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Early Almond Harvest as a Sustainable Pest Management Strategy

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# Early Almond Harvest as a Sustainable Pest Management Strategy

By

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# Abstract

This thesis explores the use of hull split regulated deficit irrigation in combination with early harvest of almonds (*Prunus dulcis* (Mill.) D. A. Webb) for improved irrigation efficiency and control of navel orangeworm (NOW) (*Amyelois transitella* (Walker)) and Hull Rot (HR) (*Rhizopus stolonifer* (Ehrenb:Fr.) Vuill.; *Monilinia fructicola* (G. Wint.) Honey). Chapter 1 contains a review of the literature regarding California almond production, almond phenology, almond water status monitoring, and NOW and HR phenology and control. Chapter 2 describes research carried out during the 2020 growing season to test the efficacy of early almond harvest for NOW and HR control and water use efficiency. Standard Harvest (SH) and Early Harvest (EH) treatments were applied to trees in two almond orchards in Denair and Woodland, California using a randomized controlled block design; EH treatments were harvested three to four weeks prior to SH. Midday Stem Water Potential (SWP) measurements were used to monitor tree water status and manipulate irrigation to prepare trees for EH treatments. Trees were maintained at -14 to -18 bars SWP for the two to three weeks leading up to both EH and SH. There were significantly lower HR strikes in EH treatment trees than in SH treatment trees. No significant difference was observed in NOW incidence between treatments, although neither site had a history of high NOW pressure. No significant kernel yield, marketable yield, or shaker efficacy differences were seen between the two treatments. Although 3.28 and 1.61 inches of water less was applied to EH trees than SH trees at the Denair and Woodland sites respectively, the trees from both treatment groups at both sites returned to approximately the same water status after Standard Harvest and mostly recovered from the induced moderate water stress by October 12. With further development of complementary harvest and processing strategies, early harvest of almonds shows promise as a strategy for pest and disease control and improved water use efficiency in almond orchards.

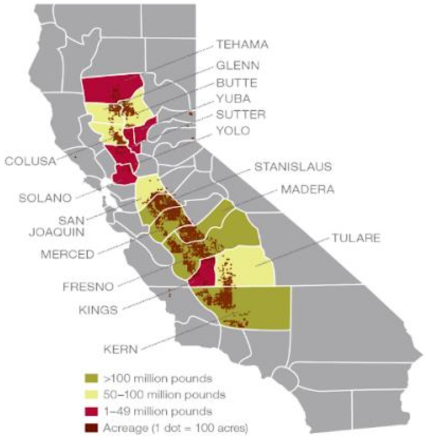
# Chapter 1: Literature Review

## Introduction to California Almond Production

Almonds (*Prunus dulcis* (Mill.) D. A. Webb*)* are the second most economically important agricultural commodity in California (Sumner et al., n.d.). Their production has increased rapidly in the last 20 years, with the number of acres under almond production more than doubling, and per-acre yields increasing dramatically in the state. Currently, almond production accounts for 1,530,000 acres of agricultural land in California (USDA/NASS, 2020), with the bulk of almond production located in California's Central Valley (Almond Board of California, 2016). Figure 1.1 indicates the distribution of almond production throughout the state.

**Figure 1.1**

*Map of California Almond Production*



*Note.* The majority of California almond production occurs in the state's Central Valley, with the highest production volumes in Kern, Fresno, Madera, Merced, and Stanislaus counties (Almond Board of California, 2016)

As almond farming continues to grow in California, producers are faced with a variety of sustainability challenges. The Almond Board of California (ABC)[1] has responded to these challenges by developing the California Almond Sustainability Program (CASP) and defining strategic sustainability goals known as the Almond Orchard 2025 Goals (Almond Board of California, 2019). These goals center around water efficiency, zero waste, pest management, and air quality (Almond Board of California, 2019). This document will focus on two of these goals: to 'reduce the amount of water used to grow a pound of almonds by 20%' and to 'increase adoption of environmentally friendly pest management tools by 25%' (Almond Board

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[1] The Almond Board of California is the almond commodity board in the state of California. They partner with research institutions, promote the adoption of best production practices, and are responsible for the marketing of California Almonds (Almond Board of California, 2020).

of California, 2019).

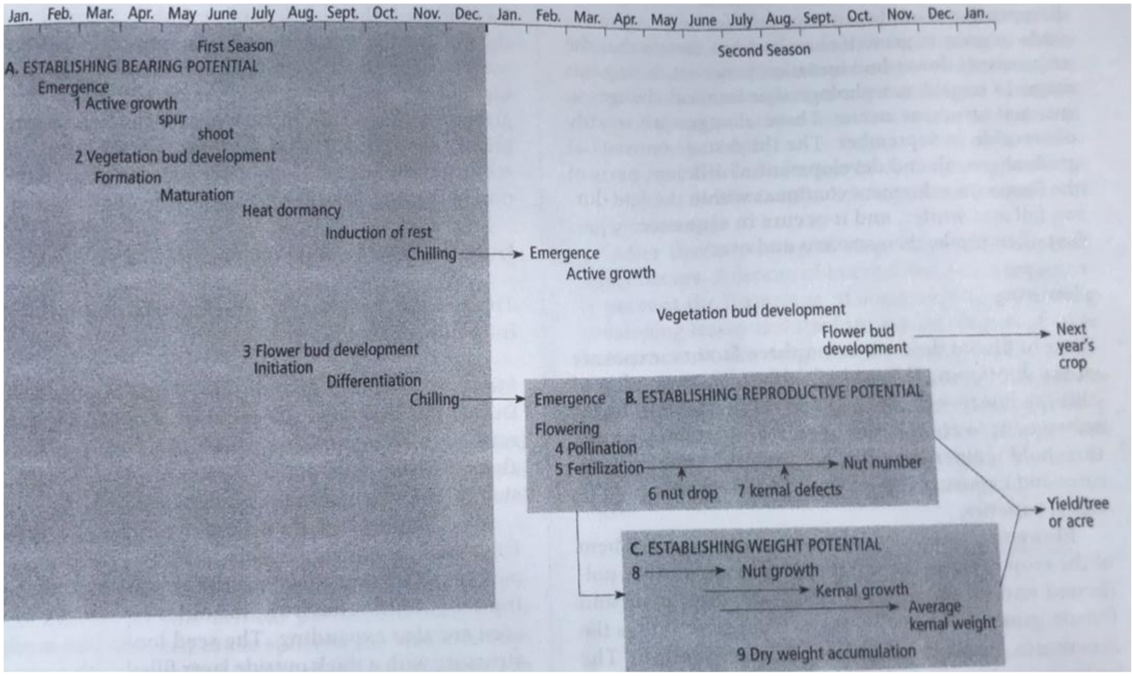
## California Almond Growth and Development

Around 30 different varieties of almonds are grown in California (Sideli et al., 2020). Nonpareil almonds, a mid-blooming, early harvest almond variety with a relatively large national and international market, account for the plurality (about 40%) of almond production (Sideli et al., 2020). Because of the economic importance of the Nonpareil variety, the research described in this document focuses on the production of Nonpareil almonds.

With the exception of self-fertile cultivars, almonds must be cross-pollinated to ensure good fruit set (Thorp, 1996). Thus other almond varieties are grown in orchards alongside Nonpareil almonds, serving as pollinizers for Nonpareil almonds in addition to meeting their own market niches (Sideli et al., 2020). Slight differences exist in the timing of almond developmental stages depending on plant variety, weather, and location. The following section outlines the general annual timeline from almond vegetative and reproductive growth. Figure 1.2 provides a visual representation of these growth stages.

**Figure 1.2**

*Almond Growth and Development*



*Note.* The 2- year cycle begins with the initiation of new shoots from a but in the spring and ends with the final harvest of the crop two years later. The model shows that the second year of the cycle overlaps with the first year of the next 2-year sequence.
Bearing potential. The bearing potential is determined by vegetative growth, which occurs during the first part of the year. Active growth (1) from terminal and lateral buds produces new buds in leaf axils of spurs and shoots. Lateral vegetative buds (2) on spurs and some shoots initiate flower primordia. After initiation (3), flower buds differentiate flower structures. After chilling, buds gradually respond to warm temperatures and eventually emerge for blooming
Reproductive potential. The reproductive potential is established by the number of nuts that are produced as a result of pollination and fertilization. Cross-pollination (4) establishes the upper limit of flower set. The proportion of pollinated flowers that also become fertilized (5) determines the actual number of nuts. Nut drop (6) decreases the number of nuts that can be harvested and establishes the final crop load. Defects of the kernel (7) decrease the number of nuts that are marketable.
Weight potential. The weight potential established the final crop tonnage and is determined by the total number of nuts marketed and the average kernel weight. Maximum nut size (8) is determined during the early growth of the fruit. Dry weight (9) of the kernel results from translocation of photosynthates from the leaves, which are stored as fats, proteins, and carbohydrates during the last half of nut development
The number of nuts multiplied by the average kernel weight determines yield.
Image and text from Kester et al. (1996).

The almond life cycle begins with a dormancy period that begins in October and lasts until the plants' chill requirement is met, which usually occurs between November and January (Kester et al., 1996). Nonpareil almonds meet their chilling requirements in November, and are in an 'paradormancy' period until mid-December. Active tree growth occurs in the spring. During this period, vegetative shoots and spurs lengthen and the trunk expands, causing an increase in tree volume. Shoots make up the majority of the structure of the tree canopy and give rise to future spurs. Spurs are shorter vegetative growth components that arise from shoots or other spurs. They are responsible for the majority of almond yield in a given year (Kester et al., 1996), although they produce only vegetative growth for their first 1-2 years (Goldhamer et al., 2006).

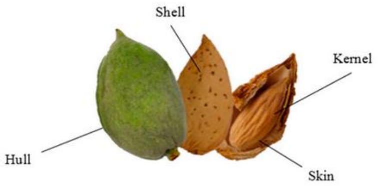
Bud break occurs in December or January. Vegetative buds expand in January and February, and grow into leaves through March and April (Kester et al., 1996). Vegetative shoot growth and spur elongation begin at bud break, with shoot growth continuing throughout the season and spur elongation terminating around April or May. From May to June, vegetative bud set for the following year occurs.

Bud differentiation begins in May for the following year's crop and continues throughout the summer (Kester et al., 1996). Flower bud induction occurs in mid-August in California almonds (Kester et al., 1996). The ratio of reproductive to vegetative bud expression is a function stress during the differentiation or induction period (Goldhamer & Viveros, 2000; Esparza et al., 2001). After induction, flower buds continue to develop and undergo anatomical changes from September through November. After reproductive bud break in late winter or early spring, blooms develop, and pollination occurs from late February through early March. During this time, bees are brought into orchards to facilitate pollination and ensure adequate fruit set (Kester et al., 1996).

Almond fruits consist of a kernel (seed), shell (endocarp), and hull (mesocarp) (Godini, 1984). The almond kernel is the marketable component of the almond fruit, while the shell and hull serve protective and structural purposes. Fruits are attached to the almond tree by a peduncle. Figure 1.3 shows these different components.

**Figure 1.3**

*Almond Fruit Anatomy*



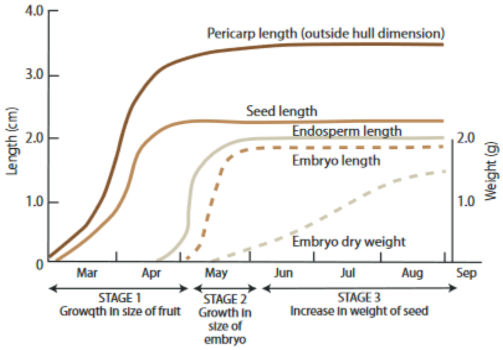
*Note.* The almond fruit is composed of the hull (mesocarp), shell (endocarp), skin (spermoderm), and kernel (seed) (Prgomet et al., 2017).

There are three stages of almond fruit growth, shown in Figure 1.4 (Kester et al., 1996).

Stage 1 of fruit growth begins in the spring after pollination. During this stage, the hull, shell, and integuments grow and pericarp and seed lengthen. Three waves of flower and fruit drop occur as the tree sheds unfertilized or otherwise damaged reproductive material (Kester et al, 1996). Stage 2 of fruit growth is a period of embryo growth and shell hardening. This period occurs in early summer and involves a rapid filling of the almond kernel. Adequate irrigation is required at this stage to meet the crop developmental demands (Doll & Shackel, 2015).

**Figure 1.4**

*Stages of almond fruit development*



*Note.* The first stage of almond fruit development involves a rapid lengthening of the hull, shell, and seed. In the second stage, the embryo strengthens rapidly. Finally, in the third stage the seed weight increases (Doll & Shackel, 2015)

Stage 3 of fruit development is the preharvest stage, which occurs during the one to two months leading up to harvest and involves maturation and ripening of the fruit. During this period, two indicators of harvest maturity develop: hull split and the formation of an abscission layer between the fruit and peduncle (Kester et al., 1996). In early July, almond hulls begin to split along their suture, a process known as *hull split* or dehiscence. Fruits lose moisture throughout July and August, with the hull split widening and the hull pulling away from the almond shell (Connell et al., 1996). As the fruits continue to dry, an abscission zone forms between the fruit and the peduncle, weakening the connection between the fruit and the tree, which is beneficial for harvest. Irrigation is important for hull split induction and abscission layer formation at this time, although moderate levels of water stress during this period do not negatively impact kernel weights (Shackel, 2011; Goldhamer & Viveros, 2000).

Almond harvest begins in mid-August and lasts through October, with different varieties reaching harvest maturity at different times. Harvest is typically conducted using mechanical shakers, which clamp on individual tree trunks and shake the trees (Reil et al., 1996). This causes the fruit to detach from the peduncle and fall to the ground. In some instances, almond crops are hand-harvested using poles and mallets to shake or knock the fruits off of individual tree branches (Reil et al., 1996). However, mechanical harvest is typically preferred due to the labor-intensive nature of hand harvesting.

Fallen fruits are swept into row middles and allowed to dry there between 4 and 14 days depending on moisture level at harvest and climatic conditions (Reil et al., 1996). They are then removed from the orchard using a mechanical pick-up machine, and taken off site for further processing.

## Almond Water Status Monitoring and Irrigation Management

The ABC has set the goal of '[reducing] the amount of water used to grow a pound of almonds by 20%' (Almond Board of California, 2019). To achieve this goal, changes must be made at agronomic, engineering, management, and institutional levels (Wallace and Batchelor, 1997). This discussion will focus on the use of management changes at the farm level to increase agricultural water productivity, or the amount of "crop per drop" of water applied in an orchard (Molden et al., 2010)

Improving water productivity requires the implementation of strategic irrigation management practices. One such practice is regulated deficit irrigation (RDI) (Wallace & Batchelor, 1997), which will be discussed in the Irrigation Management for Improved Water Use Efficiency portion of this review. To be able to implement such practices, growers must understand the water needs of their crop. Several methods for measuring this need based on soil, atmospheric, and plant water status are discussed below.

### *Soil Water Status*

The amount of water available in the soil for plant uptake and use is one of the driving factors of plant irrigation needs. Several methods can be used to monitor soil moisture in representative soil in an orchard system. Each monitoring method and the interpretation of their data outputs must be adapted to the specific system in which they are being used.

Soil moisture content is a measure of the amount of water present in the soil. It can be measured by gravimetric soil sampling (Black, 1965) as well as by the use of a neutron probe (Gear et al., 1977), dialectric soil moisture sensors (Hanson & Peters, 2000), or gypsum block (Schulbach & Schwankl, 1996). While these methods provide information about the absolute water content of the soil, they do not take into account other soil factors that may influence water availability in the soil. This combination of factors is better understood through soil-water potential measurements.

The soil-water potential is the driving force for water movement in the soil, and is therefore more closely correlated with plant irrigation needs than soil moisture measurements (Haise & Hagan, 1967). Soil water potential takes into account all of the factors that influence soil water availability, and is represented by (1)

$$\Psi_t=\Psi_g+\Psi_p+\Psi_o \tag{1}$$

where $\Psi_t$= the total soil-water potential, $\Psi_g$= the gravitational potential, $\Psi_p$ = the pressure potential or matric potential, and $\Psi_o$ = the osmotic potential (Hillel, 1998). Soil-water potential measurements are usually taken using tensiometers or gypsum blocks (Taylor, 1965; Schulbach & Schwankl, 1996).

### *Environmental Water Demand*

Although soil water status is an important indicator of irrigation needs, this measurement alone does not provide complete information about plant irrigation requirements. Because the soil is highly variable, incorrect placement of soil moisture meters can cause inaccurate measurements of soil water status. Additionally, atmospheric factors such vapor pressure deficit (VPD) play a large role in the level of plant water use and can provide indications regarding plant irrigation needs. The water balance irrigation scheduling calculates crop evapotranspiration ($ET_c$) as the amount of water lost to the atmosphere in an orchard (Howell & Meron, 2007). Once determined, $ET_c$ can be used to calculate the amount of water that needs to be applied to an orchard in order to meet the water needs of the almond trees (Howell & Meron, 2007). $ET_c$ is calculated using (2)

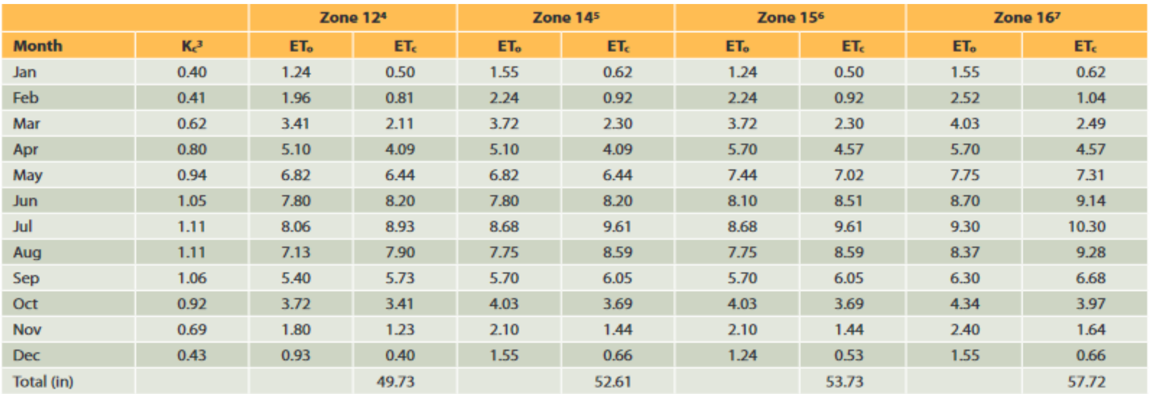
$$ET_c = ET_0 \; x \; K_c \qquad (2)$$

where $ET_c$ = crop evapotranspiration, $ET_0$ = reference evapotranspiration, and $K_c$ = crop coefficient. $ET_0$ is the amount of evapotranspiration that occurs from fully irrigated grass at a given point in time (Howell & Meron, 2007). $ET_0$ varies based on a number of environmental factors, and is thus measured and reported regularly for each production zone. $K_c$ is the crop coefficient factor used to adjust $ET_0$ for a specific crop. A crop’s $K_c$ is dependent on crop characteristics such as plant height and leaf area index (LAI) (Allen et al., 1998). $K_c$ can be determined using several methods including weighing lysimeter measurements (Espadafor et al., 2015), and the energy balance method (Stevens et al., 2012). Monthly almond $K_c$ values have been published for different almond-producing regions in California and are updated periodically as growing conditions change (Sanden et al., 2012). Sample almond orchard $K_c$,

$ET_0$, and $ET_c$ values for several almond production zones can be seen in Table 1.1.

**Table 1.1**

*Thirty-year average evapotranspiration rates for unstressed pasture ($ET_o$)[1] and almonds ($ET_c$)[2] in inches for several CIMIS zones within almond-producing areas of California*



| | | Zone 12[4] | | Zone 14[5] | | Zone 15[6] | | Zone 16[7] | |
|---|---|---|---|---|---|---|---|---|---|
| **Month** | **$K_c$[3]** | **$ET_o$** | **$ET_c$** | **$ET_o$** | **$ET_c$** | **$ET_o$** | **$ET_c$** | **$ET_o$** | **$ET_c$** |
| Jan | 0.40 | 1.24 | 0.50 | 1.55 | 0.62 | 1.24 | 0.50 | 1.55 | 0.62 |
| Feb | 0.41 | 1.96 | 0.81 | 2.24 | 0.92 | 2.24 | 0.92 | 2.52 | 1.04 |
| Mar | 0.62 | 3.41 | 2.11 | 3.72 | 2.30 | 3.72 | 2.30 | 4.03 | 2.49 |
| Apr | 0.80 | 5.10 | 4.09 | 5.10 | 4.09 | 5.70 | 4.57 | 5.70 | 4.57 |
| May | 0.94 | 6.82 | 6.44 | 6.82 | 6.44 | 7.44 | 7.02 | 7.75 | 7.31 |
| Jun | 1.05 | 7.80 | 8.20 | 7.80 | 8.20 | 8.10 | 8.51 | 8.70 | 9.14 |
| Jul | 1.11 | 8.06 | 8.93 | 8.68 | 9.61 | 8.68 | 9.61 | 9.30 | 10.30 |
| Aug | 1.11 | 7.13 | 7.90 | 7.75 | 8.59 | 7.75 | 8.59 | 8.37 | 9.28 |
| Sep | 1.06 | 5.40 | 5.73 | 5.70 | 6.05 | 5.70 | 6.05 | 6.30 | 6.68 |
| Oct | 0.92 | 3.72 | 3.41 | 4.03 | 3.69 | 4.03 | 3.69 | 4.34 | 3.97 |
| Nov | 0.69 | 1.80 | 1.23 | 2.10 | 1.44 | 2.10 | 1.44 | 2.40 | 1.64 |
| Dec | 0.43 | 0.93 | 0.40 | 1.55 | 0.66 | 1.24 | 0.53 | 1.55 | 0.66 |
| Total (in) | | | 49.73 | | 52.61 | | 53.73 | | 57.72 |

*Note.* Table and text are from Doll & Shackel (2015).

[1] Normal year evapotranspiration of unstressed grass (reference crop, $ET_0$) 30-year CIMIS average for the respective zone. See cimis.water.ca.gov/App_Themes/images/etozonemap.jpg.

[2] Evapotranspiration rates for almonds were calculated by multiplying $ET_0$ by the crop coefficient ($K_c$)

[3] Referenced crop coefficient ($K_c$) (unpublished data)

[4] Zone 12 $ET_0$ rates from Chico, Fresno, Madera, Merced, Modesto, and Visalia

[5] Zone 14 $ET_0$ rates from Newman, Red Bluff and Woodland

[6] Zone 15 $ET_0$ rates from Bakersfield and Los Banos

[7] Zone 16 $ET_0$ rates from Coalinga and Hanford

### *Plant Water Status*

While the water balance calculations described above can be a helpful and relatively easy tool for almond irrigation scheduling, plant-based water status monitoring can provide more accurate information about the water status, and thus irrigation needs, of almond trees. This is because plant water status measurements are more sensitive to the combination of atmospheric, soil, and plant conditions at work in a particular orchard (Peretz et al., 1984; Shackel, 2011). Several methods have been developed to measure plant water status. The following discussion will focus on midday Stem Water Potential (SWP). Additional methods including other plant water potential measurements as well as trunk-diameter variation (TDV) will also be discussed briefly.

### Midday Stem Water Potential.

Plant water status is a function of the integrated effects of soil, air, and plant factors known as the Soil-Plant-Air Continuum (SPAC). SWP measurements are one of several methods used to measure plant water status. Many studies have demonstrated that midday SWP is the most accurate measurement available to indicate plant water status, and therefore irrigation needs, based on plant water stress levels caused by water dynamics in the SPAC (e.g. Fereres & Goldhamer, 2003; Shackle, 2011; Garnier & Berger, 1985; McCutchan & Shackel, 1992).

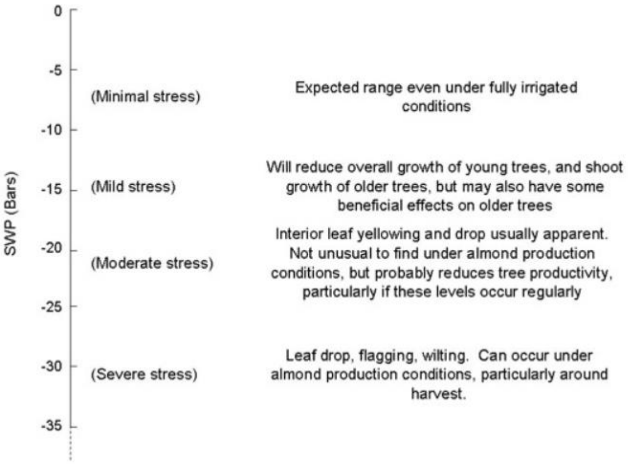
Stem Water Potential (SWP) measurements are conducted using non-transpiring leaves attached to the trunk as a proxy for the almond tree truck. The leaf is first covered with a metallic envelope for a minimum of 10 minutes (Shackel et al., 1997; Fulton et al, 2001). This effectively stops leaf transpiration, equilibrating the water status of the leaf to that of the tree trunk (Begg & Turner, 1970; McCutchan & Shackel, 1992). The leaf in the metal envelope is then cut from the tree, at which point negative hydrostatic pressure builds up in the xylem of the petiole of the removed leaf (Scholander et al., 1964). The excised leaf is then placed in a pressure chamber, and enough pressure is applied to release a small amount of water from the petiole. The amount of pressure applied is equal and opposite to the hydrostatic pressure in the plant xylem, and thus the water status of the plant (Scholander et al., 1964). SWP is measured in units of pressure such as bars or megapascals (MPa), with more negative units indicating a larger water deficit, higher water stress, and a higher amount of pressure required to express water from the leaf petiole.

A composite of SWP measurements of one leaf per tree from a minimum of 10 trees within an irrigation management unit must be taken to provide an accurate representation of the water status of the trees in an orchard (Fulton et al., 2001). SWP measurements can then be compared to a non-stressed baseline, calculated based on the VPDat the time the measurements are taken, to determine the level of water stress present in the plants (McCutchen & Shackel, 1992; Shackel, 1997; Goldhamer & Fereres 2001b).

Figure 1.5 identifies the level of water stress severity of different midday SWP measurements. Midday SWP measurements, taken between 13:00 and 15:00, are thought to be more accurate than those taken at other times of day because fluctuations in midday SWP most closely parallel fluctuations in water stress-inducing environmental factors such as VPD (Fulton et al., 2001; McCutchan & Shackel, 1992).

**Figure 1.5**

*Midday SWP Values in Almond*



*Note.* Midday SWP measurements are a good indicator of plant water status and irrigation needs. During hull split regulated deficit irrigation, almonds are maintained at a level of mild stress for several days (Fulton et al., n.d.).

### Other Plant Water Stress Measurements.

Leaf water potential (LWP) measurements are taken in a similar manner as SWP measurements with the omission of the covering of the leaf and its subsequent equilibration with the tree trunk. When taken at midday, LWP measurements tend to be highly variable based on localized environmental factors such as light exposure (McCutchan & Shackel, 1992).

Other variations of plant water stress measurements are practiced including the use of shaded rather than bagged or unshaded leaves (known as shaded leaf water potential measurements) (Goldhamer & Fereres, 2001b) as well as variations in the timing of measurements (Fulton et al., 2001). Various studies indicate correlations between these measurements as well with stomatal conductance and other indicators of plant water stress (e.g. Williams, 2012 and references therein).

### Trunk Diameter Variations (TDV).

While midday SWP measurements and other measurements of plant water stress provide effective and accurate information about tree water status and irrigation needs, adoption of these methods for irrigation scheduling is not widespread among almond producers. The time-consuming nature of the data collection process coupled with restrictions around the time of day that the data must be collected present obstacles for many producers (Fulton et al., 2001; Nortes et al., 2005). Thus, other, automated methods for plant water status monitoring and irrigation scheduling are being explored. One of these methods is based on measuring variations in tree trunk diameters in response to plant water use and water status, and correlating these numbers with plant water status measurements from stem water potential measurements (Li et al. 1989; Link et al. 1998).

Trunk diameter variations (TDV) are measured using Lineal Variable Displacement Transducers (LVDT), which are affixed to the trees where the plant water status is being measured. LVDTs record measurements of tree trunk diameter at regular intervals throughout the day. Two stress indicators commonly extrapolated from these measurements are: maximum daily shrinkage (MDS), or the difference in tree diameter between the minimum and maximum diameters of a tree in one day, and trunk growth rate (TGR), or the difference between daily maximum trunk diameters (Nortes et al., 2005).

There are conflicting study results about the correlation between TDV values and other measures of plant water status (e.g. Nortes et al., 2005; Moriana & Fereres, 2002; Goldhamer & Fereres, 2001a). However, preliminary research results indicate that both MDS and TGR are responsive to plant water stress levels and can therefore be useful indicators of plant irrigation needs (Fulton et al., 2014; Goldhamer & Fereres, 2004; Nortes et al., 2005). More research is needed on this subject to clarify correlations between measurements of TDV and plant irrigation needs (Goldhamer & Fereres, 2004).

### *Almond Irrigation*

The majority of California almonds are produced using micro sprinkler or drip irrigation systems (Almond Board of California, 2019). These systems provide higher WUE compared to other irrigation methods such as ditch-irrigation by strategically applying water specifically where it is needed in the orchard and reducing excessive water loss through evaporation from the field.

Almond trees are particularly sensitive to water stress during the early growing season when rapid vegetative and reproductive growth is occurring (Prichard et al., 1994; Goldhamer et al., 2006). However, mild to moderate water stress levels do not negatively affect fruit growth and development during the two months leading up to harvest (Shackel et al., 2011; Goldhamer & Viveros, 2000). Because almond bud differentiation for the next year's crop continues after harvest, postharvest irrigation must be returned quickly to the crop, and a level of irrigation must be maintained postharvest in order to ensure crop yields for the subsequent year (Goldhamer & Viveros, 2000).

#### **Irrigation Management for Improved Water Use Efficiency.**

With the knowledge of the amount of water loss or water stress in their almond system, and the developmental water needs of their crop, almond growers can make informed decisions about their irrigation schedules. Producers can choose to irrigate to replenish 100% of $ET_c$, or follow a deficit irrigation (DI) schedule. An DI schedule is one in which irrigation is applied at less than full $ET_c$ for all or specific period of the growing season. Research indicates that DI schedules, when used correctly, increase water productivity WUE in almond orchards (Goldhamer et al., 2006). CASP promotes DI techniques to further the ABC's sustainability goals (Schwankl et al., n.d.).

In almond there are two main DI models: hull split Regulated Deficit Irrigation (RDI) and proportional deficit irrigation, although some producers choose to follow different variations (Doll & Shackel, 2015). Producers practicing proportional deficit irrigation apply the same fixed proportion of $ET_c$ throughout the entire growing season. This strategy is useful when the producer does not have access to regular SWP measurements or in times of severe water shortages (Goldhamer et al., 2006).

In the hull split RDI model, full levels of irrigation are applied to the trees until kernel fill and 90% hull split have been achieved. At this point, SWP measurements are used to monitor plant water status and reduce the volume of water applied to their orchards to achieve a SWP of -14 to -18 bars (Doll & Shackel, 2015). This mild level of water stress is maintained until harvest (Doll & Shackel, 2015). In addition to annual orchard reducing water use by up to 15% without significant yield damages (Stewart et al, 2001), this period of drying prior to harvest has several other benefits. Using the hull split RDI model helps to increase orchard longevity by reducing the time and force required to shake almond trees at harvest (Naor, 2006; Connell et al., 1996). It also contributes to reductions in hull rot (Teviotdale et al., 2001), which will be discussed in more detail later in this review.

## Pests and Diseases

Navel Orange Worm (NOW) (*Amyelois transitella* (Walker)) and hull rot (HR) (primarily caused by the fungal pathogens *Rhizopus stolonifer* (Ehrenb:Fr.) Vuill. and *Monilinia fructicola* (G. Wint.) Honey) are two of the most economically significant almond pests and diseases in the state. Annually, almond farmers pay an average of $131 and $217 per acre to control NOW and HR respectively (Duncan et al., 2019). This section will discuss the damage caused by these two pathogens, describe current control measures in more detail, and explore opportunities for the use of early almond harvest as part of an integrated strategy to control these pathogens.

### *Navel Orange Worm*

#### Navel Orange Worm Damage.

NOW damage rates as high as 30% have been observed in some almond orchards in California (Higbee & Sigler, 2009). Damage comes directly from NOW insects as well as through secondary fruit infection from the *Apsergillus* spp. fungus.

NOW larvae move through cracks in the almond shells (Soderstrom, 1977), and cause varying degrees of damage to almond kernels by rasping the surface and boring into the nutmeat (Wade, 1961). Additional almond kernel quality damage from NOW comes from the deposition of frass as well as webbing (Wade, 1961). This damage reduces the marketability of the kernels, causing significant negative economic impacts for almond producers (Campbell, 2003; Phillips et al. 1980). Examples of varying degrees of NOW damage can be seen in Figure 1.6.

**Figure 1.6**

*NOW Damage Severity Ratings*

**NOW #1** **NOW #2** **NOW #3**

*Note.* NOW damage ranges from mild (NOW #1) to severe (NOW #3), but all NOW damage lowers nut quality

In addition to physical damage, NOW infestations are also associated with infection from the fungus *Aspergillus* spp. (Schatzki and Ong 2001). This fungus causes aflatoxin contamination in the almond kernel, which is carcinogenic in humans (Aguilar et al., 1993; Fujimoto et al., 1994; Hosono et al., 1993). Due to low *Aspergillus* thresholds for almond sales, annual economic damage from aflatoxin contamination is as high as $47 million in the US (Robens & Cardwell 2003).

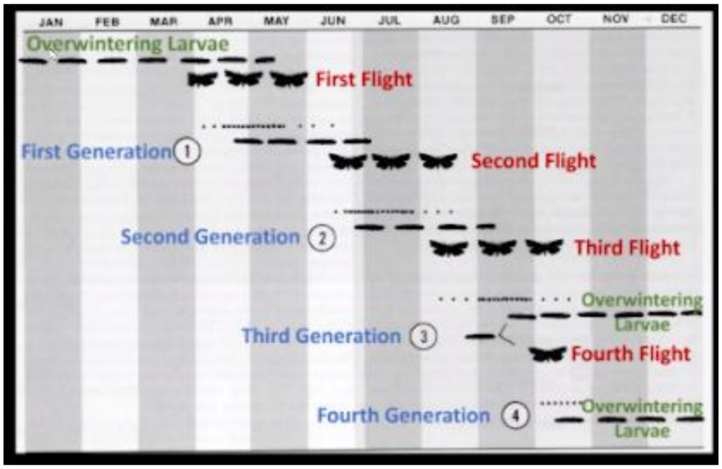
### Navel Orange Worm Life Cycle.

There are typically three to four flights or generations of NOW in one year depending on climatic conditions (Wilson et al., 2020). Oviposition for the first flight occurs in almond orchards as early as March or April on fruits left on the tree from the previous year's crop (Wade, 1961). Research from Curtis and Barnes (1977) indicates that eggs from the second NOW flight, which are oviposited close to the beginning of hull split, give rise to the highest rates of almond kernel infestation and subsequent damage. The longer NOW larvae are permitted to feed on almond kernels at hull split, the higher the level of damage done to the almond crop (Wilson et al., 2020).

At oviposition, 50% of NOW eggs are laid inside of the hull suture, while the rest are deposited on the almond hull (Curtis & Barnes, 1977). 1st instar larvae emerge 3-24 days later (Haviland et al., 2019), and then molt through a total of approximately 6 instar stages before pupating (Wade, 1961). Prior to pupation, NOW larvae in almond orchards preferentially feed on kernels (Curtis & Barnes, 1977), though they can also survive on hulls and shells (Wade, 1961). NOW pupae form their cocoons directly in almond fruits (Wade, 1961) or between the hulls and shells (Haviland et al., 2019). Moths emerge from their cocoons 42-45 days after oviposition (Curtis & Barnes, 1977), and the cycle begins again. Figure 1.7 illustrates the annual NOW growing cycle.

**Figure 1.7**

*NOW Seasonal Phenology*



*Note.* The third flight typically coincides with almond hull split, and is therefore the most economically damaging to crop yields (Strand & Ohlendorf, 2002; Wilson, 2021)

### Strategies for NOW Management in Orchards.

### ***Varietal Selection.***

Two factors that influence almond varietal susceptibility to NOW are shell softness and shell seal strength. Soft-shelled almonds are more susceptible to damage from NOW pests (Crane & Summers, 1971). Almond varieties with higher quality seals tend to have lower NOW infestation rates (Kester & Asay, 1975). Thus, these two factors are important pest resistance considerations during varietal selection. Nonpareil variety almonds are considered soft-shell almonds (Soderstrom, 1977), and have moderate to low shell seal strength (Soderstrom, 1977; Hamby et al., 2011).

### ***Insecticide Application.***

In conventionally managed orchards, it is standard for pesticides to be applied one to three times per growing season to control for NOW (Haviland et al., 2019). The most effective time to apply NOW insecticides is at or just before 1% hull split in almond orchards (Zalom & Nicola, 2014). A second application can be applied two to three weeks later (Zalom & Nicola, 2014). Insecticides are also applied in some orchards in the spring after oviposition from NOW that overwintered in the orchard (Bentley et al., 1987; Zalom et al., 2001), as well as postharvest in cases where the third NOW generation was severe (Zalom & Nicola, 2014). A list of insecticides used for these purposes can be found at https://www2.ipm.ucanr.edu/agriculture/almond/Navel-Orangeworm/.

While insecticide applications can be an important part of an integrated pest management strategy in almond orchards, they are not a stand-alone solution to the challenge of NOW control. Because NOW females frequently lay their eggs inside of the hull split suture or between the almond hull and kernel, it is challenging to completely cover and therefore eliminate NOW eggs with insecticide applications (Michelbacher & Davis, 1961).

### ***Biocontrol.***

Some biological control methods have been identified for NOW control. The California native parasitic wasps *Perisierola breviceps* (Krombein, 1954), *Mesostanus gracilis* Cr. (Wade, 1961), and *Microbracon hebetor* (Say) (Ortega, 1950) have been observed predating on NOW. However, these species do not adequately control orchard NOW levels on their own (Wilson, 2020). As a result, other imported species such as *Copidosoma (=Pentalitomastix) plethorica* (Caltagirone et al. 1964, Caltagirone 1966) and *Gonoizus legneri* (Gordh & Hawkins 1981; Gordh, 1982) are now released in some almond orchards for NOW biocontrol in almond orchards. While biocontrol can be part of an integrated pest management strategy, it is not sufficient on its own to control NOW in most orchards, and must be combined with other management strategies (Legner and Warkentin 1988, Legner and Gordh 1992).

### ***Orchard Sanitation.***

S*tick-tights*, or fruits that remain on the almond tree after harvest, facilitate the overwintering of NOW larvae and pupae in orchards (Wade, 1961). For this reason, orchard sanitation prior to the emergence of the first NOW flight in March is one of the primary means of integrated NOW management in almond orchards (Haviland et al., 2019). This process involves completing an additional pass through the orchard after standard almond harvest and shaking all trees to reduce the average number of fruits per tree to an average of 2 or less. Removed stick-tights should be destroyed to prevent reinfestation (Wade, 1961; Haviland et al., 2020).

### ***Early Harvest.***

Because the most economically significant NOW infestation occurs during almond hull split, early almond harvest is recommended as a strategy for reducing NOW incidence in almond orchards (Wade, 1961; Michelbacher & Davis, 1961; Connell et al., 1989). Curtis et al. (1984) showed that removing almonds from the tree in a timely fashion reduces the level of crop damage from NOW and contributes to breaking the infestation cycle of NOW within an orchard.

Similarly, research conducted by Connell et al. (1989) indicated that harvesting almonds up to three weeks earlier than standard harvest greatly reduced orchard NOW populations.

## *Hull Rot*

### **Hull Rot Damage.**

Hull rot is primarily caused by the fungal pathogens *Rhizopus stolonifer* and *Monilinia fructicola* (Teviotdale et al., 1994). These fungal pathogens colonize almond fruits at hull split, sporulating between the hull and shell and on the outer and inner hull surfaces respectively (Teviotdale et al., 1994). Upon infection, gray and brown lesions form on the outside of the almond hull (Ogawa & English, 1991). HR causal agents produce toxins that are transported into tree shoots and spurs adjacent to the colonized fruits (Mirocha et al., 1961). These toxins cause necrosis and death in the shoots and spurs that they reach, ultimately leading to branch dieback and a reduction in future tree yields (Teviotdale et al., 1996; Teviotdale et al., 1994).

### **Infection Factors and Control Strategies.**

Several management factors can be utilized to control HR in almond orchards. While a few fungicides show some promising results for HR control (Adaskaveg, 2011), the majority of the control methods available for HR control are cultural. Varietal selection is one. All almond varieties have some level of susceptibility to HR, and Nonpareil variety almonds are particularly susceptible (Ogawa & English, 1991). Other cultural control methods include irrigation, nitrogen management, and harvest timing, which will be discussed in more detail below.

#### ***Hull Split.***

Because HR causal agents colonize almonds at hull split, hull split period and stage are major factors in level of HR incidence in almond orchards (Ogawa, 1980; Adaskaveg, 2009). The term *hull split period* refers to the duration of time of hull split, while *hull split stage* indicates the level of dehiscence of the almond hull. The stages of almond hull split are correlated with the size (diameter) of the hull split itself. Although different researchers use slightly different systems to categorize hull split stages, the following general categories from Teviotdale et al. (1994) can be applied: *small* hull split indicates a hull split diameter of 0.04-0.20 inches, *medium* hull split sizes range from 0.20-0.50 inches, and *large* hull splits are greater than 0.50 inches.

Research conducted by Ogawa (1980) showed a positive correlation between the length of hull split period and the level of wood die back in infected trees. Further research from Teviotdale et al. (1995, 2001) as well as Adaskaveg (2009) indicates that longer periods at small and medium hull split stages is much more strongly correlated with severe HR damage to almond trees than are longer periods of large hull split. Because toxins caused by HR spread from the fruit to the spurs and shoots through peduncles, this correlation is likely due to the level of attachment of the peduncle to the almond tree at varying hull split stages (Teviotdale et al., 1994). Almonds in the small and medium stages of hull split have higher levels of attachment to the tree than do those at the large stage (Teviotdale et al., 1994). Thus, almond fruits that stay at small or medium levels of hull split for longer may increase HR severity in almond trees (Teviotdale et al., 1994).

Duration of hull split stage changes based on factors such as air temperature (Teviotdale et al., 2001), irrigation, and plant nutrition (Martin & Kester, 1978). Higher air temperatures during hull split tend to hasten fruit maturity, decreasing the hull split period before harvest and subsequently the severity of HR damage in almond orchards (Teviotdale et al., 2001). However, little can be done from a management standpoint to alter orchard air temperatures, and so this is not considered a reliable control method for HR.

### ***Irrigation.***

Both irrigation volume and timing are significant for controlling HR in almond orchards.

Orchards with high or unlimited water supplies are susceptible to HR outbreaks (Teviotdale et al., 2001; Saa et al., 2016). HR incidence tends to spike with preharvest irrigation (Teviotdale et al., 1994). Research from Teviotdale et al. (1994) showed that cutting off irrigation between 2 and 8 weeks prior to harvest led to decreased levels of HR compared to trees that received one or two irrigations in the two weeks leading up to harvest. The results of a study by Goldhamer et al. (2006) showed that mild to moderate levels of preharvest stress accelerate hull split. This being the case, hull split RDI can be used as a method for HR control by limiting the period of small and medium hull split stages. In a study conducted by Shackel (2003), hull split RDI reduced HR strikes on trial plots in several almond producing counties in California. Research from Teviotdale et al. (2001) indicates that hull split RDI is more effective at controlling HR than proportional deficit irrigation is, with RDI during early hull split significantly reducing leaf and fruiting wood dieback.

#### ***Nitrogen.***

Orchards with high nitrogen (N) applications tend to experience higher HR incidence (Saa et al., 2016; Ogawa & English, 1991). One of the reasons for this is that high rates of N applications increase the amount of time to harvest maturity in almonds, lengthening the time that hulls are at small and medium split stages and increasing the opportunity for HR-associated damage to occur (Teviotdale et al., 1994). Additionally, plants allocate N differently depending on their level of N availability. Those with access to high levels of N tend to use it for the development of new growth rather than the production of structural components such as lignin and plant cuticles (Herms & Mattson 1992; Daane et al., 1995) or secondary metabolites that would be useful in fighting disease.

#### ***Early Harvest.***

Because hull split period is positively correlated with HR damage, removal of hull split almonds from the tree as early as possible is promising as a method for controlling HR in almonds. Preliminary research from Ogawa (1980) showed a 33.8% reduction in HR by shifting harvest 10 days early. The combination of hull split RDI and early harvest may be particularly effective at controlling hull split in almond orchards as it would both shorten hull split period and remove hull split almonds from trees as early as possible to reduce the window of opportunity for the spread of the toxin from the fruit to surrounding spurs and shoots.

## Conclusion

Early harvest of almonds coupled with hull split RDI has positive implications for water use efficiency, navel orangeworm control, and hull rot management. Although research in all three of these areas has indicated positive outcomes for several decades, farmer adoption of early harvest is slow. Two major concerns are likely responsible for the slow uptake of this management strategy: implications for fruit quality and yield and impacts on orchard health and longevity. Limited research in these areas shows contrasting results, some of which are outlined below. Differences in the RDI regimes applied across different studies, particularly the time to return water to the orchard postharvest make it challenging to compare the results of experiments looking at RDI, yield outcomes, and orchard health.

Different studies have shown varying impacts of RDI on almond fruit quality and yield. Teviotdale et al. (2001) observed a reduction in fruit kernel weight with the implementation of hull split RDI, though no difference in total fruit load was recorded. Goldhamer and Viveros (2000) observed similar outcomes with the majority of the hull split RDI treatments that they tested. Goldhamer and Smith (1995) observed reduction in total fruit load in proportional deficit irrigation treatments, but no negative yield outcomes in hull split RDI treatments. Contrastingly, work by Torrecillas et al. (1989), Shackel (2002, 2003), and Micke et al. (1966) indicated no significant impacts to almond yield as a result of RDI scheduling.

The impacts of RDI schedules on long term orchard health and future yields are also unclear. Almond trees that have a high moisture content at harvest are more likely to incur damage from the mechanical shaking process than those that have undergone a period of drying before harvest (Fridley et al., 1970). This can affect the health and longevity of the damaged trees. Research conducted by Esparza et al. (2001) indicated that water stress at harvest has implications for future yields. In their study, yield declines were observed two years after hull split RDI regimes were initiated. The results of their study also indicated a negative correlation between multi-year hull split RDI and shoot and stem growth. However, many of the RDI schedules they tested also involved a period of postharvest water stress, which may have contributed to these negative long term effects (Goldhamer & Viveros, 2000).

The degree of water stress imposed at RDI as well postharvest irrigation levels are often determinants of the impacts of irrigation scheduling on primary yield components and long-term orchard productivity (Goldhamer, 2006). Because of this variability, researchers (eg. Ogawa, 1980, Teviotdale et al., 2001, and others) have called for additional research into RDI management for early harvest of almonds and its potential outcomes for sustainable almond production. Chapter 2 of this document describes preliminary research that aims to address some of those questions.

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# Chapter 2: Early Almond Harvest as a Strategy for Sustainable Pest, Disease and Irrigation Management

## Introduction

Almonds (*Prunus dulcis* (Mill.) D. A. Webb*)* are the most economically important agricultural commodity in California (Sumner et al., n.d.). Their production has increased rapidly in the last 20 years, with the number of acres under almond production more than doubling, and per-acre yields increasing dramatically in the state. Currently, almond orchards occupy 1,530,000 acres of agricultural land in California (USDA/NASS, 2020), with the bulk of almond production located in California's Central Valley (ABC, 2016). As almond farming continues to grow in California, sustainable pest and disease control and water use efficiency are emerging as two increasingly critical management priorities. Both of these factors present major costs to growers in addition to having significant environmental implications.

The period of almond development known as hull split is significant for the infection and spread of both NOW and HR (Connell et al., 1996). Hull split occurs in the two months leading up to almond harvest, in July and August in most California almond orchards. In early July, almond hulls begin to open along their suture. Fruits lose moisture throughout July and August, with the hull split widening and the hull pulling away from the almond shell. Appendix 1 shows the different stages of hull split observed in almond production.

NOW eggs oviposited close to the beginning of hull split give rise to the highest rates of almond kernel infestation and subsequent larval damage (Curtis & Barnes, 1977). NOW larvae in almond orchards preferentially feed on almond kernels, causing damage to kernels by rasping the surface, boring into the nutmeat, and depositing frass and webbing in the fruits (Curtis & Barnes, 1977; Wade, 1961). Secondary infection from NOW association with the *Aspergillus* spp. fungus also causes aflatoxin contamination in the kernels, which is carcinogenic to humans (Schatzki & Ong, 2001; Aguilar et al., 1993). Current NOW control options in almond orchards include varietal selection, insecticide application, biocontrol, and orchard sanitation. Orchard sanitation involves completing an additional pass through the orchard after standard almond harvest and shaking all trees to remove stick-tights; this control method is particularly important, as stick-tights facilitate the overwintering of NOW larvae and pupae in orchards (Wade, 1961).

The HR causal agents *Rhizopus stolonifer* and *Monilinia fructicola* colonize almond fruits at hull split, sporulating between the hull and shell and on the outer and inner hull surfaces respectively (Teviotdale et al., 1994). HR causal agents produce toxins that are transported into tree shoots and spurs adjacent to the colonized fruits (Mirocha et al., 1961). These toxins cause necrosis and death in the shoots and spurs that they reach, ultimately leading to branch dieback, reduced return bloom, and a corresponding reduction in future yields (Teviotdale et al., 1996; Teviotdale et al., 1994). Level of HR damage is positively correlated with both hull split stage and hull split duration, with higher levels of HR damage occurring in earlier hull split stages and longer hull split durations (Ogawa, 1980; Adaskaveg, 2009).

The combined use of early harvest and hull split regulated deficit irrigation (RDI) is being considered as a strategy for controlling NOW and HR in almond orchards. Under hull split RDI, full levels of irrigation (at or just below crop evapotranspiration ($ET_c$)) are applied to the trees until 90% hull split has been achieved. At this point, irrigation is reduced to achieve a SWP of -14 to -18 bars, and this moderate level of water stress is maintained until harvest (Doll & Shackel, 2015). In addition to potentially improving orchard water use efficiency, the combination of early harvest and hull split regulated deficit irrigation management practices both shortens hull split period and removes hull split almonds from trees as early as possible, reducing the window of opportunity for the spread of HR toxins from the fruit to surrounding spurs and shoots (Teviotdale et al., 1994; Goldhamer et al., 2006; Ogawa, 1980). Early removal of almond fruits can also reduce the level of crop damage from NOW and contribute to breaking the infestation cycle of NOW within an orchard (Curtis et al., 1984; Connell et al., 1989).

The research described in this paper is a preliminary study designed to test the effects of harvesting three to four weeks prior to standard almond harvest on NOW and HR incidence and water use efficiency. The objectives of the study were to: a) manipulate almond stem water potential (SWP) to induce a differential stress response two weeks before harvest for trees harvested at Early and Standard timings b) understand the impacts of early almond harvest on navel orangeworm and hull rot incidence, c) determine whether there are significant yield impacts from early harvest in almonds, and d) understand the effects of early harvest on shaker efficacy. We hypothesize that early almond harvest would reduce NOW and HR incidence without negatively affecting yields, reducing shaker efficacy, or reducing almond trees' capacity to return to mild water stress levels after early dry down and harvest.

## Materials and Methods

### *Experiment Details*

The experiment was conducted in 2020 in two commercial almond orchards in California's Central Valley. The first orchard is in Denair, CA in Stanislaus County (37° 31' 38.7" N 120° 41' 57.1" W). The region has a hot-summer Mediterranean climate. The average summer temperature in 2020 was 75.3° F (24.1° C) and the total summer rainfall was 0 inches (0 mm) (CIMIS Station #206, 2020). Precipitation in this region usually occurs between the months of November and May. The soil at the Denair site is a mixture of Madera Sandy Loam (fine, smectitic, thermic Abruptic Durixeralf) with 0 to 2 percent slopes and a Rocklin Sandy Loam (fine-loamy, mixed, superactive, thermic Typic Durixeralf) with 3 to 8 percent slopes. The experiment was conducted on 12th leaf Nonpareil cultivar almond trees. Trees were spaced 15 feet apart within rows with 24 feet between rows at a planting density of 121 trees per acre;

rows of Nonpareil trees were planted in alternating rows with almond trees of the cultivars Carmel and Wood Colony. The Denair site is managed conventionally using standard management practices for California Almond Orchards (Duncan et al., 2019). Trees were irrigated using double-line drip irrigation. Past hull rot infections were believed to have occurred in this orchard because of observations of lower canopy dieback in the susceptible Nonpareil variety as compared to the other less susceptible varieties in the orchard (Carmel or Monterey), and the visual detection of staining in the vascular tissue, caused by fumaric acid, produced by the pathogen in the hull and transported to leaves and shoots. Prior to this study there was no history of major NOW incidence in the orchard.

The second site is a 6th leaf orchard located in Woodland, CA (38° 36’ 27.4” N 121° 43’ 45.2” W). Woodland is in Yolo County, which also has a hot-summer Mediterranean climate. The average summer temperature in 2020 in Yolo County was 74.1° F (23.4° C) and the total summer rainfall was 0 inches (0 mm) (CIMIS Station #6, 2020). Precipitation usually occurs between the months of November and April in Yolo County. The soil at the Woodland site is Rincon silty clay loam (fine, smectitic, thermic Mollic Haploxeralf). The experimental trees on the Woodland site were planted in 2015; the first commercial harvest on this site was conducted during this trial. The experimental trees were Nonpareil cultivar and were planted in alternating rows with trees of the Aldrich cultivar. Tree spacing at the Woodland site was 16 feet, and row spacing was 22 feet; planting density was 124 trees per acre. The Woodland site is managed according to organic certification standards and standard organic almond production practices for California Almond Orchards (Holtz et al., 2016). Trees were irrigated using double-line drip irrigation. Prior to this study there was no history of HR or NOW incidence in the orchard.

The experimental design at each site was a randomized complete block design with four blocks and two treatments. The treatments applied in this research were Standard Harvest (SH) and Early Harvest (EH), which occurred three to four weeks apart. Each treatment was applied to one plot per block. Three pseudo-replicate trees per plot (totaling 24 trees per site) were selected for data collection through the duration of the experiment.

### *Stem Water Potential, Irrigation, and Harvest*

Hull split RDI schedule was applied to EH treatment trees (Doll & Shackel, 2015) to achieve a SWP of -14 to -18 bars for several days to two weeks prior to harvest in order to maximize harvest efficiency and minimize damage to trees during shaking (Shackel et al., 2004). Between May and July weekly or biweekly midday stem water potential (SWP) measurements were taken on the designated data trees using a model 3005F01 pressure chamber (Soil Moisture Equipment Corp., Goleta, CA). SWP measurements were taken between 13:00-17:00 local time following standard methods described in Fulton et al. (2001). From May 18 to July 4 and 2 at the Denair and Woodland sites respectively, irrigation was applied in accordance with the grower's standard irrigation schedule. Irrigation sets occurred once per week for 5-6 days at the Denair site and twice per week for 2 days per set at the Woodland site; Figure 2.1 shows the irrigation schedule for each site. Initial SWP measurements were taken on the last day of each irrigation set, when trees were at maximum hydration, and on the day before the subsequent irrigation set was to start. These data sets were compared to the baseline SWP at each site, calculated using the relative humidity and temperature from local CIMIS sites. SWP data was analyzed to understand the drying patterns of the trees at the two different sites. This information was used to develop and execute irrigation schedules that facilitated 2-3 week pre-harvest dry down periods for EH treatments at the respective sites. The EH irrigation schedules required initially shutting the irrigation off completely to reduce the SWP to the -14 to -18 bar range, and then applying a lower volume of water relative to the SH trees to maintain EH SWP in the desired range (Figure 2.1). The growers' normal irrigation schedule was used for the SH treatments at each site. SWP measurements continued on a weekly to biweekly basis from July through October to monitor tree water status response to irrigation treatments before and after harvest. SWP measurements for the Woodland site are missing for several weeks in August and September due to fires in the area.

Harvest timing was determined based on the farmers’ historic and projected timing for Standard Harvest. The goal was to harvest EH trees three to four weeks prior to Standard Harvest. At the Denair site, EH was executed 22 days before SH, with EH occurring on July 24 and SH occurring on August 14. At the Woodland site, EH was executed 27 days before SH, with EH occurring on July 30 and SH occurring on August 26.

Harvest was conducted using a mechanical shaker at the Denair site. Each treatment tree was shaken individually, and harvest-related data was collected on each tree separately. SH trees were shaken for 3 seconds, while EH trees were shaken for 5 to 6 seconds to ensure that the majority of fruits were removed from the trees. At the Woodland site, each treatment tree was manually harvested due to a lack of available mechanized harvest equipment. Poles were used to remove the total yield from each treatment tree, allowing the fruits to fall onto tarps around the base of each tree. Harvest data was collected for each tree separately.

At the Denair site, water was returned to the trees immediately after harvest for both EH and SH trees. Due to the producer’s harvest schedule, water was returned to EH trees at the Woodland site 11 days after EH and immediately after SH. After EH, the same irrigation schedule was applied to both treatment groups at each site.

### *Yield and Fruit Characteristics*

All fruits (hull + shell + kernel) along with associated orchard trash was collected and weighed for each individual experimental tree to determine the field fresh weight. A representative subsample of almond fruits and trash was weighed in the field, and then dried offsite to 3% moisture. Trash percentages were calculated for each tree, and the corresponding trash amount was then subtracted from the field fresh weight to determine the fresh fruit weight.

All fruits in each subsample were dried to a uniform kernel moisture of 3% across treatments and sites and weighed to determine the dry fruit weight. Dry fruit weight was subtracted from the fresh fruit weight and divided by the fresh fruit weight for each representative subsample to determine the percent moisture. Percent moisture was multiplied by the total fruit fresh weight to determine the total fruit dry weight for each tree.

Upon drying, subsamples were hulled using a mechanical huller and shelled manually. Kernel yield weight was recorded for each subsample. Crackout percentages were calculated by dividing the kernel yield weight by the total fruit dry weight for each subsample. Crackout percentage for each subsample was multiplied by the total fruit dry weight to determine the kernel dry weight for each tree.

### *Hull Split*

Visual hull split ratings were conducted the day before EH and SH for both trial sites. Trees were divided into quadrants and 25 fruits per quadrant were inspected. Fruits at hull split stages b1-f were considered ‘split’ (Appendix 1). The percent of hull split present for each sample tree was reported as the percentage of fruits out of the 100 observed with split hulls.

### *Hull Rot Incidence*

At the Denair site, the incidence of natural HR infection was determined on July 23 and August 14 by counting the cluster number of dead leaves per data tree in the lower 3 meters of canopy. Typically, in each diseased cluster of leaves, an infected hull was observed that was sporulating with *Rhizopus stolonifer* spores and mycelium, which were easily identified in the field by their black color and characteristic growth between the shell and the hull. At the Woodland site, return bloom was rated by counting the number of blossoms per tree on March 1, 2021 on each data tree. All flowers from up to 8 feet within the canopy were counted. The counting duration for each tree was approximately 5-7 minutes.

### *Navel Orangeworm Incidence*

NOW incidence ratings were conducted for both trial sites. Subsamples of 333 or 334 fruits were collected at harvest from each data tree, totaling 1000 fruits per plot. These fruits were subsequently cracked open and visually inspected for NOW damage. The number of kernels with NOW damage was recorded for each treatment tree, and the percent NOW damage was calculated for each plot.

### *Shaker Efficacy*

Shaker efficacy was calculated for the Denair site but not the Woodland site, as the Woodland site was hand harvested. On October 19 all 24 trees at the Denair site were shaken with a mechanical harvester to remove mummy fruits. Total mummy fruit weight along with associated orchard trash was collected for each individual tree in the field. A representative subsample of mummy fruits and trash was weighed in the field, and then dried offsite to 3% moisture. Trash percentages were calculated for each tree, and the corresponding trash amount was then subtracted from the mummy fresh field weight to determine the total mummy fresh weight. Dry matter percentage was calculated by dividing the total mummy dry weight by the total mummy fresh weight for each subsample. Total mummy fresh weight for each tree was then multiplied by the calculated dry matter percentage to determine the total mummy dry weight for each tree. Shaker efficacy values were calculated by determining the ratio of the total mummy dry weight to marketable fruit dry weight for each tree.

### *Mummy Counts*

As with shaker efficacy, mummy counts were calculated for the Denair site but not for the Woodland site. The percent trash was subtracted from the total mummy fresh field weight for each tree. Standard Harvest fruit field weights and fruit counts were then used to estimate the number of mummies removed from the tree during the mummy shake.

### *Statistical Methods*

For the analysis of postharvest effects, Hull Rot strikes, return bloom, and mummies, the data for the three subsample trees in each plot were averaged and data was compared on a per-plot basis. Data analysis was conducted using a mixed model with site and treatment as fixed effects and block as a random effect for differences in soil type and management throughout the selected orchards. ANOVA tests were used to analyze the normal dry fruit weight, kernel yield, and marketable yield data across both sites, and the shaker efficacy, return bloom, and mummy data at one site. ANOVA tests were used to analyze the log transformed harvest Hull Rot strike data at one site. Percent NOW damage was calculated on a per-plot basis; NOW data was square root transformed and analyzed using an ANOVA test. All ANOVA tests were conducted in base R (Lenth, 2020; Bates et al., 2015; Kuznetsova, et al., 2017). Descriptive statistics were calculated using Excel (Microsoft Corp., Redmond, WA).

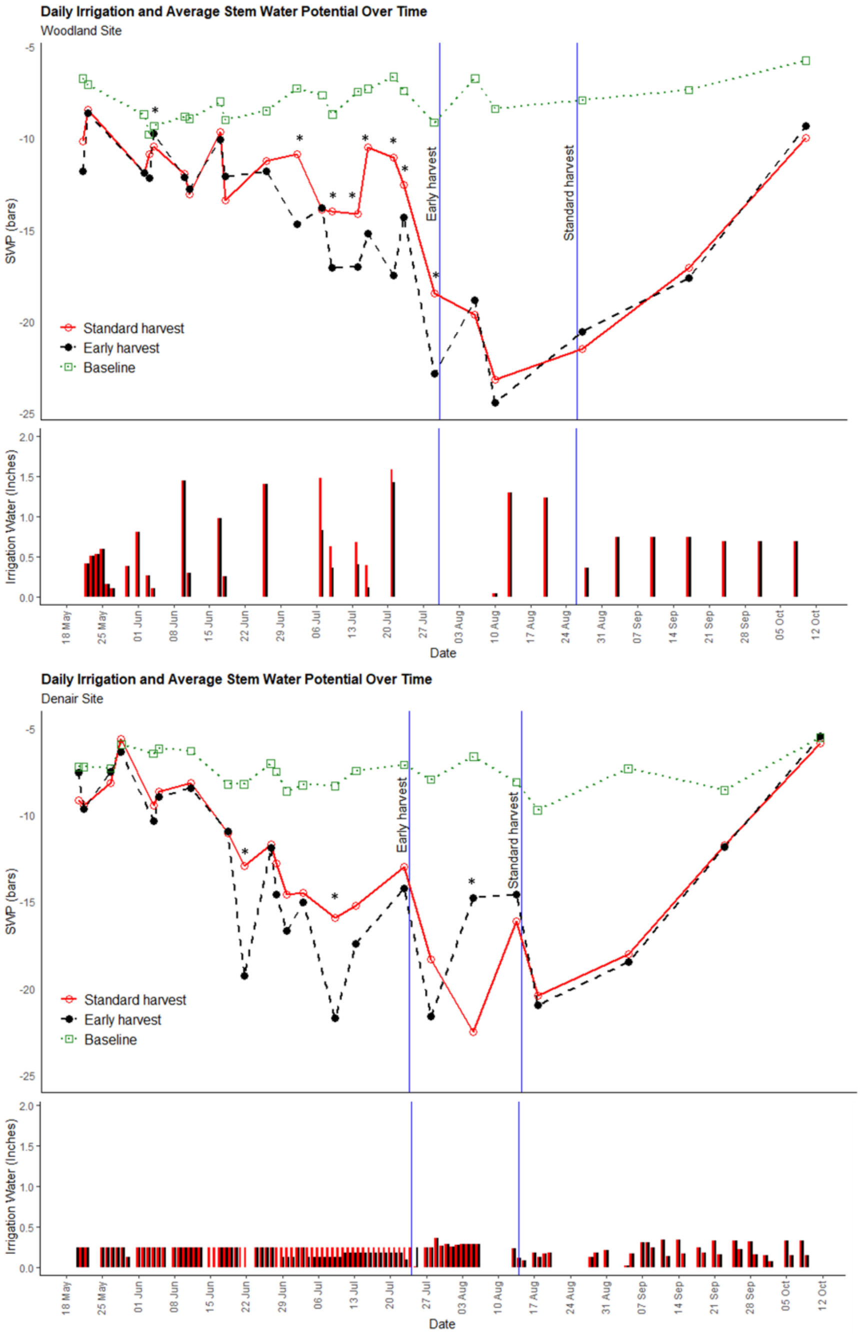
## **Results**

### *Stem Water Potential*

Figure 2.1 shows the SWP levels and irrigation schedules for the EH and SH trees before harvest at each site. At the Denair site irrigation was reduced to the EH trees on July 4. After 7 days of a applying 0.12 inches of water less per day to the EH trees than to the SH trees, SWP dropped from -15.1 bars (-6.8 bars below baseline) to -21.7 bars (-13.4 bars below baseline); a slight increase in irrigation to 0.18 inches per day raised the SWP back into the target range for the remainder of the time leading to Early Harvest. At the same time, SH trees received 0.24 inches of water per day and were less stressed during this time period, maintaining a SWP between -14.5 bars (-6.2 bars below baseline) and -13 (-7.6 bars below baseline) bars. After August 6, SH trees were subjected to deficit irrigation, and responded with a SWP of -16.1 bars. EH trees received 21.07 cumulative inches, while SH trees received a cumulative 24.35 inches of water from March 18 to October 12 (Figure 2.2).

**Figure 2.1**

*Stem water potential and daily irrigation volumes for Standard and Early Harvest treatments at Denair and Woodland sites.*



*Note.* SWP values are compared to the baseline $ET_c$ for each orchard. Irrigation was reduced for Early Harvest compared to Standard Harvest beginning on July 4 and July 2 at the Denair and Woodland sites respectively, and SWP values diverged accordingly for the two treatments. Harvest dates are indicated by horizontal lines. At the Denair site, harvest occurred on 7/24 and 8/14 for EH and SH respectively; at the Woodland site, EH was conducted on 7/30 and SH was conducted on 8/26. SWP values for EH trees increased dramatically after EH when irrigation levels were returned to SH volumes. This was likely due to the fact that the EH trees were acclimated to receiving reduced water volumes, and therefore had a more sensitive response when larger quantities of water were applied. At both sites, treatment groups returned to comparable SWP values after SH, and returned to only mild stress by October 12.

*Significant difference between treatments

At the Woodland site irrigation was reduced to the EH treatment trees on July 2. The SWP of the EH trees was maintained between the target -14 to -18 bars for the 22 days leading up to Early Harvest. Meanwhile SH trees at the Woodland site continued to receive standard irrigation volumes through July 22, at which point irrigation was cut off to dry the trees in preparation for harvest. During this drying period, SH treatment SWP values dropped from -12.54 (-5.12 bars below baseline) to -23.18 (-14.78 bars below baseline). Irrigation was returned to the SH trees starting on August 10th, initiating a rise in SWP values to -21.53 by harvest. At the Woodland site, a cumulative of 19.19 inches of water was applied to EH trees and 20.80 inches of water was applied to SH trees from March 18 to October 12 (Figure 2.2).

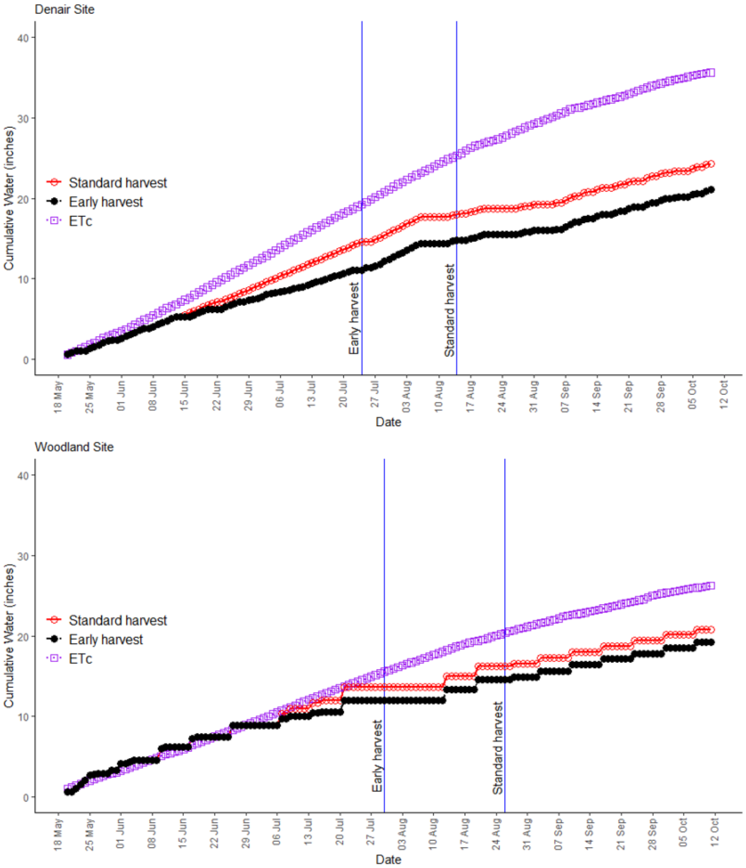


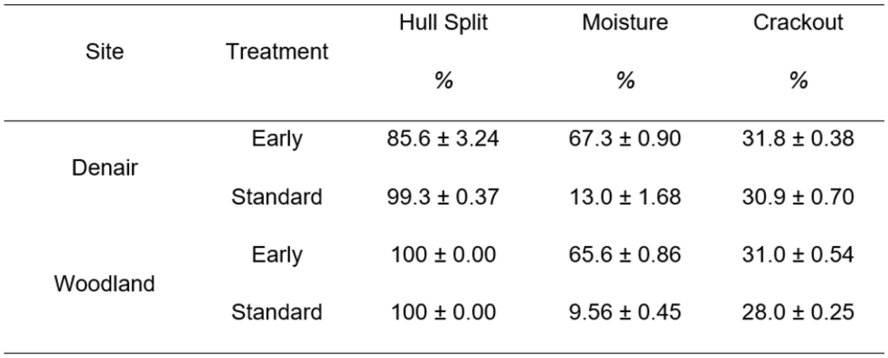
*Figure 2. Cumulative irrigation volume and $ET_c$ for Standard and Early Harvest treatments at Denair and Woodland sites from March 18 to October 12. Despite a difference in total irrigation volume of 3.28 and 1.61 inches of water between EH and SH trees at the Denair site and the Woodland site respectively, trees from both treatment groups returned to mild water stress levels by October 12 at each site.*

### *Fruit Characteristics*

At the Denair site, the average hull split for EH fruits was 85.58%, while the average hull split for SH fruits was 99.25%. Hull split percentages ranged from 71-99% and 96-100% respectively (Table 2.1). At the Woodland site, there was 100% hull split at both Early and Standard Harvests. At both sites, hull split sutures appeared smaller at Early than Standard Harvest.

**Table 2.1**

*Average hull split, moisture and crackout percentages for Early and Standard Harvest treatments at Denair and Woodland sites*



| Site | Treatment | Hull Split % | Moisture % | Crackout % |
|---|---|---|---|---|
| Denair | Early | 85.6 ± 3.24 | 67.3 ± 0.90 | 31.8 ± 0.38 |
| | Standard | 99.3 ± 0.37 | 13.0 ± 1.68 | 30.9 ± 0.70 |
| Woodland | Early | 100 ± 0.00 | 65.6 ± 0.86 | 31.0 ± 0.54 |
| | Standard | 100 ± 0.00 | 9.56 ± 0.45 | 28.0 ± 0.25 |

The average moisture content of Early Harvest fruit was much higher than that of Standard Harvest fruits (Table 2.1). Average EH moisture content was 67.3% and 65.6% while SH content was 13.0% and 9.56% at the Denair and Woodland sites respectively. EH fruits were visibly more green than SH fruits at harvest.

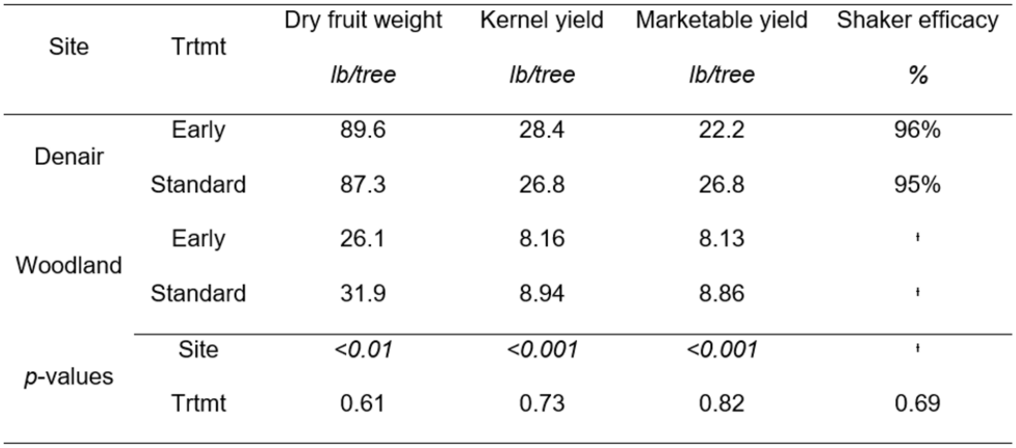
Percent crackout tended to be slightly higher for EH than SH fruits at both sites (Table 2.1). At the Denair site, average crackout percentages were 30.9% and 31.8% for SH and EH respectively, and at the Woodland site, average crackout percentages were 28.0% and 31.0%.

### *Postharvest Effects*

The average dry fruit, kernel, and marketable yield weights are reported in Table 2.2. For all three of these variables there was a site difference but no treatment differences. The percent shaker efficacy at the Denair site was 96% and 95% for Early and Standard Harvest respectively. There was no significant difference between the two treatments.

**Table 2.2**

*Comparison of postharvest effects for Standard and Early Harvest treatments at the Denair and Woodland sites (where applicable).*



| Site | Trtmt | Dry fruit weight<br>*lb/tree* | Kernel yield<br>*lb/tree* | Marketable yield<br>*lb/tree* | Shaker efficacy<br>*%* |
|---|---|---|---|---|---|
| Denair | Early | 89.6 | 28.4 | 22.2 | 96% |
| | Standard | 87.3 | 26.8 | 26.8 | 95% |
| Woodland | Early | 26.1 | 8.16 | 8.13 | ‡ |
| | Standard | 31.9 | 8.94 | 8.86 | ‡ |
| *p*-values | Site | *<0.01* | *<0.001* | *<0.001* | ‡ |
| | Trtmt | 0.61 | 0.73 | 0.82 | 0.69 |

*Note.* lb/tree are reported as the average lb/tree for all pseudoreplicates in all blocks of each treatment at each site. P-values are reported for site, treatment, and site*treatment differences; significant p-values are italicized.

‡ No data was collected at the Woodland site for this parameter.

### *Navel Orangeworm Incidence*

The average percent NOW damage at the Denair site was 0.36% and 0.31% for Early and Standard Harvest respectively. At the Woodland site, EH fruits had an average of 0.37% NOW damage and SH fruits had an average of 0.71% damage. There was a significant difference in NOW incidence between the two sites, but no significant difference in NOW incidence between the two treatments at either site (Table 2.3).

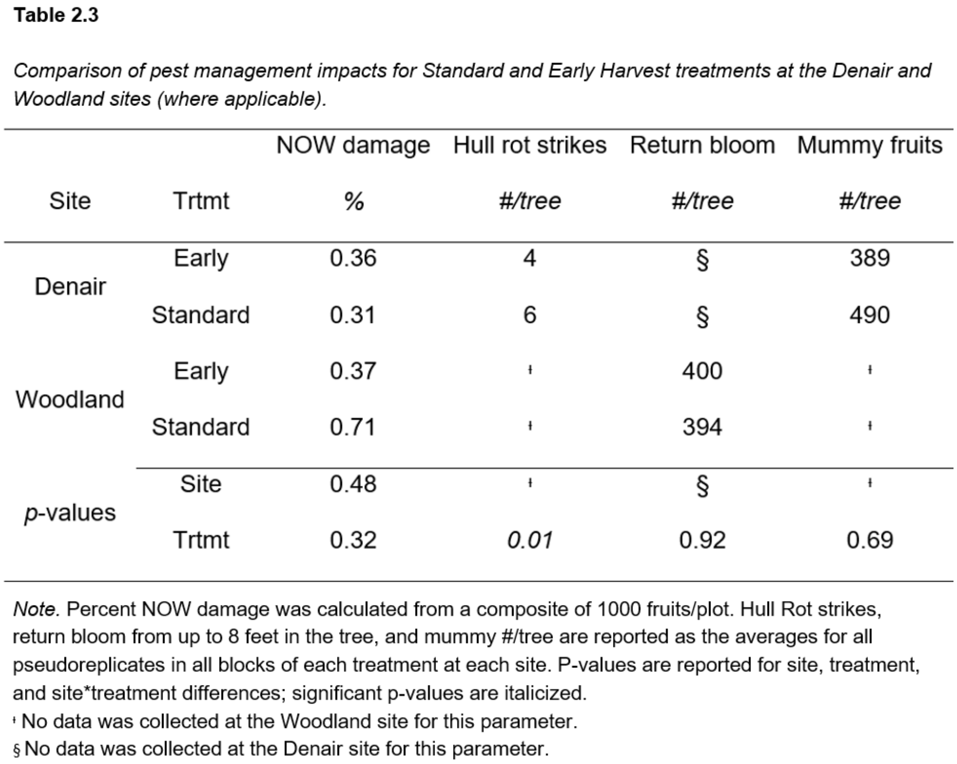


**Table 2.3**

*Comparison of pest management impacts for Standard and Early Harvest treatments at the Denair and Woodland sites (where applicable).*

| Site | Trtmt | NOW damage<br>*%* | Hull rot strikes<br>*#/tree* | Return bloom<br>*#/tree* | Mummy fruits<br>*#/tree* |
|---|---|---|---|---|---|
| Denair | Early | 0.36 | 4 | § | 389 |
| | Standard | 0.31 | 6 | § | 490 |
| Woodland | Early | 0.37 | ǂ | 400 | ǂ |
| | Standard | 0.71 | ǂ | 394 | ǂ |
| *p*-values | Site | 0.48 | ǂ | § | ǂ |
| | Trtmt | 0.32 | *0.01* | 0.92 | 0.69 |

*Note.* Percent NOW damage was calculated from a composite of 1000 fruits/plot. Hull Rot strikes, return bloom from up to 8 feet in the tree, and mummy #/tree are reported as the averages for all pseudoreplicates in all blocks of each treatment at each site. P-values are reported for site, treatment, and site*treatment differences; significant p-values are italicized.

ǂ No data was collected at the Woodland site for this parameter.

§ No data was collected at the Denair site for this parameter.

### *Hull Rot Incidence*

Significantly more hull rot strikes, caused by *Rhizopus stolonifer*, were observed in Standard Harvest than Early Harvest trees at harvest at the Denair site (Table 2.3). The number of hull rot strikes ranged from 1-6 and 2-12 for Early and Standard Harvest respectively.

At the Woodland site, no significant differences in spring return bloom were observed between the two treatments. EH trees had an average of 400 blooms, while SH trees had an average of 394 blooms. This indicates that there was no significant difference in HR incidence between the two treatments at this site.

### *Mummies*

Although no statistically significant difference was observed between mummy counts for EH and SH trees, EH trees had fewer mummies, averaging 389 compared to SH trees, which averaged 490 (Table 2.3).

## Discussion

### *Stem Water Potential*

With the use of regular SWP measurements the EH trees were successfully dried to the targeted -14 to -18 bars range for the two to three weeks preceding harvest at both sites. As irrigation was restored after harvest, the trees from both treatment groups at both sites returned to approximately the same water status after Standard Harvest and mostly recovered from the induced moderate water stress by October 12. This was true despite the fact that there was a difference of 3.28 and 1.61 inches of water between EH and SH trees at the Denair site and the Woodland site respectively (Figure 2.1).

### *Hull Split and Moisture Content*

At both sites, EH fruits tended to be at stages 1b-d of hull split, while SH fruits were mostly at hull split stages d-f (Appendix 1). 100% of fruits reached hull split before both Early and Standard Harvest at the Woodland site. At the Denair site there was a range of hull split percentages before both harvests. Differences in water stress between treatments was likely one of the factors that contributed to the differences in hull split stage within sites (Appendix 1) and hull split percentages between sites.

At both sites, fruits had much higher moisture content at EH (Table 2.1) because they had less time to dry on the tree than SH fruits. Although suture sizes were generally smaller on EH fruits than SH fruits before their respective harvests, when removed from the tree, many of the hulls popped open upon impact with the ground, releasing the kernel in the shell from the hulls. It is likely that the additional weight of the EH fruits due to the high moisture content increased the force with which the fruits hit the ground, allowing the hulls to spring open upon impact.

Higher moisture content at harvest could present a challenge for producers interested in adopting this practice. High moisture fruit will need to be dried for longer periods of time than fruit harvested at standard timing. If dried in the field, this increases the likelihood of kernel damage or contamination (Zalom & Bentley, 1985). Additionally, drying high moisture fruits in row middles would slow the return of irrigation to the orchard postharvest in orchards that do not employ drip or subsurface irrigation. Prolonged periods of water deprivation in almond orchards can lead to severe water stress in trees, accelerating leaf aging, reducing leaf $CO_2$ assimilation, and causing leaf abscission (Klein et al., 2001). High levels of leaf abscission around harvest can lead to yield reductions in subsequent years. These challenges around high fruit moisture content and in-orchard drying may necessitate other changes in harvest and postharvest practices including off-ground harvest, off-site drying, and in-field (green) hulling in orchards where the adoption of early almond harvest is being considered.

Off ground harvesting is a standard practice in other California fruit and nut crops including prunes and pistachios, and is being implemented successfully in some almond orchards. Almond growers with young orchards and those producing almonds in marginal soils use off ground harvest to capture and remove their crops rather than allowing them to dry on the orchard floor where they can be left behind, damaged, or contaminated. Apart from early crop removal from the orchard floor, off-ground harvest offers several other benefits in almond production, particularly those relating to orchard floor management. When using off-ground harvest, almond producers are able to apply fewer herbicides in their orchards and use a wider range of soil-health improving practices that build soil organic matter, increase nutrient retention, and decrease dust and soil erosion (Chen et al., 2021). These orchard floor management strategies can be used to improve long term soil and crop functioning (TerAvest et al., 2010; Hoagland et al., 2008). Farzi et al. (2017) proposed that the physical barrier that mulches provide over the soil surface reduces soil evaporation and increases crop transpiration rates; this could help promote crop development and increase the viability of early almond harvest.

The use of mechanical dryers to reduce almond fruit moisture content is common in some almond production areas where environmental conditions make it challenging to lower fruit moisture content to the necessary 7-12% moisture for hulling (Thompson et al., 1996). Research is being conducted to determine the best mechanical almond drying methods for different production situations (Chen et al., 2021; Yang et al., 2010; Li et al., 2018; Fu et al., 2016). Growers interested in harvesting their almond fruits early could take advantage of this infrastructure by immediately removing harvested fruits from their orchard and transporting them to hulling operations with this drying infrastructure. Mechanical drying practices can be combined with off-ground harvesting to maximize efficiency (Chen et al., 2021). In situations where mechanical drying is not feasible due to infrastructure or cost constraints, on- or off-site drying patios could also be utilized to air-dry almond fruits off of the orchard floor.

The observed tendency of the kernel + shell to separate from the hull may have significant implications for the processing of greener fruits after early harvest. While in-field almond hulling is not common in the industry at this time, preliminary research by Fielke & Coates (2018) shows promising potential for the use of prototypical machinery to facilitate the in-field hulling of early harvested almonds. The development of such machinery as well as the combination of harvest and drying innovations previously discussed are integral to the successful widespread adoption of early almond harvest among California growers.

### *Yield*

Although research on the effects of early harvest on water use efficiency, and pest and disease control has indicated positive outcomes for several decades, adoption of early harvest is low. Concern about impact to yield is likely one of the drivers of this slow adoption rate. Limited research in this area shows contrasting results; differences in the RDI regimes applied across different studies, particularly with respect to the time to return water to the orchard postharvest, make it challenging to compare the results of experiments looking at RDI, yield outcomes, and orchard health. Teviotdale et al. (2001) observed a reduction in fruit kernel weight with the implementation of hull split RDI, though no difference in total fruit load was recorded. Goldhamer and Viveros (2000) observed similar outcomes with the majority of hull split RDI treatments that they tested. Goldhamer and Smith (1995) observed reduction in total fruit load in proportional deficit irrigation treatments, but no negative yield outcomes in hull split RDI treatments. Contrastingly, work by Torrecillas et al. (1989), Shackel (2002, 2003), and Micke et al. (1966) indicated no significant impacts to almond yield as a result of RDI scheduling.

In this study, there was no significant treatment difference in dry fruit weight, kernel yield, or marketable yield. Treatment differences observed in field fruit weight were due to the difference in moisture content at the different harvest timings. While more research is needed on this subject, lack of significant yield differences between the two treatments indicates that early harvesting of almonds may have minimal or no impact on almond yields.

### *Navel Orangeworm Incidence*

There was no history of significant NOW infestation at either field site (Table 2.3). It is likely that this site history was a factor in the lack of significant differences in NOW incidence between the two treatments. Further research on the effects of early harvest on NOW management should be conducted in orchards with a known history of NOW.

### *Hull Rot Incidence*

Because this study was conducted during the first harvest at the Woodland site, we did not expect to see significant differences in return bloom between the two treatments. However, the trends observed at the Denair site indicated that early almond harvest may be a viable strategy for reducing HR incidence in mature almond orchards in California (Table 2.3).

### *Shaker Efficacy*

A longer shake (6 seconds vs. 3 seconds) was required to remove EH fruit than SH fruit. When this extra time was given, the results of the shaker efficacy component of this experiment reinforced the yield findings previously discussed, indicating that no more marketable yield was left on the tree at Early Harvest than at Standard Harvest timing (Table 2.2).

Additionally, there was no significant difference in the number of mummies that were left on the tree after shaking between the two treatments. Although more research is needed in this regard, these preliminary results indicate that early harvest may not represent increased sanitation costs or sites for NOW overwintering as compared to Standard Harvest timing.

## Conclusion

This research has shown that regular SWP measurements are an effective tool for imposing a hull split RDI schedule for two to three weeks prior to early almond harvest without incurring short term negative impacts of tree water status and health. Hull split RDI can be coupled with early almond harvest dates to improve hull rot control, and the early harvest of almonds has no negative implications for the control of NOW in orchards with a history of low NOW damage. This research also suggests that the combination of hull split RDI and early harvest has no significant negative impact on shaker efficacy, kernel yield, or marketable yield of almonds.

The combination of hull split RDI and early almond harvest could be important for sustainable pest and disease management and water management in California almond orchards. More research is needed in several areas to better understand these practices and their potential for use in the almond industry. Research should be conducted to understand the effects of the repeated use of this combination of practices on orchard longevity. A study aimed at assessing the impacts to long term tree health and yields would provide valuable information for almond growers interested in adopting these practices. Further research should also be directed towards assessing drying and processing options for almond fruits that are harvested at a much higher moisture content than those harvested at Standard Harvest timing. Finally, other barriers to adoption of these practices exist. An interdisciplinary research approach should be taken to identify and address those barriers is needed to promote the successful uptake of hull split RDI and early harvest practices.

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# Appendix 1: Standard Almond Hull Split Stages

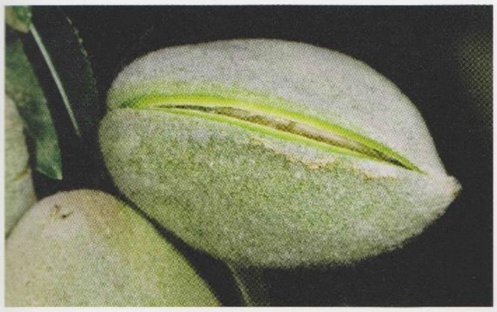
From the University of California *Integrated Pest Management for Almonds*

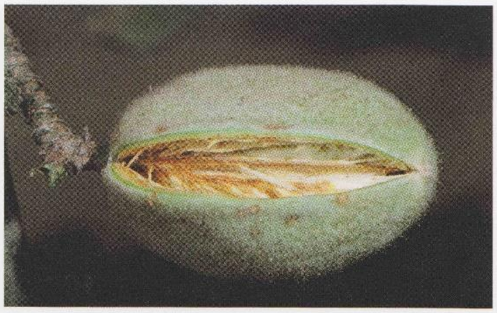
THE ALMOND TREE: DEVELOPMENT AND GROWTH REQUIREMENTS 7


(a)


(b1)


(b2)


(b3)


(c)


(d)


(e)


(f)