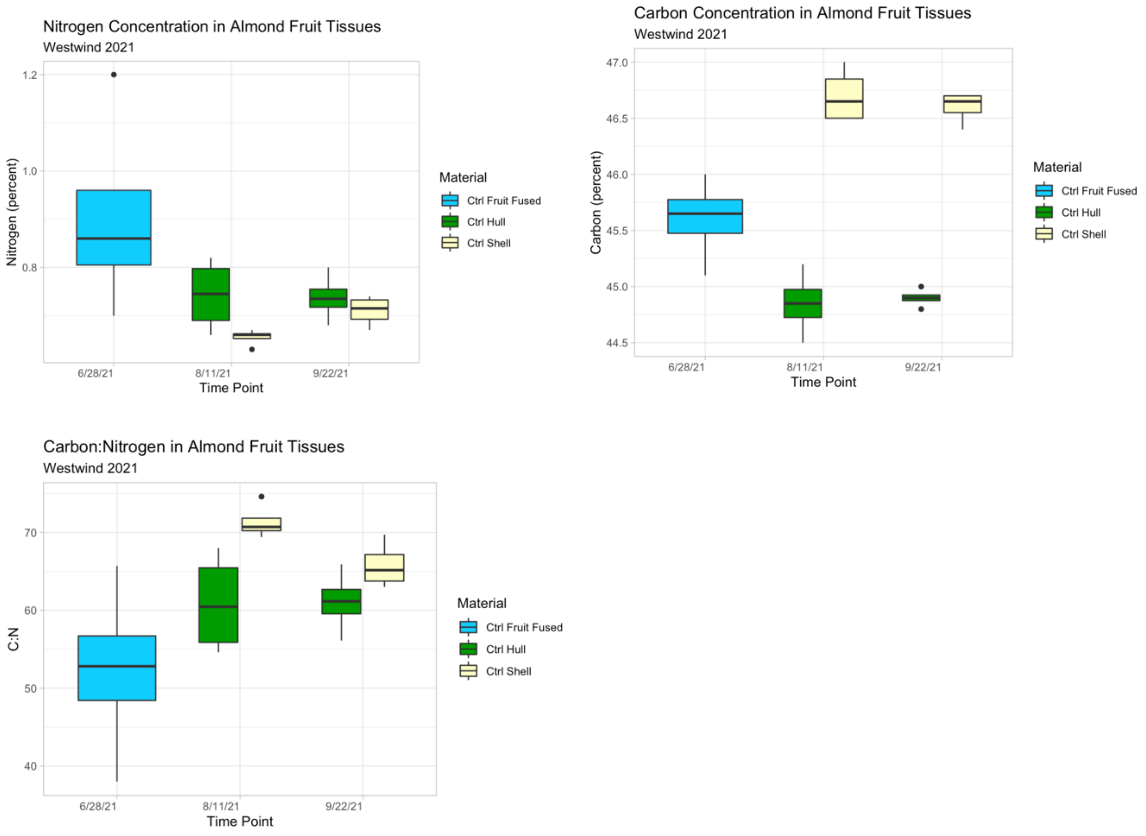
Ca declined slightly (Supplementary Figures 5.1a-g ). This data indicates harvest timing likely does not impact Nonpareil K concentration in fruit tissues at Westwind. Variation in hull/shell K concentrations is likely more related to site-specific variables such as K fertilizer management and soil type than harvest timing. From 8/11/21 to 9/22/21, shell N increased and C:N ratio fell from 71:1 to 66:1, indicating harvest date may impact shell N and C:N ratio of hull/shell amendment materials. On 7/29/2021 before harvest, the majority of fruit K was allocated to hulls, while shells and kernels contained largest fraction of Ca, and Mg and P were largely allocated to kernels (Supplementary Table 5.1).











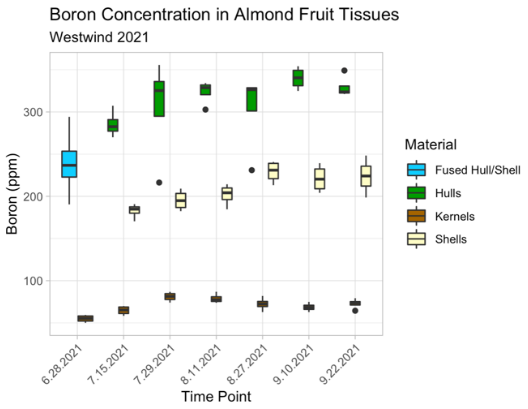
Supplementary Figures 5.1a-g. Macronutrient allocation to almond kernel, shell, and hull tissues from late June until late September in Nonpareils trees from the control treatment at Westwind.

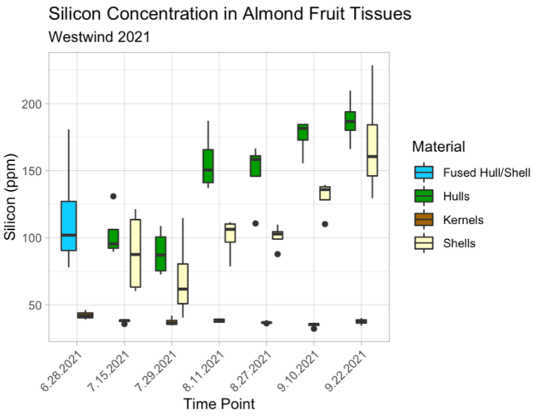
Supplementary Table 5.1. Average macronutrient and micronutrient concentrations on July 29, 2021, several days before harvest, Westwind. The hulls contained the largest fractions of boron, silicon, and aluminum. Kernels contained the largest fractions of Fe, Na, S, Zn, Mn, Cu, and Ni at this time point.

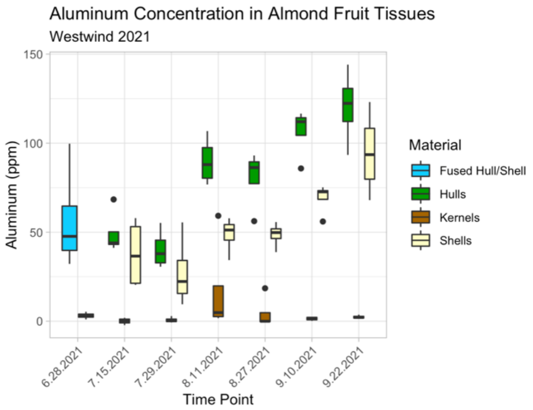
| Nutrient | Kernel | Shell | Hull |
|---|---|---|---|
| | Average Concentration (%) | | |
| Potassium (K) | 0.80 | 1.59 | 2.05 |
| Magnesium (Mg) | 0.30 | 0.07 | 0.07 |
| Calcium (Ca) | 0.26 | 0.27 | 0.18 |
| Phosphorus (P) | 0.54 | 0.04 | 0.08 |
| | Average Concentration (ppm) | | |
| Boron (B) | 80.9 | 195.3 | 305.7 |
| Silicon (Si) | 37.4 | 69.7 | 88.9 |
| Aluminum (Al) | 0.70 | 27.4 | 40.4 |
| Iron (Fe) | 53.5 | 30.6 | 43.6 |
| Sodium (Na) | 46.7 | 41.6 | 36.5 |
| Sulfur (S) | 1756.5 | 247.4 | 276.7 |

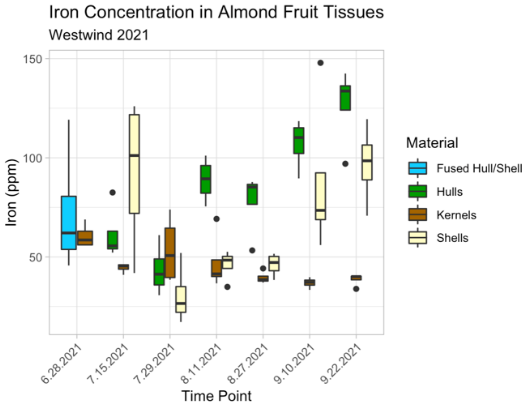
| | | | |
|---|---|---|---|
| Zinc (Zn) | 42.0 | 4.93 | 9.03 |
| Manganese (Mn) | 16.9 | 3.90 | 4.03 |
| Copper (Cu) | 18.5 | 9.28 | 7.58 |
| Nickel (Ni) | 2.83 | 0.75 | 1.35 |

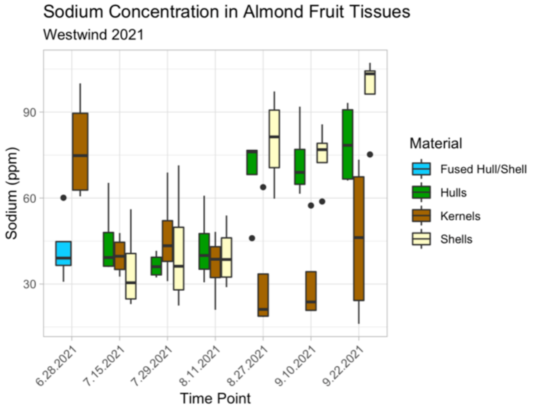
Considering micronutrient fruit allocation at Westwind (Figures 5.2a-j), B concentration remained relatively consistent over time with highest concentrations in hulls. Shifts in Si, Al, and Fe concentrations appeared somewhat similar, decreasing in hulls and shells until August, then steadily increasing through August and September. Sodium allocation appeared similar in all three fruit tissues until late August, at which point Na in hulls and shells increased dramatically. Shells appeared to accumulate Na even at the last time point in late September. Sulfur, Zn, Mn, and Cu accumulated primarily in kernels while hull and shell concentrations remained low. Nickel concentrations were very low and remained relatively steady over time. Considering the shifts that occurred from early August through late September, harvest timing likely affects concentrations of Si, Al, Fe, Na, found in hull/shell amendments, as these nutrients increased over time.

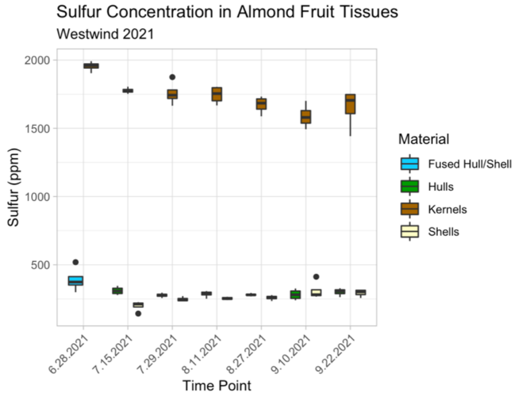


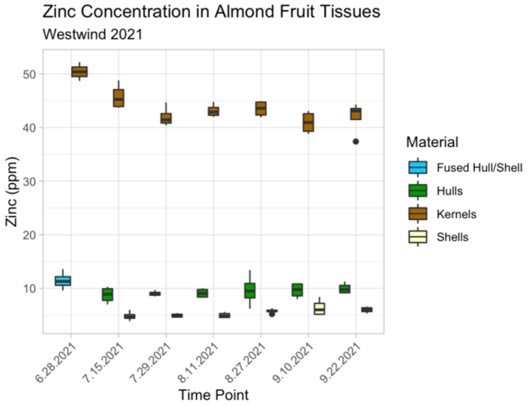


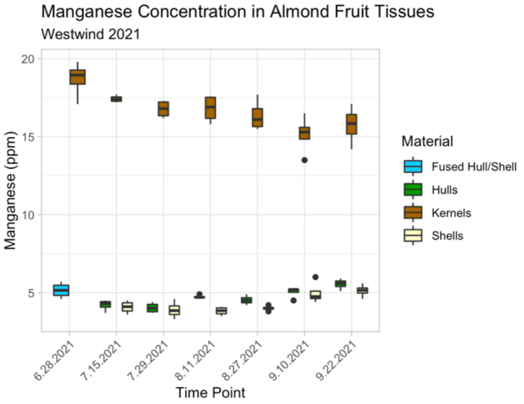

Aluminum Concentration in Almond Fruit Tissues
Westwind 2021
Aluminum (ppm)
150
100
50
0
6.28.2021
7.15.2021
7.29.2021
8.11.2021
8.27.2021
9.10.2021
9.22.2021
Time Point
Material
Fused Hull/Shell
Hulls
Kernels
Shells

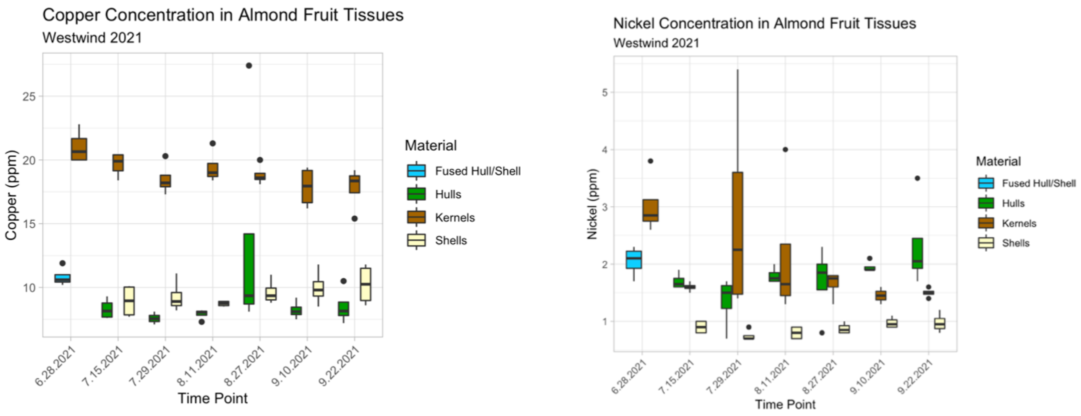

Iron Concentration in Almond Fruit Tissues
Westwind 2021
Iron (ppm)
150
100
50
6.28.2021
7.15.2021
7.29.2021
8.11.2021
8.27.2021
9.10.2021
9.22.2021
Time Point
Material
Fused Hull/Shell
Hulls
Kernels
Shells


Sodium Concentration in Almond Fruit Tissues
Westwind 2021
Sodium (ppm)
90
60
30
6.28.2021
7.15.2021
7.29.2021
8.11.2021
8.27.2021
9.10.2021
9.22.2021
Time Point
Material
Fused Hull/Shell
Hulls
Kernels
Shells


Sulfur Concentration in Almond Fruit Tissues
Westwind 2021
Sulfur (ppm)
2000
1500
1000
500
6.28.2021
7.15.2021
7.29.2021
8.11.2021
8.27.2021
9.10.2021
9.22.2021
Time Point
Material
Fused Hull/Shell
Hulls
Kernels
Shells

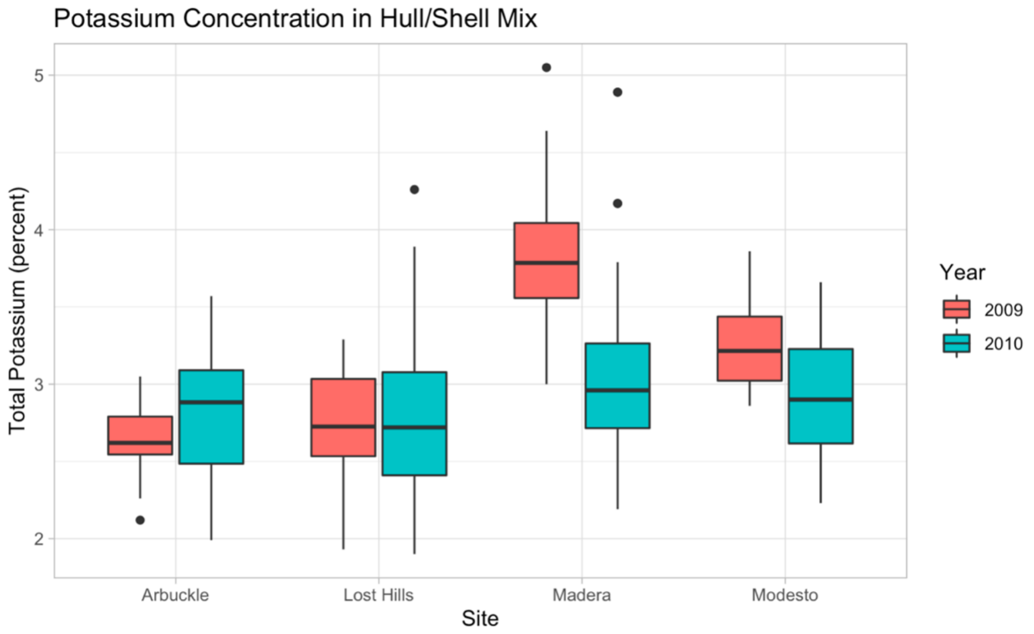

Zinc Concentration in Almond Fruit Tissues
Westwind 2021
Zinc (ppm)
50
40
30
20
10
6.28.2021
7.15.2021
7.29.2021
8.11.2021
8.27.2021
9.10.2021
9.22.2021
Time Point
Material
Fused Hull/Shell
Hulls
Kernels
Shells


Manganese Concentration in Almond Fruit Tissues
Westwind 2021
Manganese (ppm)
20
15
10
5
6.28.2021
7.15.2021
7.29.2021
8.11.2021
8.27.2021
9.10.2021
9.22.2021
Time Point
Material
Fused Hull/Shell
Hulls
Kernels
Shells

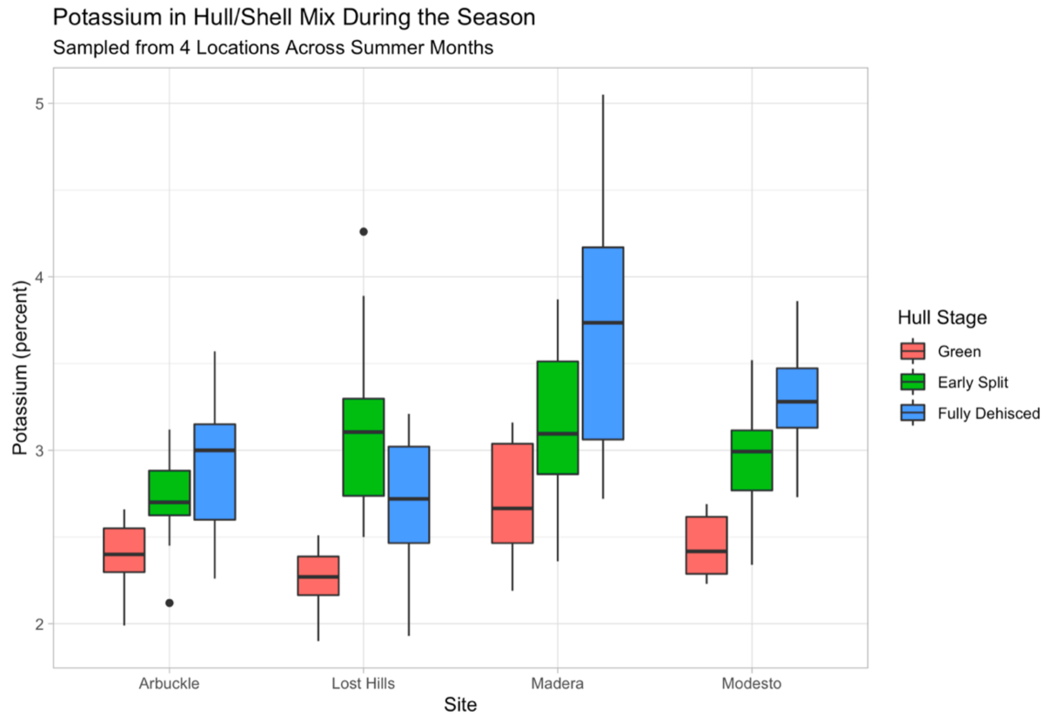


Supplementary Figures 5.2a-j. Micronutrient concentrations in developing almond kernels, shells, and hulls from late June until late September in Nonpareils, Westwind.

Saa et al. unpublished data indicate that certain orchard sites such as Madera show high variation in average K concentration between years, while other sites such as Lost Hills show more consistent annual mix K (Figure 5.3). The high outliers at Madera are much greater than any values found in field trial samples from Crown, Bullseye, or Westwind. At Arbuckle, Madera, and Modesto, K concentration in the hull/shell Nonpareil mix increased steadily during the season, while it decreased at full dehiscence at Lost Hills (Figure 5.4). This indicates K often accumulates into the full dehiscence phase (August) though this is likely site-specific, however no data was provided for September (dry hull stage) at these sites for these years.

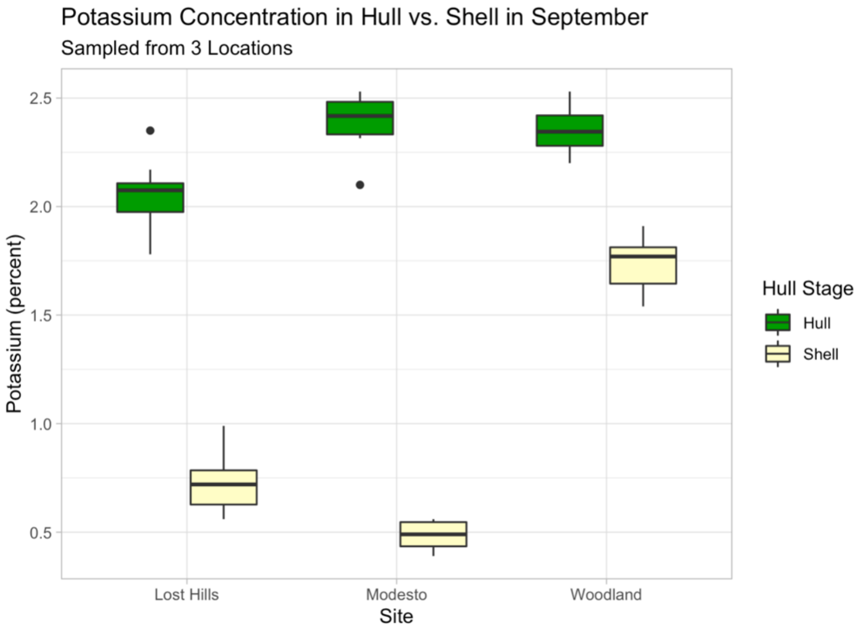


Supplementary Figure 5.3. Comparison of almond hull/shell mix K concentration across four sites over two years, June-August, from four separate orchards.



Supplementary Figure 5.4. Potassium concentrations in hull/shell mix materials from four different orchard locations across time. Data is from Saa unpublished data used with permission.

Comparing hull vs. shell K accumulation in the month of September only between Lost Hills, Modesto, and Woodland, hull concentrations were somewhat similar whereas shell K concentration was substantially higher at Westwind (Supplementary Figure 5.5). This suggests that the specific orchard site impacts on shell K accumulation. While most almond growers in the California Central Valley apply K fertilizer once annually in the fall as banded $K_2SO_4$, the Westwind orchard received K fertilizer applications during the season, which might explain elevated shell levels, though further research is needed. Variation in hull and shell K concentrations may be influenced by soil type, irrigation approach, and other site-specific factors.



Supplementary Figure 5.5. Potassium concentrations in hull vs. shell materials from three different orchard locations. Lost Hills and Modesto data was collected in 2008 by Saa et al., unpublished data (used with permission). Woodland data is from the Westwind site, 2021, control trees only.

While the degree of positive and negative correlations between fruit nutrients varied somewhat across sites, overall trends across all sites showed that K was most consistently positively correlated with boron as well as slightly positively correlated with copper, zinc, and phosphorus at some sites (data not shown). Fruit K concentration was more consistently negatively correlated with Mg at all sites particularly during full dehiscence.

By examining unpublished data from Saa et al. and fruit tissue analyses from Westwind site, results indicate that K concentrations in almond hulls and shells tend to increase from June only incrementally through late September, although there may be some site-specific variability between fields. This suggests that harvest timing likely does not substantially influence hull and shell K concentrations, with only slightly higher K concentration typically occurring at later harvest times. Understanding nutrient dynamics in fruit tissues will be useful for growers who use or are considering using in-field hulling with the intention of retaining hulls as organic matter amendments on the orchard soil surface. Annual nutrient analysis of hull/shell materials used as amendments can enable growers to estimate K recycling at a given orchard.

References

Muhammad, S., Sanden, B., Lampinen, B., Saa, S., Siddiqui, M., Smart, D., Olivos-Del Rio, A., Shackel, K., Dejong, T., & Brown, P. (2015). Seasonal changes in nutrient content and concentrations in a mature deciduous tree species: Studies in almond (*Prunus dulcis* (Mill.) D. A. Webb). European Journal of Agronomy, 65.

Muhammad, S., Sanden, B. L., Lampinen, B. D., Smart, D. R., Saa, S., Shackel, K. A., & Brown, P. H. (2020). Nutrient Storage in the Perennial Organs of Deciduous Trees and Remobilization in Spring – A Study in Almond (*Prunus dulcis*) (Mill.) D. A. Webb. Frontiers in Plant Science, 11, 658.

Saa, S., Brown, P.H., Muhammad, S., Olivos-Del Rio, A., Sanden, B.L. and E.A. Laca. (2014). Prediction of leaf nitrogen from early season samples and development of field sampling protocols for nitrogen management in Almond (*Prunus dulcis* [Mill.] DA Webb). Plant Soil 380:153-163.