An Extensive Survey On The Impacts Of Fruit Fall Before Harvest In Almond Yields In California

By

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Abstract

Almonds (*Prunus dulcis* (Mill.) D. A. Webb) are essential part of the Californian landscape and economy. Their popularity in the last decades has increased drastically thanks to newer technological and plant-specific discoveries and developments. Their production is currently facing many challenges and to maintain their sustainable production, several changes must be made. The Almond Board of California has responded by developing strategies that would aid the sustainability of almonds in the near future. This thesis focuses mainly on dust abatement strategies by introducing off-ground harvest and the impact of fruit drop that might occur if current harvest process were to be altered. During 2019 and 2020, fruit drop (incorrectly referred to as 'Windfall') before harvest was found to be present in most of the orchards though it is was inconsequential in Nonpareil except under extreme conditions of drought or very delayed harvest. In later cultivars percent fruit drop (PFD) rarely exceeds 5% in the latest harvested cultivars and was markedly exacerbated by extended harvest delay or water stress. Fruit drop is highly correlated with the days past hull split at which harvest occurs (or the number of days fruit remains hanging from peduncle) and is exacerbated by water stress and equipment passes through the orchard. 2020 represented a 'perfect storm' for PFD with Covid and smoke delaying harvest, smoke exacerbating tree stress response, and limitations on water availability in many regions. When harvested at 15-20 days post hull split (5-10 days prior to current practice), windfall was less than 0.5% in Nonpareil and Independence and <3% in all but two orchards with late harvest cultivars. Since late cultivars represent just 25% of the planted trees the true impact of PFD on whole orchard productivity would be proportionately reduced. Further research is encouraged to better understand this phenomenon as well as the full costs and benefits of earlier harvesting.

Chapter 1: Literature Review

1. California Almond Production

Almonds are one of the largest economically important commodity crops in the state of California, with production in more than 16 counties in the state of California (Sumner et al., n.d). Almonds are planted on more than 1.3 million acres from Kern to Tehama counties (USDA/NASS, 2022). California produces roughly about 2.9 billion pounds of almond kernels per year, with substantial growth from the 370 million pounds produced in 1995 (USDA/NASS, 2022). Due to demand and growth across the globe, almond production is likely to continue to increase (Sumner et al., n.d, USDA/NASS, 2022).

Healthier lifestyles and demands from consumers have increased the demand for sustainable farms across the globe, this in turn has increased the scrutiny of the farming operations and increased the demand for sustainable high quality food chain by consumers and also by government and regulatory agencies. This has led to the adoption of common goals across the entire industry to improve as water efficiency, reduce dust and improve use of inputs such as fertilizers and agrochemicals. The California Almond Sustainability Program or CASP, has been developed to ensure almond growers continue producing top quality fruit with the least amount of environmental disturbance possible (Almond Board of California, 2019). This, in turn, will demand an improvement in long-term sustainable farming operations that can be adopted not only by current but future generations.

2. Improvements in almond varieties and cultivation practices

Almonds were first planted in California around 1853 (Wickson, 1889) and have grown to be the most important agricultural commodity in the state. During the early years, almonds seemed poorly adapted to the California weather, but lack of knowledge such as cross-pollination, irrigation, pruning, and processing practices were the main reason for the early inadequate results (Fertilizer Research and Education Program, 2016). In 1886, during a Citrus Fair that took place in Sacramento, A.T. Hatch of Suisun (in Wickson, 1889) presented several cultivars, which included Nonpareil, a cultivar that has become the most predominant cultivar planted to date. Since then, there has been many shifts in industry that have contributed to the production we have today.

One of the most important production shifts is the move of almond production from Sacramento Valley, coastal counties, and Southern Valleys to the San Joaquin Valley. This was due to the increased availability of irrigation water that was made possible by the California Water Project (Johnston, 2003). This shift moved almonds to regions with better soil, more suitable chilling conditions, abundant high-quality water, and improved overall climate conditions (Kester et al., 1996; Johnston, 2003). Several other practices were also improved, these include breeding advances (Gradziel, 2011; Kester et al. 1975), irrigation (Johnston, 2003), pest management (Gradziel, 2011; Kester et., al. 1996) and mechanization (Johnston, 2003).

Almond harvest mechanization has also been one of the most significant improvements in the industry that has allowed almond production to thrive while consistent progress in variety and rootstock development, management such as fertigation, pruning, irrigation, and harvest practices. During the early 1970's, almond harvest practices made substantial improvements with overall saving costs adopted across the California almond production areas (Burlingame & Volz 1953; Murua et al., 1993; Johnston, 2003).

There are many considerations to be taken into account to produce almonds in California. One of the reasons California is a well-suited host to almonds is because almonds have adapted very well to the lighter textured sandy loams and the Mediterranean climate that is found in the Central Valley (Kester et al., 1996). With the collaboration of the University of California, California State system, and USDA among others, many research trials have taken place to develop best practices and optimal genetic resources. An example of this progress is the development and adoption of peach-almond hybrids as well as plum and multi parentage rootstocks (Kester et al., 1996). This has allowed almond production to increase not only in terms of acreage planted but also in the production per acre basis (USDA/NASS, 2022; Fertilizer Research and Education Program, 2016). This progress derives from extensive work in cultivar selection, improved pollination, updated irrigation practices, improved nutrition and superior disease and pest control (Kester et al., 1996).

Until recently, self-sterile cultivars of almonds have been planted in combinations of two or more cultivars. While there is a diversity of the pollinizers used Nonpareil remains the most economical and important cultivar, accounting for at least 25% to 50% of the acreage planted in most orchards and 40% of the total almond production in California (Sideli et al., 2020). To maximize pollination and yield, single rows are planted with pollinizer on either side of the row. This results in two things, one, the usual planting combination often results in Nonpareil and a pollinizer or a Nonpareil and two pollinizers cultivars (Faulkner & Capareda, 2012). The second result of such interplanting is the different timing of the phenological stages as each cultivar develops and fruit maturation at different times during the year (Kester et al., 1996). Growers often choose cultivars that provide sequential harvest in an attempt to extend the harvest period and allow them to utilize equipment and facilities much more efficiently. This also helps to avoid the mixture of fruit from different cultivars at the time of harvest (Faulkner & Capareda, 2012).

In order to produce the kernel and its byproducts we consume, almonds must undergo several stages starting with a dormancy period that lasts until each cultivar' chill requirement is met, this period usually starts in October and last between November to January (Kester et al., 1996), depending on the weather conditions and the cultivar needs. Once this occurs, the cultivars enter a 'paradormancy' period that is followed by bud break, in Nonpareil for example, paradormancy occurs between November (after chill requirements is met) until the half part of December. During the second part of December and the entire month of January, bud break starts to occur, which results in bloom (Kester et al., 1996). Subsequently (or coincident with early petal fall in some cultivars), vegetative bud expansion occurs around the months of January and February. These buds are then developed into leaves during the Spring (March-April months), which is when almonds have the most active vegetative growth (Kester et al., 1996; Polito et al., 1996) but continue throughout the season.

During vegetative growth period, the vegetative shoots and spurs elongate producing only vegetative growth during this first couple of years, however, as these shoots mature, they will give rise to future spurs that produce the almond kernels (Kester et al., 1996; Goldhamer et al., 2006). Vegetative bud set for the subsequent year starts around May and lasts until June. Bud differentiation, however, occurs around the same time but it continues throughout the summer (Kester et al., 1996). During this time, the flower bud induction starts to take place, roughly around August (Kester et al., 1996). In some instances, this process overlaps with early harvest cultivars such as Nonpareil. This is a critical time for the trees as the ratio of reproductive to vegetative bud expression is a function of stress during the differentiation or induction period (Goldhamer & Viveros, 2000; Esparza et al., 2001), which can coincide with heavy stress such as water deficit irrigation and bark damage produced during harvest.

Once flower bud induction has taken place, flower buds continue to develop and undergo anatomical changes during late fall to early winter, which again, might coincide with harvest, depending on the cultivar. This flower bud development is estimated to occur between September through November (Goldhamer & Viveros, 2000; Esparza et al., 2001). Then the reproductive cycle goes through flower development, blooming, and cross-pollination. Almond fruit results from the pollination of flowers from late February through early March. In California, the pollination process is characterized by the presence of beehives that are brought from in and out of state to facilitate this process and ensure proper and adequate fruit set (Kester et al., 1996, 1996). Almonds (*Prunus dulcis* (Mill.) D. A. Webb*)* fruit consist of a seed (kernel), endocarp (shell), and mesocarp (hull) (Godini, 1984; Grundy et al., 2016) The seed or kernel is of the most lucrative importance for the California grower and the reminder of the fruit is often of lesser economic importance either combined or individually.

Almond fruit must undergo three important stages to reach the desired size and quality. Bees aid in the pollination of almond flowers, once fertilization occurs, the fertilized ovule starts to develop into a seed. This is known as Stage 1, which is characterized by the growth of the hull and shell as well as the lengthening of the pericarp and seed. During this stage, almond trees shed unfertilized flowers as well as damaged or otherwise unfertilized plant material (Kester et al, 1996). Once “fruit elongation” has occurred, all fruit parts start to harden which is known as Stage 2. This stage is particularly important because it involves the filling of the almond kernel (Doll & Shackel, 2015). The final stage or stage 3 involves the maturation and final ripening of the almond fruit. This stage is particularly identified by the presence of abscission layer in the peduncle (attachment between the almond fruit and almond tree) and the dehiscence or split of the mesocarp (hull) also known as the hull split stage (Kester et al., 1996; Connell et al., 1996).

3. Almond harvesting California

The initiation of Stage 3 of fruit development in almonds signals the beginning of almond harvest. During this time, growers monitor and practice water deficit irrigation as it aids with the formation of the abscission layer and hull split. Water cut off during this time is also believed to be necessary to prevent bark damage (Fridley, et al., 1970; Esparza et al., 2001), and ensures the soil is dry at shaking since almonds are left in the ground before picking up (Goldhamer & Viveros, 2000). As the fruit loses its moisture, the hull naturally peels away from the shell and the abscission layer is more evident in the peduncle, this often results in easier detachment of fruit from their respective spurs (Connell et al., 1996). During this time, growers prepare the soil, the equipment, the roads, and the personnel to ensure a clean and steady harvest.

Almonds in California commence harvest in early August, Nonpareil being one of the first cultivars to be harvested. During this time, dry weather conditions allow for the hull to split, dehiscence completes and the hull pulls away from the shell (mesoderm). Deficit irrigation is thought to play a vital role in exacerbating the weak connection formed by the abscission zone between the peduncle and fruit (appendix 1: Standard Almond Hull split Stages [f]). This is beneficial for the shaker efficiency as it facilitates the dislocation of fruits from their respective spurs (Riel at al., 1996; King et al., 1970).

3.1 Harvesting of almond orchards

Harvesting is a multi-step process that can be carried out by a very small or very large crews, depending on the speed the harvest is required. Step one consists of a shaker wrapping around the tree trunk to shake as much fruit as possible in a single shake to reduce bark damage (King et al., 1970). The dropped fruit will then be swept into windrows to allow further drying and facilitate fruit pick up. Historically, almonds would be picked up at this stage but in recent years it is increasingly common to have a conditioning step included before the actual pick up. A conditioner machine temporarily picks up the almonds along with all debris (leaves, rocks, branches, and soil), but in a series of mechanized steps aided by turbine force, it removes the debris leaving the almond fruit as clean as possible for easier pick up and grading. This step not only reduces load rejects but increases income by avoiding clean-up fees at the processing facilities. From this point, almonds are picked up and taken to gondolas or trailers to be transported into to huller/sheller. These steps are repeated in orchards until all different cultivars are harvested (Riel at al., 1996; King et al., 1970).

3.1.1 Issues with existing on-ground almond harvesting

Dust

Almonds are planted on more than 1.3 million acres across the state, although not all is bearing (USDA/NASS, 2022). Almond harvest in California is performed mechanically through the state during the months of August to late October (Faulkner & Capareda, 2012; Faulkner & Capareda, 2011), during which an estimated of 11,350 tons of dust or Particulate Matter (PM) between 2.5 to 50 microns are produced (PM 2.5 to PM 10) (Faulkner & Capareda, 2011; Faulkner & Capareda, 2012). This number results from multiplying an emission factor by an activity factor or acres harvested as indicated in the following formula (California Air Resources Board, 2003):

Emission = Emission Factor X Acres Harvested

Where Emission Factor is defined by EPA as "a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant" (*Basic Information of Air Emissions Factors and Quantification,* 2022)).

As a comparison, the emission factor for almond shaking, sweeping, and pickup are 3.47, 4.15, and 23.60 respectively for a total of 31.20 Lb. PM 10/Ac (California Air Resources Board, 2003). In contrast, the combined operations of wheat and cotton picking is only 5.8 and 3.4 Lb. PM 10/Ac respectively (California Air Resources Board, 2003; Faulkner & Capareda, 2012. The emission factor is multiplied by the number of acres harvested, thus resulting in a large number. In the past, the Emission in almonds was higher largely larger (4.5 Lb. PM 10/Ac) due to the use of less efficient machines, with newer technologies and improvements, the number has been greatly reduced (Faulkner & Capareda, 2012). For example, by reducing the number of passes within an orchard reduces the amount of dust by about 11 Gg of PM 10 are produced each year (Faulkner & Capareda, 2012; Faulkner et al., 2011).

Dust is a main concern for air quality because of its negative impact on human health (Sharratt & Auvermann, 2014). According to the American Lung Association, California is already home to 17 out of 25 of the most populated counties in the country (*Most Polluted Places to Live | State of the Air*, n.d.), where PM pollution is at the highest (*Most Polluted Places to Live | State of the Air*, n.d.; Chow et al., 1992)). Coincidentally, several counties where PM is the highest in California are also home for a vast majority of almond orchards also known for their high almond fruit productivity (*Most Polluted Places to Live | State of the Air*, n.d.; USDA/NASS, 2022). These almond growing counties include Fresno, Kern, Madera, Merced, San Joaquin, Stanislaus, and Tulare counties (USDA/NASS, 2022; *Most Polluted Places to Live | State of the Air*, n.d.; Fertilizer Research and Education Program, 2016). While the full attribution of human health costs from almond production are hard to estimate, it is certainly true that the addition of 11, 350 tons of dust to the Californian air during harvest on top of the already present pollution, is not favorable.

While large particle dust is not known to be directly correlated to asthma cases and other respiratory diseases such as bronchitis, and emphysema (Smith et al., 2008), there are direct links between exposure to dust and negative effects on the health of respiratory conditioned patients such as allergic reactions, serious breathing-related problems, reduction in life span, and contribution to cardiovascular or hearth disease (Smith et al., 2008; Schenker et al., 2009).

During almond harvest, the most concerning dust fraction is that which falls within 2.5 to 10 micrometers also known as PM 2.5 and PM 10 respectively (Smith et al., 2008; Faulkner & Capareda, 2012). This is important because PM 10 and lower can filter through the respiratory system (Smith et al., 2008; Brown et al., 2013; Emmett et al., 1982; Heyder et al., 1986) or more specifically, the thoracic area or larynx. It is estimated that PM 10 have a 40% chance of filtering through the thoracic area and entering the alveoli, where they can produce several negative respiratory conditions (Smith et al., 2008; Schenker et al., 2009; "Respiratory Health Hazards in Agriculture", 1998b). As the diameter of a PM size decreases, the penetration efficiency of dust to filter into the thoracic area increases (Smith et al., 2008). Similarly, Emmer et al., 1982 found that smaller particle aerodynamic sizes (3.5 microns) were more likely to be found (deposited) in the alveolar zone, whereas the larger particle aerodynamic sizes (8 & 10 microns) were more likely to be found (deposited) in the oral (mouth) and throat zones. Both the health effects of PM 2.5 and 10 and the nuisance' effects of large particles that coat vehicles, clothes and surfaces and can be 'seen' by populations represent threats to the air quality in California (Almond Board of California, 2019). In response the Almond Board of California has developed the California Almond Sustainability Program (CASP) known as the Almond Orchard 2025 Goals that aim to reduce dust produced during harvest among other benefits such as pest management and irrigation improvement to reduce water.

Irrigation

Harvesting practices can bring concerning and costly issues to growers. One major issue is the delay in return of water to trees during critical periods of postharvest. This is a crucial stage of future yield development as almond flower initiation occurs at the same time of harvest; thus, the plant is more vulnerable to reduced bud development if water stress is induced (Esparza et al., 2001). For this reason, irrigation not only must be returned quickly to the crop post-harvest, but it also must be maintained to ensure bud differentiation in subsequent years and thus fruit yield (Goldhamer & Viveros, 2000; Esparza et al., 2001).

A second less problematic but costly issue that harvesting equipment may produce is the disturbance of irrigation equipment. Since irrigation equipment is not buried, exposed fittings are often damaged by harvesting machinery. Depending on the system of each orchard and the type of equipment used, irrigation equipment may need extensive repair postharvest. These repairs are often a result of complete removal, destruction, or relocation of irrigation lines produced by sweepers, blowers, pick up machines, and other orchard preparation machines such as planners and mowers. Since non-self-fertilizing orchards require multiple cultivars to be planted in adjacent rows to ensure pollination, multiple passes by harvesting machinery must occur in the same row. Although the lines can be repaired between harvest of each cultivar, it is difficult to juggle with the logistics during hectic times, thus water is often delayed for longer periods of time allowing for more than needed water stress. During this time, partial defoliation, reduced photosynthesis and reduced assimilation can occur later in the year and can be exacerbated if water stress is induced. Irrigation deprivation reduces carbohydrate accumulation (Klein et al., 2001; Esparza et al., 2001) both possibly affecting the tree health and yield potential for subsequent years (Klein et al., 2001; Goldhamer & Viveros, 2000; Esparza et al., 2001).

Pests and diseases

The current almond harvest is very dependent on dryness of the fruit, this is turn is often a result of on weather conditions and orchard managements practices. Depending on the cultivars present in the orchard and the demand of the fruit, almond fruit can be exposed to several pests between shake and pick up (Flint, 2002) Two main pests that can be detrimental to yield are Navel orange worm (NOW) and Hull rot (HR) (Haviland et al., 2019; Flint, 2002, p. 61-71 & 137-139). Navel Orange Worm (NOW) (*Amyelois transitella* (Walker)) along with hull rot (HR), are the most economically significant almond pests and diseases in the California orchards (Haviland et al., 2019; Flint, 2002, p. 61-71 & 137-1390; Duncan et al., 2019). These pests are primarily caused by the fungal pathogens *Rhizopus stolonifer* (Ehrenb:Fr.) Vuill. and *Monilinia fructicola* (G. Wint. Honey) respectively. Farmers battle every year to control these pests and it is estimated that they pay between $131 to $217 per acre to help control them (Duncan et al., 2019).

Navel Orange Worm

California is home for dozens of cultivars, but Nonpareil is approximately 40% of total production in the state due to its market demand. Nonpareil is considered a soft-shell almond (Soderstrom, 1977) with moderate low shell seal strength (Soderstrom, 1977; Hamby et al., 2011). This is important because NOW thrives better particularly in these types of cultivars, where damage can be as high as 30% of the hanging fruit (Higbee & Sigler, 2009). During the start of hull split to the time of harvest, NOW females deposit their eggs in the suture of hull split almonds from where the larvae bores through the shell and directly damages the fruit by rasping and boring it as a food source (Wade, 1961). Once the larvae install themselves inside the shell, they can undergo several instar stages where it deposits frass and webbing along the way, thus reducing the marketability of infected kernels (Campbell, 2003; Phillips et al., 1980).

During a year, growers can expect three to four NOW flights or generations, which are dependent on weather conditions and the efficacy of pest control techniques (Duncan et al., 2019). The longer NOW larvae are permitted to feed, and the greater the number of generations the higher the level of damage done to the almond crop will be for that particular year (Wilson 2021; Wilson et al., 2020). Several techniques are used to control damage produced by this pest (Duncan Et al., 2019). NOW must also be controlled as they are known to be associated with infection from the fungus Aspergillus spp. (Schatzki and Ong, 2001). Aspergillus spp. is known to cause aflatoxin contamination in almonds, these metabolites may cause cancers in humans (Aguilar et al., 1993; Fujimoto et al., 1994; Hosono et al., 1993).

Hull Rot

Hull rot, a major infestation in almonds is caused by *Rhizopus stolonifer* and *Monilinia fructicola*, both fungal pathogens (Teviotdale et al., 1994). Hull rot is more prominent at hull split time and can be worsened by humid weather conditions (Teviotdale et al., 1994; Ogawa, 1980; Adaskaveg, 2009; Teviotdale et al., 2001). Once almond hulls and/or shells are infected by the fungi, gray and brown lesions are formed on the outside of the almond hull, which is one of the major characteristics of the infected fruit. During this time, there are toxins produced by causal agents, which can infect tree shoots and spurs adjacent to the infected fruits (Mirocha et al., 1961). The toxins can cause necrosis and death of the shoots and spurs infected, if infection is unattended, it can lead to branch dieback and ultimately death of an entire shoot. This in turn, can reduce the amount of fruiting spurs produced by almond trees at a given year and/or life span of the tree, thus reducing tree yield and ultimately the grower's profit (Teviotdale et al., 1996; Teviotdale et al., 1994).

Since the causal toxins of dieback are transported through the peduncles it is the timing of infection and the duration of attachment of the fruit to the tree will increase the chance of toxin transport to the stem and increase the severity of infections by HR (Teviotdale et al., 1994). Teviotdale et al. (1994 & 1995) concluded that the longer the almond fruit is allowed to dry on the tree the higher the risk of infection would be for Hull Rot.

Orchard floor sanitation

One very important aspect of current food quality demands is the desire for sustainable and cleaner food. In the recent years, we have seen a surge of food quality control protocols across all farms and crops (Isaak & Lentz, 2020; Barbosa & Carvalho Junior, 2022). Almost the entire farming industry is moving towards sustainable production of some sort and demand continues in the conventional and organic sectors (Isaak & Lentz, 2020; Thompson, 1998; Li et. al., 2007; Zander & Hamm, 2010). The latter is one of the main drivers of the 2025 California Sustainable Goals, as these goals highlight and entice the overall orchard and environmental health orchards activities do have in the ecosystem (The Almond Board of California, 2019). One particular concerning activity surrounding the almond industry is the need for almonds to touch the ground, which may be a detrimental to food quality. Almonds are dropped to the ground and dried in their windows between 4 to 14 days until desired dryness is achieved (Riel et al., 1996). During the drying time, almonds can easily become food for ants, and rodents (Flint, 2002; Bentley et al., 1982), where they can be moved around neighboring orchards, possibly spreading disease and pests as well as reducing yield and profits (Duncan et al., 2019). During this time, almonds can be exposed to undesirable moisture that can be detrimental to fruit quality (Luo et al., 2020).

Almond contact with the ground can also expose fruit to undesirable pesticides. This is a particular problem with on-ground harvest since orchards must be sanitized or cleansed with cocktail of herbicides prior to harvest to ensure proper almond collection. This procedure is also recommended as a step to control other pests such as ants (Bentley et al., 1982). Ant-controlling pesticides are often applied prior to harvest to ensure the ant population is reduced or eradicated by harvest time ("Ants / Almond / Agriculture: Pest Management Guidelines / UC Statewide IPM Program (UC IPM)", 2022). These products are often applied as bait that may or might not make it into the harvest bins since they can be applied up to the same day of harvest. Clinch ® for example, is a Abamectin bait whose active ingredient starts to degrade rapidly and is no longer effective after 24-36 hours after application ("Clinch® Ant Bait," n.d.). Other products such as Roundup ® can be applied as close as 3 days prior to harvest (Roundup Label), although there is no direct link between the pesticides mentioned and health-related causes, there might a certain consensus on how much the public wants their food to be exposed to pesticides.

The amount of in tree and on ground drying time increases the opportunity for fungus, viruses, carcinogens, and enteric microorganisms to interact with edible fruit. One major concern is the exposure of almond fruit to aflatoxins that are known to cause negative health conditions in humans and possibly cancers (Aguilar et al., 1993; Fujimoto et al., 1994; Hosono et al., 1993). While there is no direct evidence that almonds that do not touch the ground would have reduced contamination, it is a very sound presumption (King et al., 1970; Pan et al., 2012). Besides the possible contamination certain vectors can cause, exposure to these risks can also reducing the overall yield of a particular orchard (Duncan et al., 2019).

One of the major characteristics of almond orchards is the cleanliness and flatness of their orchard floors. This is a required cultural control technique used to facilitate fruit pick up from the floor (Kester et al, 1996)). Fruit is often left behind in weedy, cracked, and uneven floors due the physical design of the blowers, sweepers, and picking machines used for harvesting (Riel et al., 1996). If there is presence of weeds, cracks, or uneven surfaces, the increased duration and decreased efficiency of each machine pass can add substantially to grower costs.

Typically, there is at least three types of machines used for harvest. The blower/sweeper is one of the first machines used after almonds had been shaken from their trees. The blower and sweeper can blow the almonds from one row to another, and it is easier to blow even, clean, and solid surfaces compared to uneven, weedy, and cracked surfaces. At the same time, the sweeper can only sweep rows that had been blown into narrower windrows. Again, the presence of foreign objects, plants, and animals can make this task difficult. Finally, the pickup machines can only pick up almonds that the sweepers had windrowed into 2 feet by two to three inches tall windows (Faulkner, 2012). If the blower doesn't do a good job at pushing the almond onto the opposite row, then the sweeper cannot bring them into windrows and thus the pickup machine will never pick them up.

To achieve proper and maximum fruit pick up, almond orchard floors have to be as clean from debris as possible, many resembling a tabletop or floor. Often, almond orchards are treated with a cocktail of herbicides that control the diverse weed population, these treatments may occur multiple times a year (Flint, 2002, p. 158-181). Although herbicides are becoming more targeted to certain species, it is common practice to use broad-spectrum herbicides to achieve broad control of the population present in the orchard. Another method to control weed population is the avoidance of moisture between the rows as much as possible, this latter also being one of the main reasons growers are adopting the double drip irrigation system compared to other irrigation regimes (Torrecillas et al., 1989; Shock 2013; Grattan et al., 1988). To achieve flat surfaces, it is common to level the orchard floors during the non-bearing years of the trees to ensure the leveling is complete once trees are bearing and to avoid disturbances during the harvesting years. However, occasionally, orchards floors mush be re-levelled during the lifetime of the trees planted. This ensures the maximum number of almonds to be picked up during harvest.

The aforementioned cultural practices are beneficial to growers, but they may bring negative effects on the soil ecosystems. One negative effect is the excess compaction of the in row space, which limits the growth of any vegetation that can be beneficial to the root systems and nutrient uptake as this may provide soil aeration and percolation (Grattan et al., 1988; Shock 2013) benefits. Adding localized (drip, micro sprinkler) irrigation does limit the extent to which roots can expand beyond the wet zone, which may limit the utilization of the full orchard area for nutrient uptake. Another negative effect of excess compaction is the possible run-off of applied chemical elements (such as herbicides and fertilizers). This can add a significant amount of nitrates and other pollutants to the ecosystem that not only disrupt the microorganism biodiversity but can also cause serious human health issues such as premature babies and blue baby syndrome in pregnant women (Manassaram et al., 2006; Bahadoran et al., 2018).

3.2 Off-ground harvesting method

Ideally, off-ground harvesting consists in using mechanized machines large enough to shake and catch the fruit before it touches the ground. In an ideal system the mechanized system would also remove the hull and shell from the kernel. The hulls and shells would be recycled back and incorporated into the soil, while only the kernels would be taken for further processing. Currently, there are several options to perform these practices, however, the machines can only do the job partially, as certain steps, such as removing fruit from the orchard entirely is challenging since fruit needs to be dried before this step can be carried out. Additionally, there are not functioning de-hulling machines that are operating commercially in California.

3.2.1 Possible Benefits of Off-ground harvest

Agriculture is a dynamic industry that needs constant adjustment to meet the demand of current and future markets. Almond harvest has made great improvements throughout the years, but it is believed that it can be improved greatly by using newer and sophisticated technology that not only can reduce current sustainability problems but can also provide doorways for newer improvements. One of these developments is the implementation of off ground harvest that consists in avoiding the fruit ever touching the ground as well as the possibility of early harvest. This newer technique would improve the sustainability of the industry. Off-ground harvest would bring many benefits that are currently unavailable. One significant improvement would be the reduction of dust from 11,000+ tons to virtually zero (Faulkner & Capareda, 2012). This single step alone would be considered a major milestone to the industry in terms of environmental sustainability, human, and tree health. The suggested technology may also open doors to other improvements that are now considered unattainable with current harvest practices. These benefits are not limited to reduced use of herbicides, pesticides, and fertilizers, increase of water use efficiency, increase microflora present in almond orchards, increased element uptake efficiency, reduces pest damage, reduced susceptibility to carcinogens, reduced production of green gasses, potential increase of yield by reducing the amount of water stress of trees throughout the season, these are some among many other benefits that may come from using the Off-ground techniques.

3.2.2 Challenges in Off-ground harvesting method

There are many concerns about the adaptation of off-ground harvest techniques. Some of them include the potential amount of premature fruit drop (known as windfall in the industry), which is an unknown variable but an open concern among farmers. A second issue is the possible amount of moisture in fruit at time of harvest, this would greatly affect drying costs and possibly require new or better fruit drying methods. Typically, fruit drying is an added costs to farmers but there is also the concern of the costs associated with acquiring new machines and disposing of older machines. Additionally, the current off ground machines available are often made as one-fit-for-all, but there is a great variability among orchard physical features (such as age, tree size, trunk circumference, orchard floor characteristics) that might require further modifications.

3.2.3 Conclusion

Almonds will remain profitable for the foreseeable future in California. Increasing labor prices and shortages can be partially addressed with improvements in mechanization and will be essential for the sustained production of almonds in the future. To address issues of dust, drought, soil health and food safety, off-ground harvest innovations are needed. This presents opportunities for improvements including off-ground harvest and earlier harvesting that can mitigate yield loss, dust, and enable the development of a more sustainable orchard ecosystem.

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Chapter 2: Quantitative impacts of premature fruit drop in almond yield

1. Introduction

The global demand for almonds has grown dramatically and currently almonds is one of the 2 most important crops in California. Almonds can be found in more than 16 counties across the state (Sumner et al., n.d) where they have been planted on more than 1.3 million acres (USDA/NASS, 2022). Almond production has increased from around 370 million pounds (kernel) in 1995 to around 2.9 billion pounds (kernel) produced in 2020 (USDA/NASS, 2022). Their demand and growth across the globe are likely to increase in the upcoming years or decades (Sumner et al., n.d, USDA/NASS, 2022).

Almond production has become a subject of concern among environmental advocates due to the intensive agricultural activities required to cultivate, harvest, and process them. With ongoing shifts in social sentiment and the adoption of healthier lifestyles, the demand for sustainable high quality food chain by consumers, government, and regulatory agencies has placed almond operations in the spotlight, particularly in the improvement of practices that aid with water efficiency, dust abatement, and pest control. This has led to the formation of the California Almond Sustainability Program or CASP, which has been developed to ensure almond growers continue producing top quality fruit with the least amount of environmental disturbance possible (Almond Board of California, 2019) in hopes to improve long-term sustainable farming operations.

There are multiple approaches to improve almond practices including off-ground harvest which has considerable potential for dust abatement and for improvement in soil health and farming practices (Niederholzer, 2016). Off-ground harvest, however, has the potential unknown loss of marketable yield in the form of windfall or premature fruit drop. To date, there has been no record of any previous windfall study in almonds. The main objective was to characterize the windfall dynamic and estimate fruit drop per cultivar. Our initial hypothesis was that ‘windfall’ may be a significant factor and that the amount of windfall would differ by management practice, cultivar, and location.

2. Materials and Methods

2.1 Orchard selection

Several regions within the Central Valley were chosen for the purpose of conducting surveys and monitoring activities in collaboration with various partners from the University of California and the industry. Multiple orchards were chosen with the aim of optimizing the quantity of cultivars, tree age, and management variations. Figure 1 displays the geographical distribution of the locations. Additionally, the state was divided into three regions that were denominated into South (Bakerfield/Shasta to Fresno/Manning Ave), Central (Fresno/Manning Ave to Stockton/Eight Mile Rd), and North (Stockton/Eight Mile Rd to Corning/South Ave).

Each orchard selected had at least one and no more than three cultivars (refer to figure 2). Orchards were voluntarily selected by growers, many of which asked to keep certain information confidential. Each orchard had to be at least 6 years old to represent bearing orchards, they had to be relatively healthy and must be managed as a typical orchard in California; avoiding certain systems such as high density, very low density, and organic farms, flood irrigation, and greenhouse/indoor farms. Additionally, any orchard less than 5 acres was avoided. An orchard summary can be found in Table 1 with detailed information about each selected orchard. Initially, more than 100 orchards were enrolled to be surveyed, but due to logistics and lack of labor, the number of orchards was reduced significantly. The same orchards were surveyed in 2019 and 2020, except that due to labor shortages and pandemic events, only 47 orchards were visited in 2020 instead of the 65 visited in 2019. Carmel, Independence, Monterrey, Nonpareil, Wood Colony, and Fritz cultivars were included in both years.

2.2 Sampling method & data collection

The fruit drop rate was measured on individual almond trees in a given orchard by setting up one sampling kit per tree (the sampling kit is a rope/string with 3 bar codes on the top, middle, and bottom of the string and a photograph could be taken at each barcode to record the number of almond fruit on the ground at that moment), with the sampling kits facing different directions (one along the tree row at 0 degrees and the other is perpendicular to tree row at 90 degrees). Figure 3 shows an artistic view of the sampling kits used. The images were taken starting at the barcode closest to the trunk along the tree line, then followed by images taken closest to the trunk across the tree line.

Using the sampling kit we recorded the total number of almonds present at the specific location for that day (this could be normalized to a fruit drop rate once the yield was recorded after harvest). Data was taken for each cultivar. Three representative trees (reps) of each cultivar at each orchard were then selected to be monitored (refer to figure 2). The types and number of cultivars per orchard varied from orchard to orchard, but the main cultivar of interest (Non-Pareil) was typically 50% of the trees planted in a given orchard. The remaining trees had an equal proportion across the remaining cultivars, e.g., if there are two more cultivars in the same orchard, then each would have been planted accounting for a 25% of the remaining total. The sampling of trees for each cultivar was done in triplicate, but the replicates were taken at different positions in the field (top, middle, bottom) and at different rows (figure 2).

One of the goals of the study was to see how fruit drop changes over time, and hence sampling was taken on a weekly basis for each orchard when possible (sometimes sampling days were missed due to external circumstances). Sampling began after the hull split date (the hull of the almond that contains the kernel starts to split round ~30-40 days before it can be harvested. Sampling days were recorded as days after initial hull split date i.e., post hull split (PHS). Sampling continued until the harvest date of that orchard, which varied significantly (as low as 15 days or up to 70 days). A sample of the final images taken immediately before and after shaking the trees can be found in image 4.

The harvest date varies due to many factors but particularly due to limitations on availability of harvesting equipment. Larger orchards tend to harvest earlier as they often own their own equipment or have firm contracts with harvesting companies, while smaller orchards may have to wait way past their ideal harvest date.

In addition to the drop rate information, environmental conditions were recorded from the nearest weather station using publicly available data. Since the data is public, and not specific to this experiment, the data is on a ¼-2-mile radius that sometimes contains multiple orchards. A water stress indicator (mild, moderate, heavy, severe) was also recorded post-harvest based upon the orchard's owner's subjective assessment.

2.3 Fruit Drop Calculation

To estimate premature fruit drop and the possible drivers, frequent counts of windfall almonds under selected trees were conducted and contrasted with total orchard nut yield at grower harvest date using each individual orchard yields respectively. Below is a more detailed process:

1) Each representative tree was visited once a week and images were taken from the various locations around the tree. This included 3 images along the

row (0-degree images), and 3 images across the rows (90-degree images), using the sampling kits mentioned above (figures 3 and 4).

2) The fruit in each image were counted and tabulated to estimate the number of fruits dropped per tree, assuming the fruit would be distributed across the entire area beneath each tree.
3) A representative fruit sample was then obtained, which was dried and cracked out to get average fruit dry weight and crack out ratio for each cultivar and for each orchard.
4) Using the average amount of fruits dropped per tree calculated from above, the average dry weight of fruit, and the crack out ratio of each respective cultivar and orchard, as well as the density of trees per acre, the total fruit drop yield per acre was calculated.
5) The percentage fruit drop at different time stages was then calculated by dividing the calculated total fruit drop yield per acre (above) by the total orchard nut yield at grower harvest.

2.4 Statistical analyses

Data analysis was conducted using different techniques. The fruit drop percentage, graphing, and descriptive statistics analysis was performed using Microsoft Excel software. Using the hull-split date, harvest date, and the calculated total fruit drop yield per acre as well as total orchard nut yield at grower's harvest, it was possible to graph each orchard's fruit drop percent with respect to days post hull split. Using this information, it was then possible to tabulate the maximum fruit drop immediately before harvest from each orchard (all cultivars) and create histograms that gave us a visual representation of the frequency of fruit drop percent across the study.

A deeper study of the relationship between fruit drop and its potential factors was performed using a mixed linear regression model within the base R software (Lenth, 2020; Kuznetsova, et al., 2017; Bates et al., 2015). Where cultivars and orchards being the random effects across the different parameters, and only the most informative ANOVA table was selected and used in the results section.

Additionally, there was a secondary study (Poisson distribution) performed to estimate the probability of fruit drop every 7 days and the possible factors affecting it, to match and contrast with our initial mixed linear regression study. This last study was performed using Poisson distribution under SAS software using the Kenward-Roger degrees of freedom method as well as the fixed effects SE adjustment.

3. Results

3.1 Descriptive statistics

As expected, windfall is sporadic, generally very low but occasionally significant. Statistical analysis shows a significant positive effect of harvest days past hull-split and orchard water status on windfall. This is most significant in late cultivars likely due to extended water stress particularly in orchards with an inability to maintain irrigation on late cultivars. The most significant cause of 'windfall' is equipment passing through the orchard, thus dropping the fruit mechanically. This typically occurred in later cultivars after the earlier cultivar were harvested.

Over all orchards and years, Nonpareil had the lowest sensitivity to windfall followed by Fritz and Independence, while Monterrey had the highest windfall with Wood Colony and

Carmel also being sensitive cultivars to windfall. The chance for windfall increases dramatically with the delayed harvest and with late season harvest (September onwards).

In 2019, windfall in Fritz was minimal with only a single, very late harvested orchard exhibiting greater than 2% windfall. The greatest windfall in 2019 was seen in Monterrey and Wood Colony with 5 of 23 orchards exceeding 5% windfall and 3 orchards exceeding 10% windfall. In 2020, Independence and Nonpareil had the lowest recorded fruit drop percent with only 5 orchards exceeding 5% windfall and the majority of orchards (22 of 27) having windfall of less than 3%. Very high windfall (>10%) was observed in 3 orchards that had extreme delayed harvest of >40 days post hull split. In 2020 the late cultivars Carmel and Monterrey accumulated the largest average fruit drop with 7 of 15 orchards exceeding 10% windfall.

3.1.1 *2019*

Maximum Accumulated Fruit Drop

During 2019, maximum fruit drop was recorded immediately prior to grower shaking and ranged between 0.10% to the highest of 19.80% in a single orchard on the eve of harvest. Eighty-six percent of the orchards had less than 5% fruit drop across all the cultivars, with only 9 orchards having more than 5% fruit drop. The cultivars surveyed were Carmel, Independence, Monterrey, Nonpareil, Wood Colony, and Fritz. Nonpareil cultivar had the lowest windfall percentage, while Monterrey had the largest.

Some premature fruit drop occurs in almost all orchards though it is highly variable. As seen in figure 1 (A & B), the range of fruit drop immediately before harvest ranges drastically even among the same cultivars (Figure 1B). The data used to build the histograms was the recorded amount of windfall at the very last day of the survey. This can be considered as the maximum fruit drop observed at every orchard. It was observed that prior to any mechanical intervention of any kind, such as hull split sprays, weed sprays, and occasional pruning, there was little to no fruit drop in any orchard. However, fruit drop did occur after any motor-driven vehicle passed through the data collection row. The effect of machine passes becomes greater in later varieties, where the number of machine passes could be between 6 to 12 in some instances. The implementation of off-ground harvest would dramatically reduce orchard passes from the current 6-12 to 2-4.

Accumulation of Fruit Drop

The previous section describes the maximum fruit drop at the eve of harvest. However, all the orchards were visited multiple occasions, starting around 5% hull-split until no more than a day prior to harvest. The goal was to try to estimate the pattern of fruit drop accumulation and compare these values as if we had harvested at different times. The results for 2019 are shown in figure 1 C. Each line represents one orchard, and, in all cases, we observe an increase of fruit drop as days post hull split accumulate. Nonpareil had the lowest fruit drop accumulation across the entire survey, while Monterrey and Wood colony have significantly higher fruit drop.

Using Nonpareil as an example (Figure 1 D) it is observed that windfall in most orchards does not commence until 15 days post hull split. The rate of fruit drop then increases as the fruit hangs longer and when fruit is 30 days post hull split, the rate of fruit drop grows exponentially. Most growers harvested between 26 to 37 days post hull split with increasing windfall over time.

3.1.2 *2020*

Maximum Accumulated Fruit Drop Average

During 2020, the same orchards were visited but due to lack of labor, a smaller group of 47 was successfully surveyed. The range of fruit drop was 0.2% to 30% in one extreme example, overall drop was much greater in 2020 than 2019. This corresponded with an increase of days the fruit hanged from the trees post hull split, which in many cases was doubled from the previous year (Figure 2A and 2B). In 2020, 61% of the orchards had less than 5% fruit drop immediately before harvest. Nonpareil and Independence had the lowest average windfall percentage while Monterrey once again had the largest windfall percentage immediately before harvest.

Fig 2 (A & B) illustrates a significantly greater windfall in 2020 than in 2019. In 2020 fruit remained in orchards significantly longer than in 2019 (Table 1 B), with harvest delayed for multiple reasons. The Covid lockdown had severe effects on the speed of harvest and the amount of labor available. Harvest not only started later but it was often prolonged far more than is acceptable in a “normal” year. This delay coincided with heavier water stress, excessive drying of the abscission layer and increase in the senescence processes. Orchard health was visually much worse in 2020 (figure 2 E) with many orchards showing excessive leaf drop and wilt.

Accumulation of Fruit Drop

Similar to 2019, in 2020 all 47 orchards were surveyed (visited) multiple occasions from 5% hull split until immediately before harvest. Figure 2 C (each line represents an orchard), shows greater fruit drop than 2019 with a substantially delayed harvest in a majority of orchards.

In 2020, Independence and Nonpareil had lowest fruit drop, while Monterrey had the greatest. In Nonpareil (Figure 2 D), fruit starts to drop at 15 days post hull split and continues accumulating until it is harvested. As the fruit starts to reach the 20-25 days post hull split, fruit drop grows exponentially. Unlike 2019 when average harvest date was 20-30 days post hull split, in 2020 harvesting commenced on average 40 days post hull split.

Using a mixed linear regression model (Table 1C) we determined the primary drivers of windfall. Hull split date, days past hull split and cultivar where measured values while the effect of tree stress was categorized from verbal communication with grower and knowledge of the presence of cultivar specific irrigation systems. The most significant determinant of windfall was the number of days fruit hangs from the trees and the level of water stress both of which had a significant positive effect on windfall. Other significant factors such as the soil temperature and region influenced windfall with the typically hotter and drier conditions in the south may have exacerbated windfall, particularly in the late harvested cultivars in 2020.

3.2 Mixed Linear regression

Table (C) shows results of mixed modelling analyses. The low variance of orchards and cultivars masks the significant range of standard deviation. The occurrence of fruit drop is thus highly dependent upon local orchard conditions, particularly environment effects.

Using the different parameters (Av. Eto, water stress levels, elevation, soil temperature, and days post hull split), our ANOVA table indicates a strong and positive relationship between fruit drop and days fruit stays hanging from the tree, water stress levels (severe in particular), and regional location of orchards. In our study, severe or extreme water stress increased fruit drop by nearly 2%. Additionally, the South state exhibited greater fruit drop than North and Central state regions. Thus, indicating that the longer a fruit stays in a severely water stressed tree in the south regions of California the higher the fruit drop.

3.3 Poisson Distribution

The Poisson distribution is a discrete probability distribution that is utilized to model the count of events taking place within a predetermined time or space interval. It is often used for the examination of count data characterized by infrequent, stochastic, and uncorrelated events.

The distribution was mainly used due to the rare occurrences of windfall or premature fruit drop, which have a low average rate of incidence in comparison to the overall number of potential events. The dataset used for the Poisson distribution contained data on the number of fallen almonds within a 7-day period (FallenNuts7day), then it was transformed into a log (Link function) system to linearize the Poisson distribution, since the data is not possible to normalize in linear regression models. The Variance Matrix blocked by “Orchard” was set up as it was assumed that each orchard will result in a variable response. Kenward-Roger degrees of freedom method was employed to adjust for the number of parameters estimated in the model (Table 3A).

The AICc (Akaike Information Criterion corrected) criterion was utilized in the execution of the stepwise regression analysis. The process of variable selection in a model involves evaluating the potential of each variable to enhance the model's fit while simultaneously considering the number of parameters in the model. The dependent variable was FallenNuts7day. The findings of the analysis indicate that the most suitable model comprises the following variables: Average Evapotranspiration (AvEto), Week, and Rootstcok (Table 3B and figure 3A). The AICc corrected sample size value implies that the model exhibits a high degree of congruence with the data, and the probability of a more rudimentary model yielding a superior fit is low.

In this model, average Evapotranspiration or AvEto exerts the most substantial positive influence on fruit drop, followed by time post hull split (week), and Rootstcok (Krymsk).

4. Discussion

The higher windfall in 2020 can be explained by delayed harvest across the state due to Covid, severe water stress, and air quality issues, however this does not appear to be a complete explanation and the possible role of smoke from fires and plant-water relations should be considered (Singh et al., 2020; Goldhamer & Viveros 2000; Klein et al., 2001; Esparza et al., 2001). As late harvested cultivars are generally only 15-30% of the total yield and generate lower prices, the loss from an occasional windfall event in Monterey is less economically significant than if it occurs in Nonpareil (Sumner et al., n.d; Faulkner & Capareda 2012).

Nonpareil and Independence shows significantly less fruit drop in both years while Monterrey has the heaviest fruit drop percentages. In many of the worst affected orchards, the late harvested cultivars were susceptible to the greatest windfall as a result of a long period of reduced irrigation (Klein et al., 2001; Faulkner & Capareda 2012) and numerous equipment passes through the field associated with early cultivar harvest. In all cultivars, a delay in harvesting or imposition of a strong stress post hull split dramatically increases windfall. This was most evident in 2020 where water and labor shortages delayed harvest in many locations (Singh et al., 2020; Pu & Zhong, 2020).

Windfall was dramatically lower at 12-17 days post hull split than at the 20-30 days when harvest typically happens. At 15 days post hull split, none of the Nonpareil and Independence orchards of the 112 orchards surveyed had a windfall exceeding 0.7%. In later cultivars at 15 days post hull split, 3 and 4 of 50 sampled orchards (2019, 2020) exhibited windfall above 5%, which is unacceptably high. Several of the highest windfall orchards exhibited substantial water stress due to inability of growers to maintain full irrigation to late cultivars, which causes tree stress and thus can accelerate leaf aging, reducing CO2 assimilation and ultimately leaf abscission (Klein et al., 2001; Esparza et al., 2001).

According to Kester & Micke (1996), water stress can hasten ripening, this however can also increase the number of sticktights making nut removal more difficult (pg. 255-257)

5. Conclusion

Overall, windfall or fruit drop is present in most of the orchards though it is a sporadic phenomenon that results from multiple and interconnected factors, most significantly being harvest date post hull split, machine knockdown, water stress, and excess fruit drying. Windfall is almost non-existent in Nonpareil except under extreme conditions of drought or very delayed harvest, and rarely exceeds 5% in the latest harvested cultivars becoming markedly worse with extended harvest delay or water stress. Windfall is highly correlated with the days past hull split at which harvest occurs and is exacerbated by water stress and equipment passes (machine knockdown) through the orchard.

2020 represented a 'perfect storm' for windfall with Covid and smoke delaying harvest, smoke exacerbating tree stress response, and limitations on water availability in many regions. When harvested at 15-20 days post hull split (5-10 days prior to current practice), windfall was less than 0.5% in nonpareil and independence and <3% in all but two orchards with late harvest cultivars. Since late cultivars represent just 25% of the planted trees the true impact of windfall on whole orchard productivity would be proportionately reduced.

These data suggest that windfall in traditional orchard harvesting practices (on-ground) is predominantly man-made and can be minimized by avoiding delayed harvest especially in late cultivars. Windfall is mitigated by avoidance of prolonged tree dry down and reduction of orchard equipment passes. In the two years of trial, in 60 orchards spanning the major growing regions we did not record a single event of windfall that could be unequivocally attributed to a strong 'wind' event. Freak, high wind events and highly localized micro-tornado's/dust devils can occasionally cause severe windfall though they are rare and highly localized. It is expected that the same environmental conditions (water stress and delayed harvest date) that cause the fruit drop measured in this project, would also exacerbate dame from true wind driven fruit drop. The same mitigation strategies would help prevent this occurrence.

The use of off-ground harvesters has great potential to improve almond production practices and can be expected to reduce windfall events for a number of reasons 1) off-ground harvest requires significantly fewer machine passes which is the primary cause of ‘windfall’, 2) off ground harvest can be effectively performed earlier than traditional on ground harvest thereby reducing prolonged stress 3) off ground harvest permits the rapid resupply of water post-harvest as nuts will not be lying in the wetted root zone, 4) the removal of the sweeping/blowing operation reduces damage to irrigation systems and thereby reduces plant stress, 5) off-ground harvest facilitates use of soil amendments such as composts, hulls and shells etc. and protects surface soil from degradation during the blowing/windrowing phase and thus improves soil water retention and reduces plant stress.

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Tables and Figures

Table 1: A) Orchards surveyed in 2019 and 2020. Note that each cultivar was counted as one individual orchard.

Name	Cultivar	Row Space (ft)	Tree Space (ft)	Trees Per Acre	Rootstock	Age (Yrs.)	Irrigation Type	Row Orientation
277	Carmel	23	15	126	Brights	7	Double line Drip	North to South
278	Carmel	24	15	121	Brights	7	Double line Drip	North to South
27N	Carmel	24	18	101	Nemaguard	15	FanJet	North to South
8N	Carmel	24	21	86	Nemaguard	19	Double line Drip	East to West
Texas	Carmel	22	22	90	Nemaguard	38	Double line Drip	East to West
F-95	Carmel	24	16	113	Nemaguard	6	MicroSprinklers	East to West
F96-97	Carmel	24	16	113	Nemaguard	11	MicroSprinklers	East to West
F-98	Carmel	24	16	113	Nemaguard	12	MicroSprinklers	East to West
Field 2	Carmel	20	22	99	Nemaguard	17	FanJet	East to West
Field 3	Carmel	20	22	99	Nemaguard	12	FanJet	East to West
Field 4	Carmel	20	22	99	Nemaguard	15	FanJet	East to West
MA47	Carmel	24	15	121	Titan	6	Double line Drip	East to West
MA48	Carmel	24	15	121	Titan	6	Double line Drip	East to West
MB5	Carmel	24	15	121	Titan	6	Double line Drip	East to West
RI28	Carmel	22	13	152	Krymsk	8	Double line Drip	East to West
SR4	Carmel	24	16	113	Titan	6	Double line Drip	East to West
270	Fritz	24	16	113	Titan	10	Double line Drip	East to West
271	Fritz	24	15	121	Titan	9	Double line Drip	East to West
272	Fritz	24	15	121	Titan	11	Double line Drip	East to West
28N	Fritz	24	20	91	Nemaguard	6	Double line Drip	East to West
9S	Fritz	24	20	91	Nemaguard	11	Double line Drip	East to West
445	Independence	22	13	152	Nemaguard	6	Double line Drip	North to South
588	Independence	22	13	152	Nemaguard	6	Double line Drip	North to South
1026	Independence	22	13	152	Nemaguard	6	Double line Drip	North to South
Cesar	Independence	22	15	132	Nemaguard	6	MicroSprinklers	North to South
Hanson 1	Independence	22	13	152	Nemaguard	6	Double line Drip	North to South
Hanson 2	Independence	22	13	152	Nemaguard	6	Double line Drip	North to South
17	Monterrey	24	18	101	Nemaguard	6	Double line Drip	East to West
265	Monterrey	24	15	121	Titan	9	Double line Drip	East to West
270	Monterrey	24	16	113	Titan	10	Double line Drip	East to West
271	Monterrey	24	15	121	Titan	9	Double line Drip	East to West
272	Monterrey	24	15	121	Titan	11	Double line Drip	East to West
27N	Monterrey	24	18	101	Nemaguard	15	FanJet	North to South
28N	Monterrey	24	20	91	Nemaguard	6	Double line Drip	East to West
8AW	Monterrey	24	21	86	Nemaguard	19	Double line Drip	East to West
F-95	Monterrey	24	16	113	Nemaguard	9	MicroSprinklers	East to West
F96-97	Monterrey	24	16	113	Nemaguard	11	MicroSprinklers	East to West
F-98	Monterrey	24	16	113	Nemaguard	12	MicroSprinklers	East to West
HH1	Monterrey	24	15	121	Nemaguard	7	Double line Drip	East to West
Ratto 1	Monterrey	22	13	152	Nemaguard	7	MicroSprinklers	East to West
17	NonPareil	24	18	101	Nemaguard	6	Double line Drip	East to West
265	NonPareil	24	15	121	Titan	9	Double line Drip	East to West
270	NonPareil	24	16	113	Titan	10	Double line Drip	East to West
271	NonPareil	24	15	121	Titan	9	Double line Drip	East to West
272	NonPareil	24	15	121	Titan	11	Double line Drip	East to West
277	NonPareil	23	15	126	Brights	7	Double line Drip	North to South
278	NonPareil	24	15	121	Brights	7	Double line Drip	North to South
27N	NonPareil	24	18	101	Nemaguard	15	FanJet	North to South
28N	NonPareil	24	20	91	Nemaguard	6	Double line Drip	East to West
8AW	NonPareil	24	21	86	Nemaguard	19	Double line Drip	East to West
8N	NonPareil	24	21	86	Nemaguard	19	Double line Drip	East to West
Texas	NonPareil	22	22	90	Nemaguard	38	Double line Drip	East to West
9S	NonPareil	24	20	91	Nemaguard	11	Double line Drip	East to West
F-95	NonPareil	24	16	113	Nemaguard	9	MicroSprinklers	East to West
F96-97	NonPareil	24	16	113	Nemaguard	11	MicroSprinklers	East to West
F-98	NonPareil	24	16	113	Nemaguard	12	MicroSprinklers	East to West

Field 2	NonPareil	20	22	99	Nemaguard	17	FanJet	East to West
Field 3	NonPareil	20	22	99	Nemaguard	12	FanJet	East to West
Field 4	NonPareil	20	22	99	Nemaguard	15	FanJet	East to West
HH1	NonPareil	24	15	121	Nemaguard	7	Double line Drip	East to West
Jeffrey 17	NonPareil	22	13	152	Nemaguard	6	Double line Drip	East to West
MA47	NonPareil	24	15	121	Titan	6	Double line Drip	East to West
MA48	NonPareil	24	15	121	Titan	6	Double line Drip	East to West
MB5	NonPareil	24	15	121	Titan	6	Double line Drip	East to West
Ratto 1	NonPareil	22	13	152	Nemaguard	7	MicroSprinklers	East to West
Ratto 3	NonPareil	22	13	152	Nemaguard	6	MicroSprinklers	North to South
RI28	NonPareil	22	13	152	Krymsk	8	Double line Drip	East to West
SR4	NonPareil	24	16	113	Titan	6	Double line Drip	East to West
Ratto 3	Wood colony	22	13	152	Nemaguard	6	MicroSprinklers	North to South
265	Woodcolony	24	15	121	Titan	9	Double line Drip	East to West
277	Woodcolony	23	15	126	Brights	7	Double line Drip	North to South
278	Woodcolony	24	15	121	Brights	7	Double line Drip	North to South
HH1	Woodcolony	24	15	121	Nemaguard	7	Double line Drip	East to West
MA47	Woodcolony	24	15	121	Titan	6	Double line Drip	East to West
MA48	Woodcolony	24	15	121	Titan	6	Double line Drip	East to West
MB5	Woodcolony	24	15	121	Titan	6	Double line Drip	East to West
RI28	Woodcolony	22	13	152	Krymsk	8	Double line Drip	East to West
SR4	Woodcolony	24	16	113	Titan	6	Double line Drip	East to West

B) Recorded harvest dates for orchards surveyed in 2019 and 2020.

		2019		2020	
Name	Cultivar	Hull Split Date Recorded by grower	Harvest Date	Hull Split Date Recorded by grower	Harvest Date
Field 2	Carmel	8/12	9/2	NA	NA
Field 3	Carmel	8/12	9/2	NA	NA
Field 4	Carmel	8/12	9/2	NA	NA
277	Carmel	8/19	9/3	8/10	9/20
278	Carmel	8/15	9/3	NA	NA
MA47	Carmel	8/19	9/10	NA	NA
Ri-48	Carmel	8/19	9/10	8/15	9/18
MA48	Carmel	8/19	9/10	NA	NA
8N	Carmel	8/15	9/12	NA	NA
27	Carmel	8/15	9/17	NA	NA
F-98	Carmel	8/13	9/18	8/11	9/28
F-95	Carmel	8/13	9/18	8/11	9/28
F96-97	Carmel	8/13	9/18	8/11	9/28
MB5	Carmel	8/15	9/19	NA	NA
Texas	Carmel	8/11	9/24	NA	NA
272	Fritz	8/20	9/3	NA	NA
9S	Fritz	8/18	9/17	8/15	9/27
28N	Fritz	8/20	9/17	NA	NA
270	Fritz	8/20	9/20	8/15	9/24
271	Fritz	8/20	9/20	NA	NA
SR4	Fritz	NA	NA	8/15	9/25

1026	Independence	7/8	8/19	7/1	8/24
Cesar	Independence	7/7	8/21	7/2	8/16
Hanson 1	Independence	7/9	8/23	7/2	8/27
Hanson 2	Independence	7/9	8/23	7/2	8/27
588E	Independence	7/9	NA	7/1	8/17
588W	Independence	NA	NA	7/1	8/17
445	Independence	NA	NA	7/1	8/17
17	Monterrey	8/20	9/15	NA	NA
272	Monterrey	8/15	9/10	NA	NA
Ratto 1S	Monterrey	8/13	9/11	NA	NA
Ratto 1N	Monterrey	8/13	9/11	8/8	9/19
F96-97	Monterrey	8/21	10/3	8/19	10/9
F-95	Monterrey	8/21	10/3	8/19	10/9
8AW	Monterrey	8/20	9/12	NA	NA
F-98	Monterrey	8/21	9/12	NA	NA
28N	Monterrey	8/10	9/17	NA	NA
27	Monterrey	8/10	9/17	NA	NA
265	Monterrey	8/15	9/19	8/14	9/21
SR4	Monterrey	8/15	9/19	NA	NA
270	Monterrey	8/15	9/20	8/14	9/23
271	Monterrey	8/15	9/20	NA	NA
Ratto 1 N	NP	7/4	8/10	7/1	8/16
Ratto 1 S	NP	7/4	8/10	7/1	8/16
8N	NP	7/6	8/5	7/3	8/18
17	NP	7/6	8/5	7/3	8/18
MB5	NP	7/5	8/7	7/4	8/25
MA47	NP	7/5	8/8	7/4	8/17
MA48	NP	7/5	8/8	NA	NA
SR4	NP	7/5	8/8	7/1	8/13
Jeffrey 17	NP	7/4	8/8	7/1	8/13
HH1	NP	7/5	8/9	7/3	8/12
270	NP	7/5	8/12	7/3	8/17
271	NP	7/5	8/12	7/3	NA
278	NP	7/5	8/13	NA	NA
8AW	NP	7/6	8/13	7/3	8/24
9S	NP	7/6	8/13	7/3	8/30
F-95	NP	7/5	8/14	7/2	9/9
F96-97	NP	7/5	8/14	7/2	9/9
F-98	NP	7/5	8/14	7/2	9/9
277	NP	7/5	8/10	7/3	8/14

265	NP	7/5	8/10	7/3	8/22
27N	NP	7/6	8/17	7/3	8/21
28N	NP	7/6	8/21	7/3	8/30
Texas	NP	7/11	8/28	7/5	9/2
Field 2	NP	NA	NA	7/6	8/15
Field 3	NP	NA	NA	7/6	8/15
Field 4	NP	NA	NA	7/6	8/12
RI28	NP	NA	NA	7/3	8/17
265	Woodcolony	8/5	8/20	8/1	9/3
MA48	Woodcolony	8/5	9/2	8/1	9/3
277	Woodcolony	8/5	9/3	NA	NA
278	Woodcolony	8/5	9/3	NA	NA
Ri-28	Woodcolony	NA	NA	8/1	9/11
NA = No Data collected; Orchard not enrolled					

C) Results from mixed linear regression model for 2019 and 2020.

# Groups	Name	Variance	Std.Dev.		
# orchard	(Intercept)	0.04618	0.2149		
# cultivar	(Intercept)	0.03920	0.1980		
# Residual		0.51634	0.7186		
	Estimate	Std. Error	Df	T value	Pr(>|t|)
# (Intercept)	6.051816	0.854591	388.116985	7.082	6.74e-12 ***
# day	0.031692	0.002683	289.323510	11.813	< 2e-16 ***
# water_stressModerate	0.143944	0.090905	332.731539	1.583	0.1143
# water_stressHeavy	0.893041	0.115986	449.640896	7.700	8.76e-14 ***
# water_stressSevere	2.085408	0.106841	479.025621	19.519	< 2e-16 ***
# av_eto	-3.843835	1.511727	174.044646	-2.543	0.0119 *
# regionCentral	-0.217304	0.107155	34.741997	-2.028	0.0503
# regionSouth	0.387340	0.143494	38.839317	2.699	0.0102 *
# soil_temp	-0.069580	0.011360	406.957009	-6.125	2.14e-09 ***

Figures

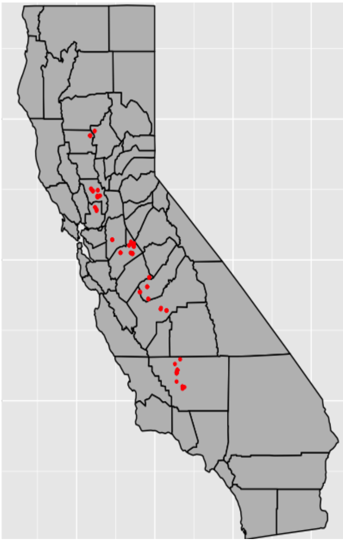


Figure 1: Geographical distribution of the orchards surveyed across the different California landscapes.

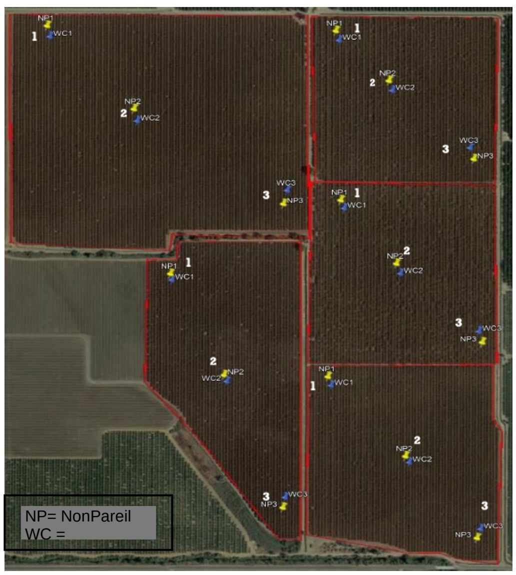


Figure 2: Orchard arrangement for different cultivars and reps per cultivar. Three representative trees were chosen per cultivar, and each was chosen from the top, middle, and south of each orchard. In this image there are 5 different orchards, each with two cultivars (for sample purposes only), each cultivar has three representative trees to be studied.

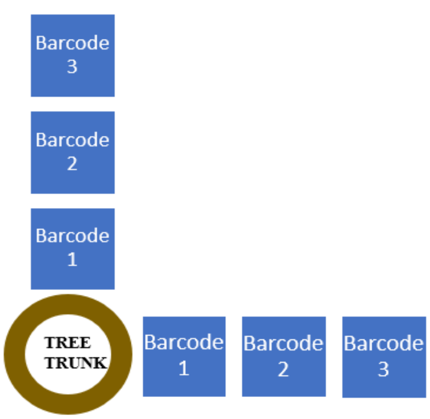
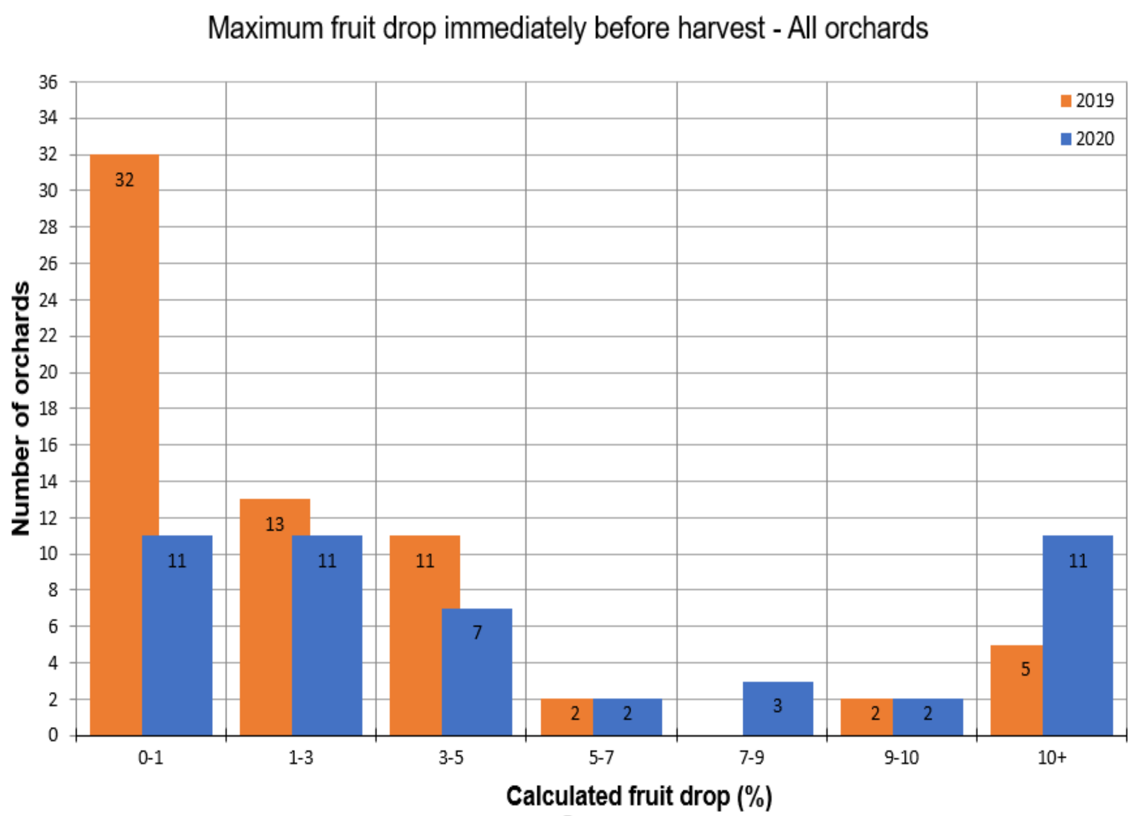


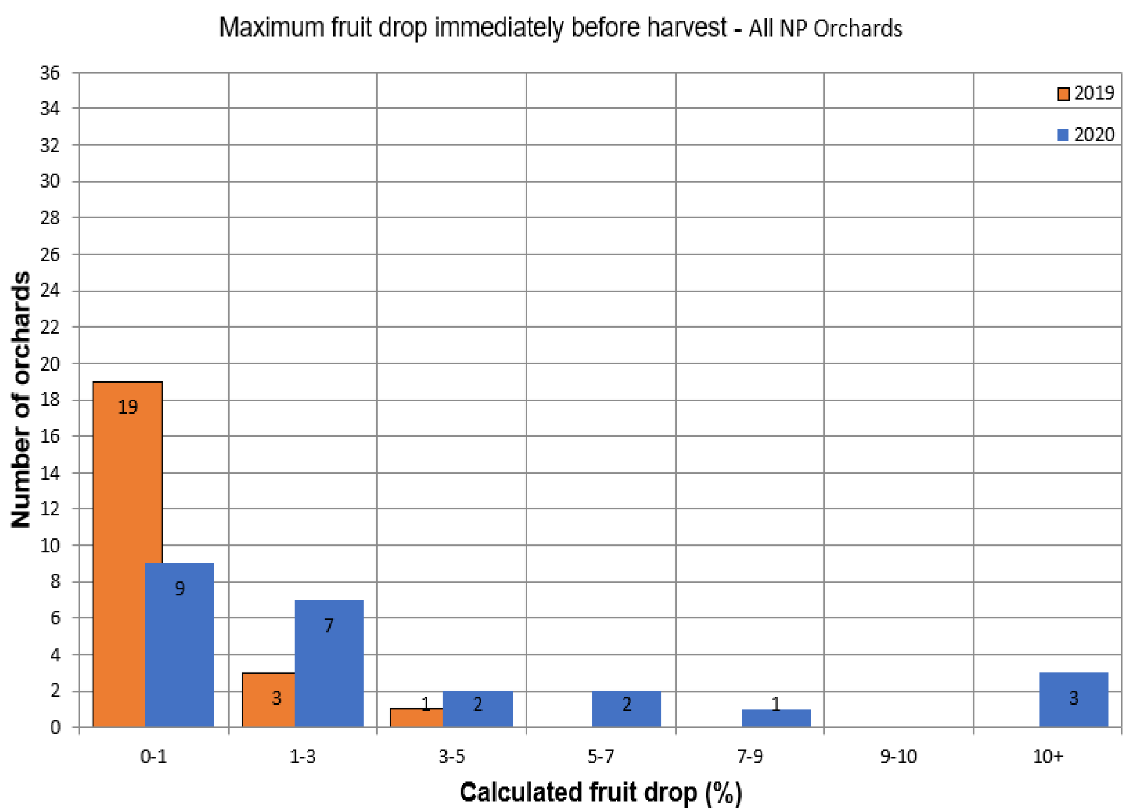
Figure 3: Artistic representation of sampling kit set up. The barcodes were the same, except the images were always taken by staring at barcode 1, 2, and 3 along the tree line and then starting at barcode 1, 2, and 3 across the tree line.

Figure 4: Visual representation of one sampling kit immediately before and after shaking the tree. These images were taken from the same location one year apart. In this image, low NP windfall was observed.



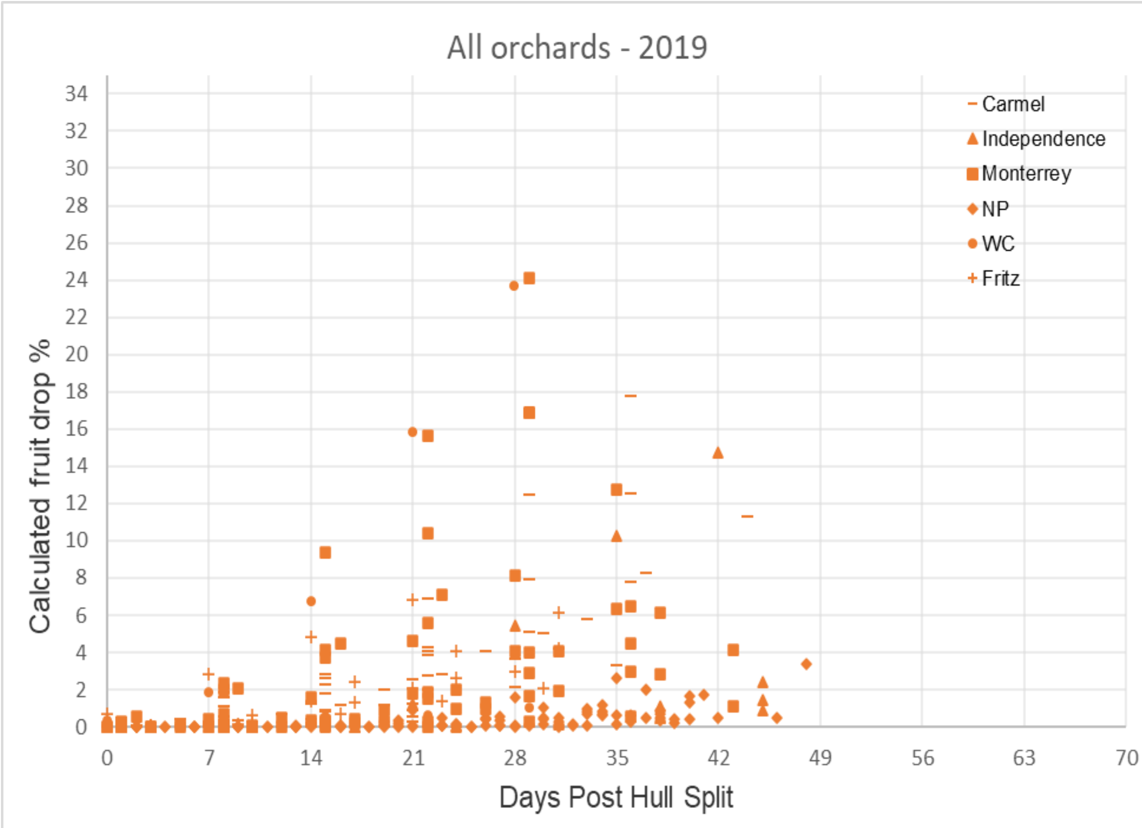
Maximum fruit drop immediately before harvest - All orchards
2019
2020
Number of orchards
Calculated fruit drop (%)
0-1
1-3
3-5
5-7
7-9
9-10
10+
32
11
13
11
11
7
2
2
3
2
2
5
11

A)

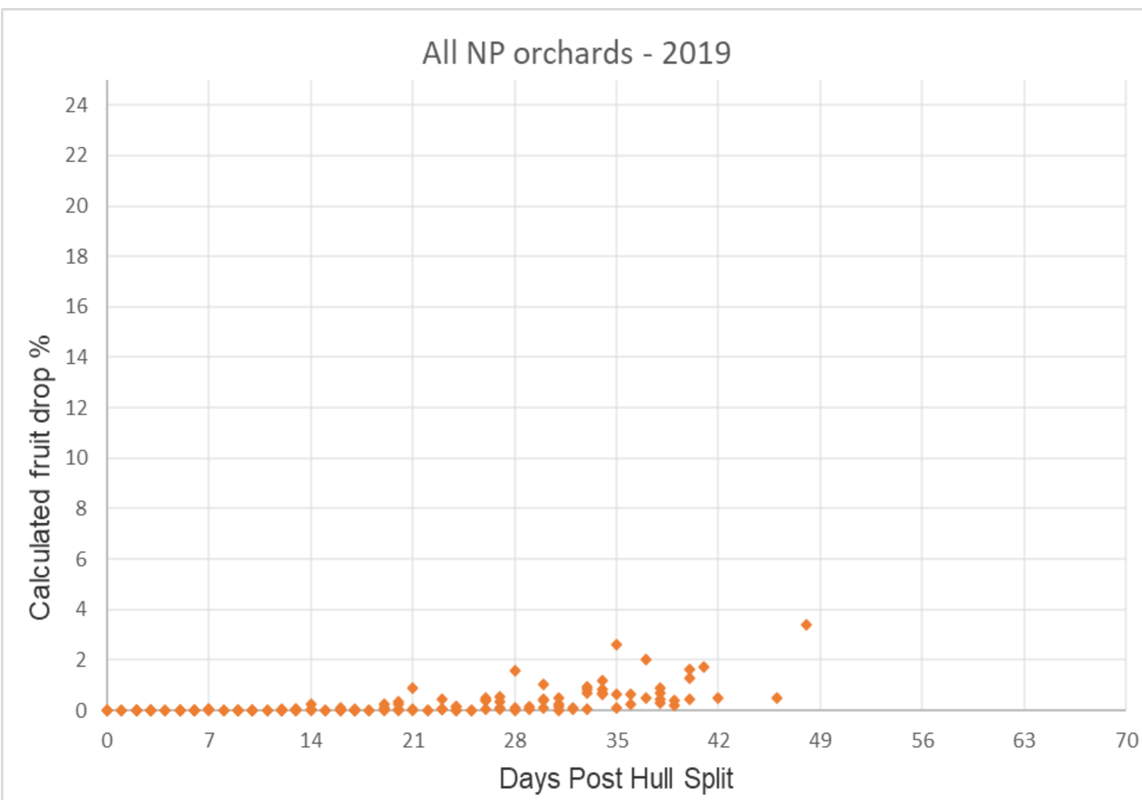


Maximum fruit drop immediately before harvest - All NP Orchards
2019
2020
Number of orchards
Calculated fruit drop (%)
0-1
1-3
3-5
5-7
7-9
9-10
10+
19
9
3
7
1
2
2
1
3

B)

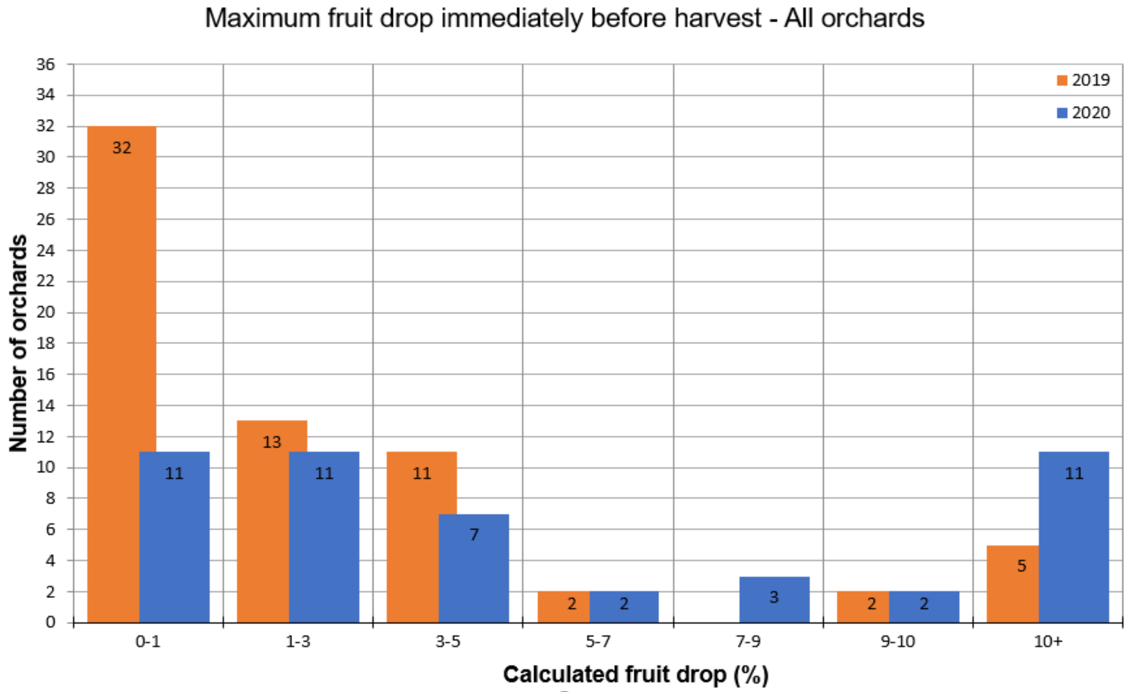

All orchards - 2019
Carmel
Independence
Monterrey
NP
WC
Fritz
Calculated fruit drop %
Days Post Hull Split
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
0
7
14
21
28
35
42
49
56
63
70

C)

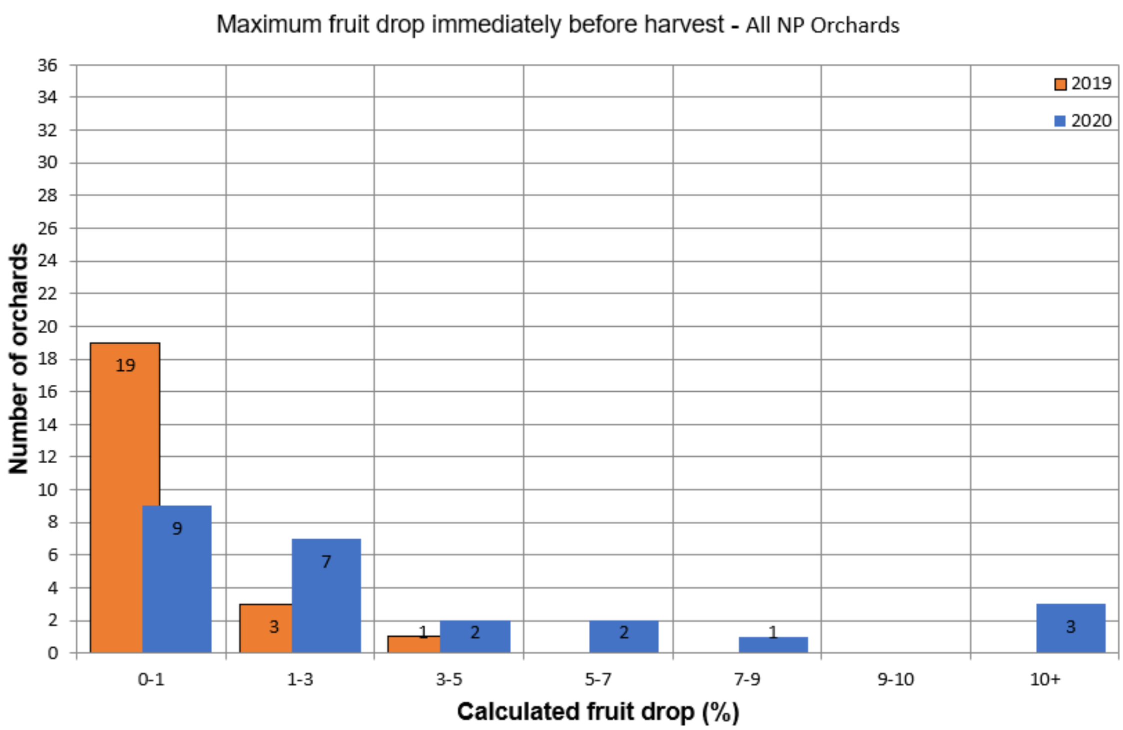

All NP orchards - 2019
Calculated fruit drop %
Days Post Hull Split
0
2
4
6
8
10
12
14
16
18
20
22
24
0
7
14
21
28
35
42
49
56
63
70

D)

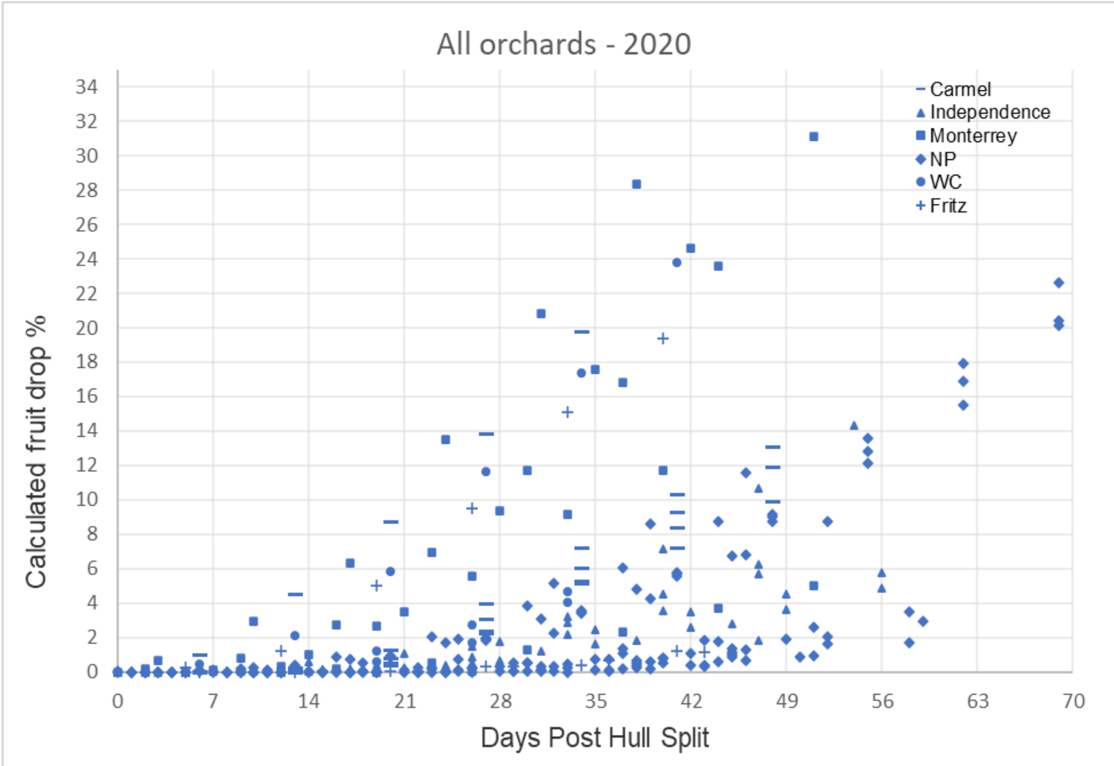
Figure 1. A) Fruit Drop frequency from all orchards and cultivars surveyed in 2019. B) Fruit drop frequency of Nonpareil orchards in 2019 show that most of the orchards had less than 0.7% fruit drop. C) Fruit drop percentage accumulation by days post hull split for all orchards in 2019. D) Fruit drop accumulation by days post hull split in Nonpareil orchards 2019.



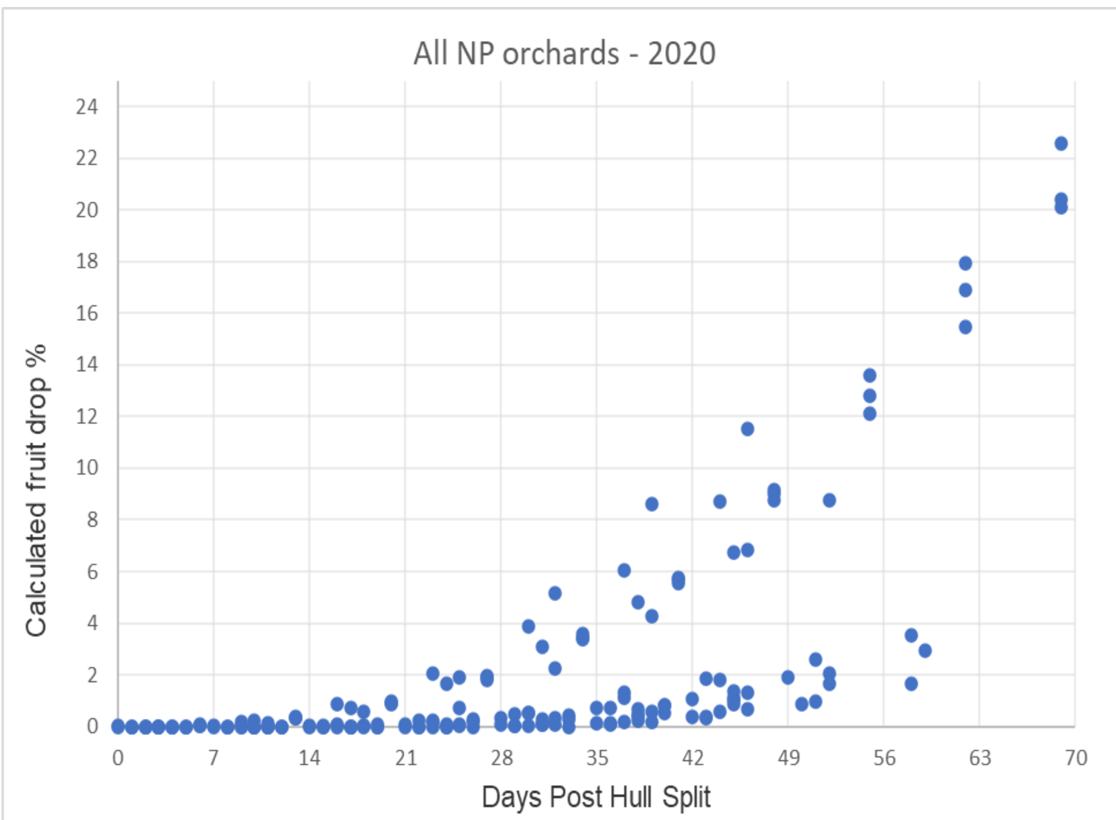
A)



B)


All orchards - 2020
Carmel
Independence
Monterrey
NP
WC
Fritz
Calculated fruit drop %
Days Post Hull Split
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
7
14
21
28
35
42
49
56
63
70

C)


All NP orchards - 2020
Calculated fruit drop %
Days Post Hull Split
24
22
20
18
16
14
12
10
8
6
4
2
0
0
7
14
21
28
35
42
49
56
63
70

D)

E)

Figure 2. A) Fruit Drop frequency of all cultivars surveyed in 2020. B) Fruit Drop frequency of Nonpareil orchards in 2020. C) Fruit drop percentage accumulation by days post hull split for all orchards in 2020. D) Fruit drop accumulation by days post hull split in Nonpareil orchards 2020. E) Conditions in 2022 might have been worse by adding stress to trees such as smoke and excess leaf drop prior to harvest.

Appendix 1: Standard Almond Hull Split Stages

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

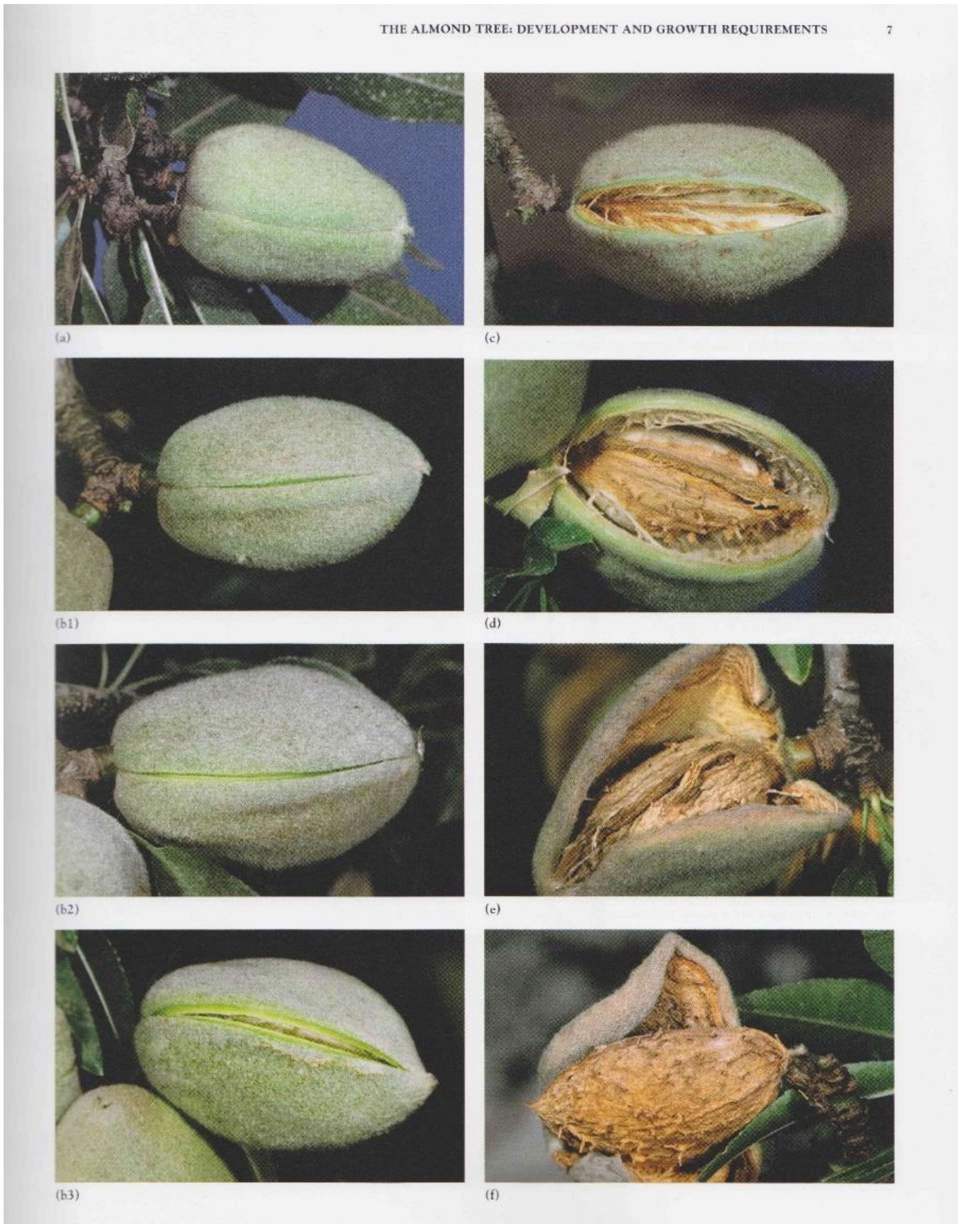


Table 3A: Poisson Distribution results show that 5-7 Weeks post hull split date have the most critical fruit dropping events occurring.

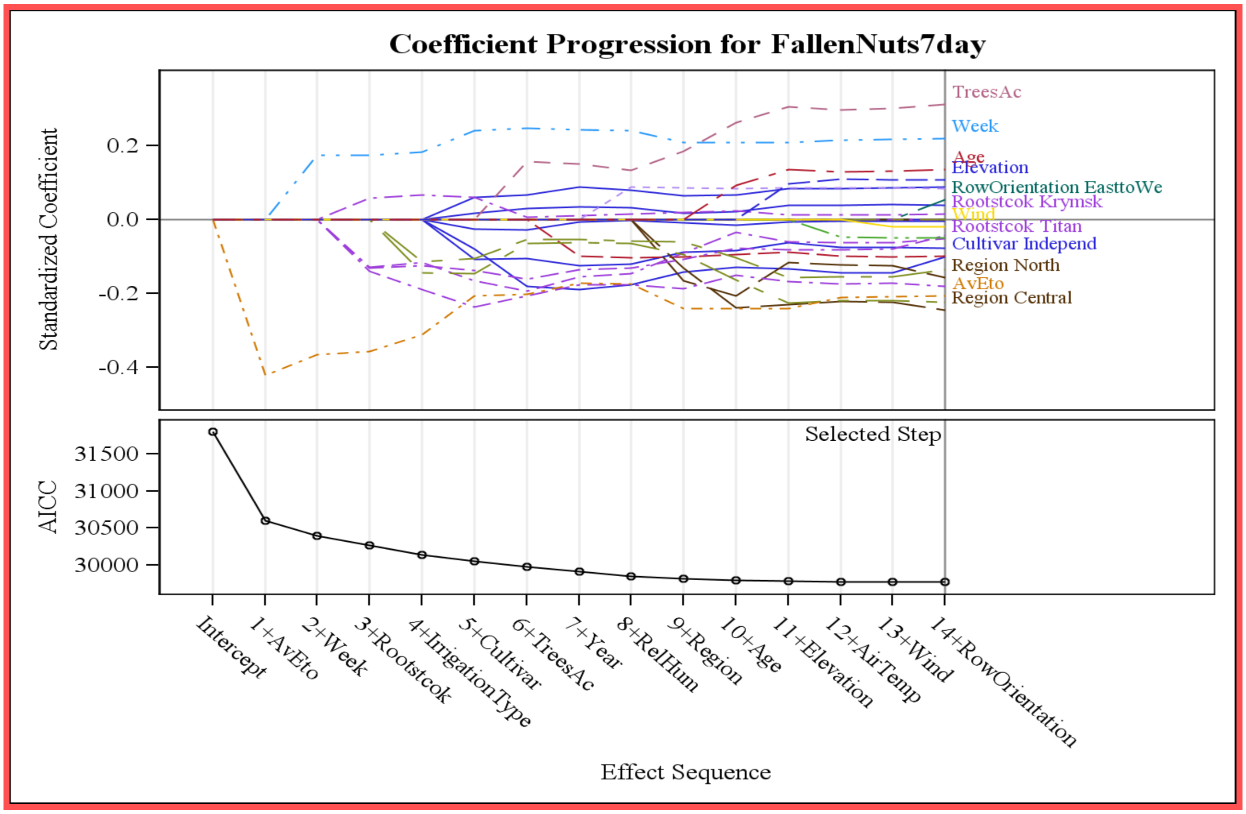
Cultivar*Week Least Squares Means						
Cultivar	**Week**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Carmel	5	1.7253	0.1766	38.55	9.77	<.0001
Carmel	6	1.8286	0.1771	39.02	10.32	<.0001
Carmel	7	1.5707	0.1792	41.04	8.76	<.0001
Fritz	5	2.4681	0.1791	40.86	13.78	<.0001
Fritz	6	2.4424	0.1819	43.71	13.43	<.0001
Fritz	7	2.6850	0.2406	141.9	11.16	<.0001
Independ	7	0.8204	0.3808	37.29	2.15	0.0377
Independ	8	0.8309	0.3845	38.78	2.16	0.0369
Independ	9	0.9973	0.3896	40.98	2.56	0.0143
Monterre	5	1.7495	0.1762	38.16	9.93	<.0001
Monterre	6	1.8230	0.1764	38.33	10.33	<.0001
Monterre	8	1.9227	0.1799	41.74	10.69	<.0001
NP	8	1.2757	0.1777	39.57	7.18	<.0001
NP	9	1.8005	0.1783	40.13	10.10	<.0001
NP	10	1.8729	0.1786	40.45	10.49	<.0001
Woodcolo	4	0.9213	0.1792	41.05	5.14	<.0001
Woodcolo	5	0.9504	0.1791	40.95	5.31	<.0001
Woodcolo	6	1.3611	0.1827	44.6	7.45	<.0001

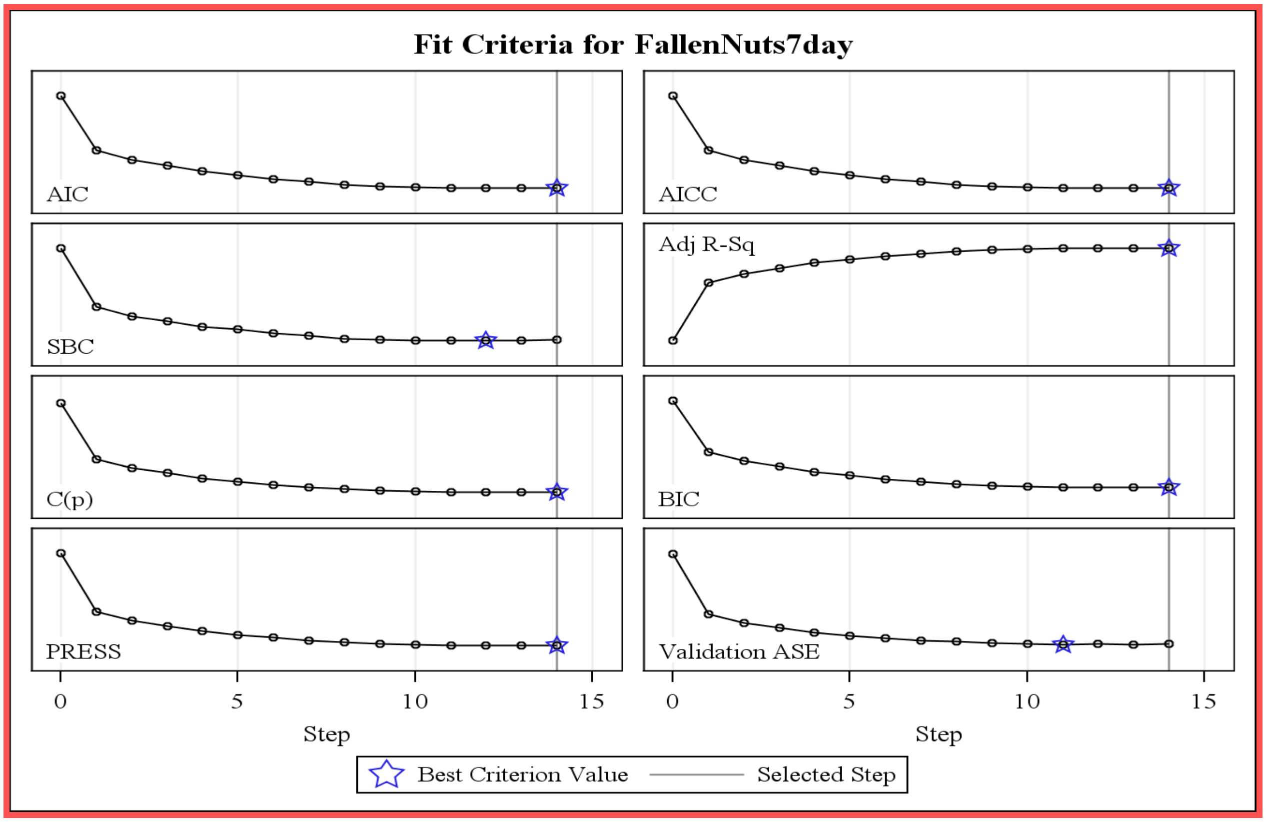
Table 3B: Stepwise regression analysis using AICC criterion, where AvEto, Week, and Rootstock have the greatest positive impact on fruit drop.

Step	Effect Entered	Number Effects In	Number Parms In	Model R-Square	Adjusted R-Square	AIC	AICC	BIC
0	Intercept	1	1	0.0000	0.0000	31802.9883	31802.9903	25659.2585
1	AvEto	2	2	0.1786	0.1785	30596.4369	30596.4408	24452.8898
2	Week	3	3	0.2058	0.2055	30391.6867	30391.6933	24248.0751
3	Rootstcok	4	7	0.2233	0.2225	30262.7467	30262.7702	24118.6370
4	IrrigationType	5	9	0.2391	0.2381	30140.1474	30140.1833	23996.0749
5	Cultivar	6	14	0.2510	0.2494	30053.3796	30053.4580	23909.1366
6	TreesAc	7	15	0.2608	0.2591	29974.7961	29974.8849	23830.8451
7	Year	8	16	0.2687	0.2669	29910.6097	29910.7096	23766.9322
8	RelHum	9	17	0.2761	0.2742	29850.1960	29850.3077	23706.8167
9	Region	10	19	0.2802	0.2781	29818.9349	29819.0721	23675.7274
10	Age	11	20	0.2833	0.2811	29794.8456	29794.9965	23651.7966
11	Elevation	12	21	0.2849	0.2826	29783.0200	29783.1854	23640.0631
12	AirTemp	13	22	0.2862	0.2837	29774.2389	29774.4193	23631.3614
13	Wind	14	23	0.2865	0.2839	29773.2133	29773.4095	23630.3641
14	RowOrientation	15	24	0.2868	**0.2841***	29772.7527*	29772.9653*	23629.9294*

Stepwise Selection Summary — * Optimal Value Of Criterion

Figure 3A: Visual representation of the stepwise regression analysis results using AICC criterion or table above.




Fit Criteria for FallenNuts7day
AIC
AICC
SBC
Adj R-Sq
C(p)
BIC
PRESS
Validation ASE
0
5
10
15
Step
Best Criterion Value
Selected Step