Mechanical harvesting of California table and oil olives

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Abstract: Mechanical harvesting must be developed for successful table and olive oil production in California. Both canopy contact shaking head and trunk shaking harvesters can produce processed black ripe olives that trained sensory panels and consumer panels cannot distinguish from hand-harvested olives. However, both types of harvesters remove and capture less than the 80% efficiency required for economically feasible mechanical table olive harvesting. The harvesters differ in their removal patterns, efficiency, and types of tree damage. No successful abscission compounds to decrease fruit removal force have been identified. Therefore, as with oil olives, the tree shape must be modified for successful mechanical table olive harvesting. Recent results demonstrate training to an espalier shape, with and without a trellis, in high density hedgerows, does not decrease yield. These espaliered hedgerow orchards can be harvested with both canopy contact and trunk shakers. Therefore, the traditional California table olive industry must adapt a modified version of the high density and super high density orchards, designed specifically for mechanical harvesting, now being developed for olive oil production in California.

1. Introduction

When and how the olives are harvested are among the most important factors in both the quantity and quality, and therefore value of processed table olives and olive oil. Efficiency of harvest, the percent of fruit removed from the total crop on the tree, is the first component of total processed product value. Quality of the fruit, partially a function of maturity for table olives and oil, and size for table olives, and condition when delivered to the processing facility is the second component of total processed oil or table value. Harvesting is the final step in field production of an olive crop, but if done at the wrong time or in the wrong way it can markedly affect net return to the grower. However, within limits, depending upon the use of the harvested fruit, the two factors are ranked differently.

Efficiency of harvest removal and collection is the more important factor in developing mechanical harvesting for olives destined for olive oil. Fruit quality and condition, within limits, is secondary. Fruit quality and condition, the potential for producing an acceptable table fruit when delivered to the processing plant, is the most important factor in developing mechanical harvesting in olives destined for table fruit. Efficiency of harvest is secondary. Given the relative size of the world’s olive oil and table olive industries, and the relative difficulty of developing mechanical harvest for oil or table fruit, successful harvesting of olives for oil is being developed sooner and more easily than successful harvesting of olives for table fruit processing.

The major reason for developing mechanical olive harvesting is the high cost of hand harvesting; currently the single most expensive cost in olive production worldwide. In California’s San Joaquin Valley the 2009 average hand harvest cost per ton was approximately 50% of the gross return per ton. Other major olive pro-
2. History of olive harvesting

The first method of harvesting olives was to collect fruit from the ground late in the growing season when the physiologically mature fruit abscises naturally. Or the fruit may have been diseased or infested with insects which hastened abscission. On the ground fruit can be further degraded, infected and infested. The result was a decrease in olive oil or table fruit quality. Thus harvesting fully mature olives from the ground for table or oil processing was abandoned early in olive production and replaced with hand harvesting, a method still used extensively. Hand harvested fruit removed directly from the tree is stripped with a downward motion and placed into baskets, bags or boxes. If the olives are destined for table fruit processing the laborers often wear knitted cotton gloves. These gloves protect both the fruit and the laborer. Hand reach can be extended with hand held wooden or metal toothed devices resembling coarse combs or rakes, used with the same downward motion. Poles have also been used to beat the branches. The latter method is only effective with mature fruit for oil extraction. These methods of extending hand harvest have improved efficiency of removal, but poling results in tree damage, and all methods are inefficient and slow, and require fruit to be picked up from the ground. The first harvest innovation was to string plastic nets under the trees or spread them on the ground. As interest in improving harvest efficiency grew harvest aids, platforms that positioned pickers were investigated. However, Fridley (1969) soon demonstrated that these only improved the speed of the slowest laborers and actually slowed the more efficient ones. In the 1940s in California, USA and in the 1960s in Europe both universities and the commercial sector began investigating adapting the mechanical harvesting methods used in other tree, bush and vine crops for olive harvest. Among the technologies investigated have been ground sweeping, hand held combing and limb shaking devices, trunk shakers, both orbital and multidirectional, inertia or impact shakers, double or single sided picking head mechanisms, and straddle type harvesters adapted from bush and vine harvesters. While the body of research has been wide ranging it has not been, as with most applied field work, systematic or thorough. Trials have been conducted in most of the major olive growing countries, on the major cultivars with trees of different ages, with and without abscission agents. The results, as a body, are extremely variable. Nonetheless, the commercial sector has used this data to develop harvesters. As a result mechanical harvesting of olives is slowly gaining in most of the major production areas of the world.

The first mechanical harvesting investigations were conceived in the 1940s through the 1960s and conducted in all the major olive producing countries. Though the technologies investigated have differed the goal has remained the same; a mechanical harvester that economically and efficiently harvests olives capable of producing quality table fruit and oil. Unfortunately, not all investigations have incorporated investigations of final processed product quality, a serious experimental deficiency, particularly for table olives as flesh bruises and cuts will produce an unacceptable processed fruit. Further, in the early experiments, and even now, it is difficult to integrate all the factors that affect final processed olive quality; cultivar, orchard spacing, production practices, particularly irrigation and canopy shape as a result of pruning, fruit maturity, the machine itself, how, when and by whom it is operated, and the final use of the olive. The last factor complicates the mechanical harvesting experimentation further as the physiologically immature olives required for some table processing cures do not have a fully developed abscission zone and therefore require more force to detach the olive; the fruit removal force (FRF) is routinely as high as 5 to 10 N. This circumstance precipitated the thus far unsuccessful attempts to develop abscission agents to aid olive harvest. In this review the fruit, tree, and other parameters affecting mechanical harvest will be discussed followed by a review of the currently most promising mechanical harvesting technology.

3. Tree and fruit parameters of harvesting olives

Olive fruits are borne in groups of one to three, laterally on paniculate inflorescences in the axils of oppositely arranged leaves, on one year old wood. The natural growth habit of the mature tree produces long cascades of pendulous, weeping, branches with these one year old fruit bearing shoots at the extremities. Thus the bearing surface of a mature olive tree allowed to grow naturally is a 0.5 to 1 m shell around the tree’s periphery. Mature trees are generally 3-6 m tall. Depending upon variety the mature olive fruits have a wide size range, designated by weight. Most olive fruit
cultivars weigh between 1.0 to 15 g. Fruit under 1 g are difficult to mechanically harvest with any method. Fruit weighing 3 g and above are more amenable to mechanical harvest. Visco et al. (2004) has demonstrated fruits with a shorter peduncle are more amenable to mechanical harvest. It is the combination of tree height, pendulous, apical bearing habit, far from the tree trunk, and light fruit weight that generates, particularly for table olive production, the major problem of mechanical olive harvesting technology; generating sufficient fruit removal force, (FRF) properly transmitted to the olive abscission zone, to remove the olive fruit without damage. Generally, when fruit is still green the FRF is 800-1000 g or 10 N. It drops markedly at maturity and much more slowly thereafter. Research done by Martin (1994) in California and others in Spain, as summarized by Kouraba et al. (2004) demonstrates that not only does FRF affect the efficiency of mechanical harvest but it can also be used as an indicator of when to begin, and terminate, mechanical harvest.

4. Factors affecting mechanical olive harvest

A. Cultivar

Olive cultivars vary greatly in fruit weight and FRF, and therefore in the ratio of the two. However, in all cultivars there is a decline of this ratio through full maturity, and then it plateaus. Fridley et al. (1971) and Tombesi (1990) have demonstrated, and Kouraba et al. (2004) recently summarized, the importance of this ratio, in assessing the suitability of specific cultivars for mechanical olive harvest. However, though fruit weight and FRF can be measured directly, and the ratio calculated, fruit color development is often used as the indicator, or proxy, for maturity. Most olive producing regions have developed maturity indices, based upon color development for the different cultivars, often different for different regions, which indicate when to harvest (Kouraba et al., 2004). However, while the FRF/fruit weight ratio is useful experimentally, and the color maturity indices useful in production, neither has played a major role in cultivar selection when planting an orchard even if mechanical harvesting is planned. Only recently, with the introduction of ‘Arbequina IRTA-i-18’, ‘Arbosana i-43’ and ‘Koroneiki i-38’ have olive cultivars been recommended or selected for their ability to be mechanically harvested. Further, it appears the reason for their selection is that the tree stature and growth habit of these cultivars make them more suitable for high densities and straddle type comb mechanical harvesters, as opposed to fruit weight and FRF, or the ratio of the two. Probably, because mechanical harvesting technology is still being developed, it has not yet become a major factor in cultivar selection, nor is cultivar a limiting factor for mechanical harvest.

However, efforts are being made to evaluate the relative merits of different cultivars for mechanical harvest under specific conditions, and why. For example, Visco et al. (2004) ranked ‘Lecino’, ‘Frantoio’, ‘Pendolino’ and ‘Dritta’, from best to worst, as suitable for mechanical harvest when trained to a vase with a cubic volume of 29-39 m³ and using a trunk shaker. Similarly, Kouraba et al. (2004), have ranked 19 varieties for the efficiency of unidirectional branch shaking. Among the 19 they tested ‘Datilerio’ and ‘Temperano’ were best suited to unidirectional branch shaking and ‘Sevillena’ and ‘Chemlali’ were least suited. Further they determined fruit weight and fruit maturity were the primary factors in producing the efficiency of this harvest method. Interestingly, and unlike with trunk shakers, FRF was a less important factor than fruit weight in determining harvest efficiency.

B. Tree shape, canopy density and pruning

The tree trunk and branch architecture and height, shape and density of a canopy can markedly affect mechanical harvesting efficiency and harvested olive quality for two reasons. Tree and canopy structure affect first, the ability of the shaker to remove the fruit, and second, the potential to damage the fruit after it drops through the canopy after detachment. The latter factor is particularly important for olives destined for table processing as bruised or cut olives cannot be successfully processed into marketable table olives. Tree and canopy shape best for specific harvests differs somewhat for different machines but some factors are common to all.

Generally, tree height is the first limitation. As with hand harvesting, tree height is an impediment to all forms of mechanical harvesting. If the technology is hand held, or requires contact with the canopy as with picking head technology the problem is simply the physical ability to make canopy contact. With hand held shaker technology the length and diameter of the branch, as well as the angle of shaker attachment, affects efficiency of removal (Kouraba et al., 2004). Tree height is an obvious limitation for over the row harvesters. If the harvester uses trunk shaking or impact technology the impediment is the ability to transmit the force to the fruit-bearing surface (Martin, 1994).

Canopy shape, width and length, and density also affect mechanical harvesting (Tombesi et al., 2002). Generally, canopy shape and density are less limiting for hand held branch shakers or combs but dense canopies slow the operator and can damp the efficiency of the shaker or comb. Similarly, canopy density can damp the efficiency of trunk shaking (Martin, 1994). Dense canopies will also decrease the efficiency of picking head harvesters when the dense sections of the canopy overlap onto adjacent sections of the canopy impeding picking head’s access to unharvested fruit. Shaking technology, whether hand held, or self pro-
pelled and mounted, requires skirt pruning for trunk or branch access. Mounted, self-propelled shaking and combing harvesters, both single and double sided, and over the row harvesters with catching frames all require a tree below a certain height, width, and with trunk access or clearance below the canopy for the fruit catching frame. Single sided and double sided combing harvesters are more efficient if the fruiting wall of the tree is flat, not rounded, and continuous (Ferguson et al., 1999).

Collectively, these requirements suggest the ideal olive orchard for efficient mechanical harvest will be a hedgerow of limited width and height with trunk access and clearance below the canopy. The ideal way to achieve this shape is with mechanical topping, hedging and skirting combined with some selective hand pruning (Ferguson et al., 1999) to produce a tree that is roughly no more 4 m high, 2 m in width with a lower canopy that is 1.5 m from the ground.

However, because olives bear their crop on a 1 m shell of one year old shoots in a cascade, mechanical hedging can greatly reduce crop, particularly on existing trees at commercial densities of 300 trees per hectare (Ferguson et al., 1999). In the collective research trials investigating mechanical harvesting it is well demonstrated per tree yields will be decreased by the mechanical and hand pruning necessary to shape a tree for efficient mechanical harvest (Camerini et al., 1999; Ferguson et al., 1999). However, collectively the accumulating data is also suggesting higher tree densities, combined with reduced pruning and harvesting costs, will offset the yield decreases produced by the pruning. Most experimental trials, and most commercial orchards, integrating high densities, and mechanical harvesting and pruning, have not reached full bearing but economic projections indicate they will be economically viable at maturity (Vossen et al., 2004; Klon-sky et al., 2007; Krueger, 2009)

C. Orchard density

As the preceding discussion suggested, as mechanical harvesting is incorporated into olive production, tree densities in olive orchards will increase from the very wide spacing of dry land production or from the 7-8 m by 5-6 m spacing in irrigated orchards to 1.25-1.5 m in row by 3.75-4.0 m between row spacing of hedge row orchards. This is an increase from as few as 125 trees to the hectare to as many as 2225 trees to the hectare.

These high-density orchards will, due to between tree competitions, naturally limit tree size, facilitating tree harvesting and fruit collection with most mechanical harvesters. The orchards will also have the added benefit of producing higher yields earlier. Initial trials of high density orchards for olive oil production are confirming the ability to produce higher yields earlier and be successfully harvested mechanically. However, most of these high density orchards are too young to fully demonstrate if annual economical crop production can be achieved while maintaining the tree size required for successful mechanical harvesting, particularly with the over the row harvesters. It has not been fully demonstrated that the topping, hedging and hand pruning required to maintain the adequate tree size will produce annual economic crops. However, as increasing number of trials, and commercial orchards are being planted at these densities this data will be generated within ten years (Vossen et al., 2004).

D. Fruit loosening agent

In the late 1960s, when it became obvious mechanical harvesting the physiologically immature olives destined for table production required a fruit removal force that damaged the fruit, investigations of abscission compounds were initiated. The collective results thus far have not produced any reliable fruit loosening agents. Early research by Martin (1994), Ben-Tal and Woodner (1994), Metzidakis (1999), and Gerasopoulos et al. (1999) focused on ethylene releasing compounds (ERC) and how to apply them. Though many of the ERCs successfully promoted development of the abscission zone between the fruit and pedicel they failed to loosen fruits, damaged the fruit, or produced unacceptable leaf loss. In 1993 Banno et al. demonstrated phosphates enhanced the performance of ERCs. Arquero et al. (1997) later produced promising results in a number of trials using monopotassium phosphate (MPK). The MPK, with and without Ethephon, and surfactants, was investigated by Barranco et al. (2002) as a fruit loosener for the oil cultivars Arbequina and Picual. However, Burns et al. (2008) found no advantage to combining Ethephon with MPK. Among the results thus far the most interesting finding is that MPK and Ethephon appears to produce abscission in different zones of the fruit attachment. MPK produced more abscission in the pedicule-branch zone. With the addition of Ethephon, abscission was greatest in the pedicel-pedicule zone. Their experimental results appeared promising in that FRF was reduced to 3-4 N and leaf loss was limited, but mechanical harvesting efficiency was only 60% with a vibrating type harvester. Finally, Burns et al. (2008) demonstrated that addition of 1-methylecyclopropene (1-MCP), added to decrease the leaf drop incurred with Ethephon decreased the efficacy of Ethephon and delayed leaf drop. Compounds such as methyl jasmonate, coronatine, Dikegulac, MAXCEL, traumatic acid, and 5-chloro-3-methyl-4-nitro-1H-pyrazole were not efficacious. In summary, no reliable fruit abscission agents with commercial potential for oil or table olives have been identified.

5. Mechanical olive harvesters

A. Harvest aids

Olive harvest technology can be broadly divided
into hand held machines and larger machines mounted on tractors or on self propelled units. Technically, hand held harvesting units are harvest aids and serve a function in smaller, particularly hilly, orchards, but cannot be considered mechanical harvesting because the speed and efficiency of the unit is determined by the operator, and there is no collection mechanism. The units are usually pneumatic, can extend an operator’s reach by 4 m and remove fruit with a vibrating motion of the comb, or by clamping on the branch and shaking. Using either a pneumatic, hand held combing unit, or a clamping shaking unit a single operator can harvest 300-450 kilos per day, before fruit collection. This is at least 50 kilos per day better than the best hand harvest laborers. However, collection of the dropped fruit onto nets, as opposed to already being deposited in the picker’s bag, can eliminate some of the efficiency of removal.

B. Mechanical olive harvesters

Most olive harvesters fall into two general categories based upon the principle of removal. They either clamp and shake the trunk or branches, or have canopy contact heads with rods that extend into the canopy. The trunk shaker technology for other nut and tree fruit crop harvesters could not be adapted for table olive harvest so scientists at the University of California Davis developed a new trunk shaking harvester, the “inertia head” for table olives in the 1960s (Martin, 1994). The canopy contact head technology was adapted from grape harvesters in California in the 1990s (Ferguson et al., 1999). The most modern versions of both are self propelled with catch frames incorporated in the machine and are therefore capable of continuous operation. Each technology has advantages and disadvantages.

For a trunk shaking harvester to achieve the 80% removal efficiency Klonsky (2009) has demonstrated is required either a short stroke, less than 2.5 cm and a frequency above 42 Hz - 2520 cycles per minute, or a long stroke, 10 cm and low frequency, 17 Hz - 1020 cycles per minute, is required. Efficiency would probably be higher when harvesting mature olives for oil. With the latter combination limb breakage is a problem and with the former leaf loss is a problem. The most efficient versions have an integrated catching frame with a mechanism for downloading that allows continuous operation. This type of shaker can be used with traditional trees pruned to an upright vase with vertically oriented scaffolds. Bark damage to the trunk can occur if the clamping strength is too great, over 6.9 kPa. Fruit damage, both bruising and cutting can result from the fruit falling through the canopy into the catch frame, and being conveyed to the bins.

Canopy contact harvesters were adapted from wine grape harvesters. The picking head consists of ranks of 1 m long graphite or fiberglass rods radiating from a central upright cylinder, 400 rods to a cylinder. The cylinder rotates passively on its central axis when the rods connect with the hanging shoots as the machine moves forward. The rods have a 30 cm horizontal whipping motion, and as they connect with the shoots this motion removes the fruit. This harvester can achieve as high as 98% fruit removal efficiency if the tree is properly configured and the canopy does not overlap on itself as the picking head moves forward. The initial limiting factor with this type of harvester is the fruit bruising and cutting when harvesting immature olive for table processing (Castro-Garcia et al., 2009). However, recent modifications of this picking head produced “California style” processed black ripe olives that neither trained sensory panels nor consumer panels could distinguish from hand harvested olives (Lee et al., 2009). Dual harvesting heads have been mounted on over the row units for harvesting olives for oil processing. These over the row harvesters were adapted from grape, berry and coffee harvesters.

6. Recent olive mechanical harvesting research in California

California’s table olive industry is primarily based upon a single cultivar, the ‘Manzanillo’, processed in a style called “California black ripe”. Much smaller amounts of ‘Mission’, ‘Sevillano’ and ‘Ascolano’ are also processed in this style. The name is misleading as the fruit is harvested physiologically immature, therefore the abscission zone is unformed, and the fruit has a higher FRF than oil olives, which are generally harvested at physiological maturity. Immature ‘Manzanillo’ routinely have an FRF as high as 10 N when harvested. When physiologically mature the FRF is less than 1 N. This immaturity, combined with the traditionally large trees, 4-6 m tall and 3-5 m wide, and pendulous, thick growth habit of California’s irrigated ‘Manzanillo’ olive orchards makes mechanical harvesting difficult.

Mechanical harvesting of oil olives has developed much more rapidly because new olive oil cultivars have been bred for slow growth, planted in high to super high densities, 486-1800 trees per hectare, and trellised or trained in a hedgerow that is easily harvested by over the row grape, coffee and blueberry harvesters. The olive oil industry pursued the long term goal of tree genetics, the mid term goal of new orchard conformations with hedgerow tree training and pruning, and the short term goal of adapting existing mechanical harvesters from other crops.

Similarly, if the California table olive industry is to ultimately succeed it must also pursue tree breeding, new orchard conformation with hedgerow training and pruning, and mechanical harvesting technology. However, there is no current table olive tree breeding program in California and only one currently active in Spain. Therefore, California’s table olive industry must
pursue the short and midterm goals as follows. For the short term this means developing a picking technology and tree pruning method for the current California table olive orchards. For the midterm this means developing a picking technology and new orchard conformations, with new training and pruning methods.

Therefore, the focus of California Black table olive mechanical harvesting research for the last decade has been dual; developing successful mechanical harvesting for current and new orchards. The effort has required the simultaneous input of University of California’s agricultural engineers, plant physiologists, food scientists, agricultural economists and horticulturists, California’s two major table olive processors, multiple commercial mechanical harvester fabricator/contractors, and the support of the California Olive Committee (COC), the grower funded organization that supports production research. The project included research cooperators from Spain and Argentina and has been conducted in California, Argentina and Portugal. The project has had two distinct phases and a long evolution as new harvesters have been evaluated and modified. Only the most recent summarized 2008 and 2009 research results will be given here.

a. Table olive mechanical harvesting research from 1996 through 1999

The first phase was initiated in 1996 with a call from the olive marketing order, the California Olive Committee (COC) to harvest equipment fabricators for potential olive harvesters. AgRight of Madera, CA presented a modified wine grape harvester with a “canopy contact” head. Research trials by Ferguson et al. (1999) from 1996 through 1999 demonstrated this picking technology was very efficient if the rods of the harvester head made direct contact with the portion of the canopy bearing fruit. However, the rounded shape of a traditional olive tree rendered all but the portion of the tree canopy within the horizontal and vertical range of the picking rods, and facing the row middles, unharvestable. The harvest head could remove up to 98% of the canopy fruit facing the middle of the row, but fruit above or below the harvester head, or in the canopy between trees, was removed with less than 50% efficiency. Later versions of this machine have multiple heads that could move along a horizontal axis deeper into the canopy, slightly improving the overall harvester efficiency (Fig. 1). Additionally, the catch frames with the early iterations of the canopy contact head harvesters were incompetent, losing 19% of the fruit removed by the picking head. This overall removal efficiency, combined with the catch frame incompetence put final fruit harvester efficiency at approximately 60% or less. Additionally, the fruit was often bruised and cut, figure 2, and unacceptable for processing as California black ripe table olives. With the appearance of the olive fly (Bactrocera olea) in 1999, mechanical harvesting research was discontinued.

b. Table olive mechanical harvesting research from 2006 through 2009

Though most California table olive orchards are generally part of a diversified ranch operation, the increasing hand harvest costs, and stagnant olive prices/ton of recent years, precipitated the removal of an increasing number of olive orchards. The reason was the increasing table olive hand harvest costs were eroding the total diversified ranch returns. However, the United States is still the single largest table olive market in the world, giving California growers a marketing advantage. Recognizing this problem, and the potential opportunity, the remaining olive growers organized for the resumption of mechanical harvesting research, again supported by the COC, in late 2005.

When research was resumed in 2006 there were two parallel and equal objectives. The first was to develop an efficient picking technology. Once this was defined,
how to propel the harvester, catch the fruit, and convey it to a bin could be designed around the picking technology. The second objective was to identify an abscission compound that would decrease the FRF, and make the harvester more efficient.

As the following results will demonstrate; two viable picking technologies have been identified. However, development of an abscission compound remains as elusive as it has for the past 50 years (Martin, 1994; Burns et al., 2008). As the discussion of abscission earlier in this manuscript concluded, development of an abscission agent, much less registration for a crop as small as olives, remains a goal not achievable within the next decade. Both the California and international research from 2006 through 2009 has identified no new potential candidates and confirmed the earlier results that ethylene releasing compounds are as unreliable as previously demonstrated (Martin, 1994; Burns et al., 2008). As a result, the mechanical harvesters being developed for the California table olive industry need to achieve economic efficiency without the use of fruit loosening agents.

The two viable picking technologies currently being evaluated are canopy contact harvesting heads, and trunk shakers. The canopy contact harvester can be successfully used in existing orchards that have been pruned to a hedgerow. It can also be used for newer high density orchards trained to a hedgerow. The trunk shaking technology can be used in new high density orchards with straight trunks but is ineffective in older conventionally trained orchards. Interestingly, both have approximately the same final harvest efficiency, from 58% to 64%. However, the mechanism of fruit removal is different, the two machines harvest different parts of the canopy more efficiently, and the potential for tree damage is different. However, the final fruit quality as determined by grade at the receiving station of the olive processor is remarkably similar. A summary of 2008 and 2009 research with both shakers is given in the table below.

### Materials and Methods

In both harvester evaluations experimental orchards were hedgerows. The canopy contact harvester, figure 3, was evaluated in October, 2008 a 14 year old (3.5x8 m) commercial ‘Manzanillo’ orchard with 335 trees/ha. The trunk shaker, figure 4, was evaluated in October, 2009 in a 9 year old high density experimental trellised ‘Manzanillo’ orchard spaced at 3.7x5.5 m and 490 trees/ha. Both orchards were maintained as commercial orchards with drip irrigation, and annual pruning and thinning if necessary to achieve commercial fruit sizes.

The harvesting trials were done at commercial maturity; the fruit just beginning to develop color. The FRF in both orchards averaged 6.8 N in the canopy contact orchard and 7 N in the trunk shaking orchard. The harvesters were run down 6 (canopy contact head) and 4, trunk shaker, row replications. A hand harvest sample was obtained from each row. The fruit captured in the harvest bins, the fruit collected from the ground after harvesting, and the fruit remaining on the tree were weighed in the field using a portable bin scale.

The three weights were reweighed at the receiving station. The weight of the fruit in the bins was divided by the sum of the three weights to give the final harvester efficiency. The calculation is below.

\[
\text{Weight of olives in bin} = \text{final efficiency} \\
(\text{Weight of olives in bin + fruit left in the tree + fruit on the ground})
\]

Calculated harvester fruit removal efficiency, the fruit in the bin plus the fruit on the ground, is always higher than final efficiency as the fruit dropped on the ground is not collected for processing.

The assumption was made that fruit dropped to the ground and fruit remaining in the tree would not be captured for processing. As a result samples from the mechanically harvested, but not the ground or tree gleaning, were submitted for receiving station grading and calculation of canning percentage and adjusted value per ton. The first value is the percentage of olives large enough and in good enough condition to be processed into California black ripe table olives. The adjusted price per ton is what the grower is paid per ton delivered and is based on total tonnage, and fruit size,
color and condition. Finally, two 40 pound (18 kg) identical samples of fruit from each replication were sent to each of the two major processors in California. The respective two processors’ laboratories again graded these samples. These samples were then divided; half was processed immediately and half were stored in brine through March and then processed. In June of 2008 the fresh and stored processed olives, along with supermarket purchased California black ripe processed olives processed by both processors, were evaluated by both a trained sensory panel and by a consumer panel. The objective was to determine if a trained sensory panel trained to detect characteristics and defects, and consumer panels, could detect the hand from machine harvested olives. A diagram of the entire process is given in figure 5 below.

Results and discussion: 2008 canopy contact harvester evaluations

As can be seen in Table 1 below the canopy contact harvester had a harvesting efficiency of 58%. However, the efficiency ranged from 41 to 78%. Earlier research by Ferguson et al. (2007), with one of the first versions of a canopy contact harvester, figure 2, demonstrated the removal efficiency could be as high as 98% on the row side of the tree but dropped to as little as 45% on between tree surface in the row. This suggests that with current conventional orchards pruned to a topped hedgerow with no bearing surface between the trees the canopy contact harvester could achieve much higher removal efficiencies.

As can be seen in Table 1, the olives harvested by the canopy contact harvester in 2008 had a significantly lower cannable percentage and adjusted value per ton than the hand harvested olives. However, 88% cannable olives and $1013.00/ton is well with acceptable ranges for the California black ripe table olives. These receiving station grades strongly suggested that mechanical harvesting should not affect the quality of California black ripe processed table olives.

When these olives were processed and evaluated by Lee et al. (2009) of the Food Science and Technology Department, the analyzied data presented in figures 6, 7 and 8 supported this contention; mechanical harvesting had no effect on the evaluations of by trained sensory or consumer panels. Figures 6, 7 and 8 present a principal component analyses (PCI) of the eight final sample sets presented to a trained test panel for descriptive analysis. The sample sets were mechanically and hand harvested olives, Hand and Mach, divided and sent to two processors, A and B, who again divided the samples and processed them fresh and stored, F and S. This was 2 harvest methods times 2 processors times 2 processing methods or 2x2x2 = 8 samples, plus commercial samples. Figure 9 demonstrates that a consumer panel also could not distinguish between mechanically harvested and hand harvested olives, and that consumers had a strong preference for olives processed fresh, as opposed to olives processed after storage in brine.

In summary both a sensory panel trained to evaluate California black ripe processed olives for specific qualities, and a consumer panel drawn from the public could not distinguish mechanically harvested from hand-harvested olives. These three sets of data, the receiving station quality evaluation of the fresh olives, the evaluation by the trained sensory panel, and the evaluation by the consumer panel strongly supported the conclusion that mechanical harvesting does not decrease processed California black ripe table olive quality. Therefore, the most limiting factor in mechan-

Table 1 - Relative harvest efficiency, and fruit value parameters of a canopy contact harvested evaluated versus hand harvest control in 2008 and of a trunk shaking harvester evaluated versus hand harvested control in 2009

| Research season | Harvester                     | % Final efficiency | % Cannable (c) | Adjusted price/ton ($)*
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<tbody>
<tr>
<td>2008</td>
<td>Canopy contact harvester</td>
<td>58%</td>
<td>88% ***</td>
<td>1137.00 ***</td>
</tr>
<tr>
<td>2008</td>
<td>Hand harvested control</td>
<td>100%</td>
<td>96% ***</td>
<td>1013.00 ***</td>
</tr>
<tr>
<td>2009</td>
<td>Trunk shaker</td>
<td>64%</td>
<td>96% NSD</td>
<td>1147.00 NSD</td>
</tr>
<tr>
<td>2009</td>
<td>Hand harvested control</td>
<td>100%</td>
<td>97% NSD</td>
<td>1197.00 NSD</td>
</tr>
</tbody>
</table>

The % final efficiency is defined as final percentage of fruit removed from the tree that is captured in the harvest bin. The percentage of cannable fruit is defined as the % of fruit suitable for California black ripe processing. The adjusted price per ton is the price paid to the grower per ton of fruit delivered.

(c) Values within a harvest season, and a column, followed by *** are significantly different at the P = 0.0005 level.
ical harvesting of olives, producing commercially competitive California black ripe table olives, has been eliminated for olives harvested by the canopy contact harvester. However, the final harvest efficiency of canopy contact harvesters must be improved to make mechanically harvesting economically feasible.

Results and discussion: 2009 trunk shaking harvester evaluations

In 2009 only trunk-shaking harvesters were evaluated; figure 4. As can be seen in Table 1 the final harvest efficiency was similar to that of the canopy contact harvester, 64% for the trunk shaker versus 58% for the canopy contact harvester. However, these two values cannot be compared statistically as these were different harvest years and different orchards.

Similarly, the 2009 trunk shaker harvested olive values, as indicated by the percentage cannable olives and adjusted price per ton in Table 1, were close to those obtained in 2008 with the canopy contact harvester. However, unlike the values for the olives harvested by the canopy contact harvester in 2008, the fruit values for the olives harvested by the trunk shaker in 2009 were not significantly different from those of hand-har-
vested fruit. In 2009, 96% versus 97% of the hand-harvested olives were cannable and were worth $1,147.00 versus $1,197.00 per ton for the hand harvested fruit.

This strongly suggests that after these olives are stored and processed the sensory panel and consumer evaluations will again demonstrate neither group can distinguish mechanically harvested from hand-harvested olives. Therefore, as with the canopy contact harvester, the most limiting factor in mechanical harvesting of olives, producing commercially competitive California black ripe table olives, has been eliminated for olives harvested by the trunk-shaking harvester. However, as with canopy contact harvesters the final harvest efficiency of trunk shaking harvesters must be improved if mechanical harvesting is to become economically feasible for table olives.

**Improving harvester efficiency with orchard modification**

The new super high density olive oil orchards being developed in Argentina, Spain, Tunisia and California among others were all developed as orchards that could be harvested with existing mechanical harvesters; wine grape, blueberry and coffee harvesters. All are straddle type harvesters with limited height and width. Figure 10 is an example of a super high-density olive orchard being harvested by a modified grape harvester.

Our early research suggested high-density hedgerow orchards could improve the efficiency of both canopy contact and hedgerow orchards (Ferguson et al., 1999). Efficiency would improve with canopy contact harvesters because the olives would be more accessible to the harvest head rods as shown in figure 3. And efficiency would improve with trunk shakers because more of the olives would be closer to the axis of shaking, the main trunk, as shown in figure 4.

Based on this concept a high-density hedgerow orchard with three different training treatments was established in 2002. The objective was to produce a tree no more than 4 m tall, 2 m wide and skirted up to 1 m, and spaced at 3.7 m in the row and 5.5 m between rows with 490 trees/ha. The training treatments were a free standing espalier with all the major structural branches trained within the tree row, an espalier woven vertically through three horizontal wires at 1, 2, and 3 m, shown in figure 11, a treatment espaliered and clipped to the trellis wires, and a conventionally trained control. The objective was to determine if these training methods decreased yields per acre.

This orchard began bearing in year 4. The yields among the four training treatments are given in Table 2. None of the three trellised training treatments has a significantly decreased yield relative to the conventionally pruned control. This suggests ‘Manzanillo’ table olive orchards can be trained and pruned for mechanical harvesting with both canopy contact and trunk shaking harvesters without significant losses in yield. However, data will be collected until the yields plateau for at least three successive years.

![Image of high-density olive orchard](image1.png)

**Fig. 10 - Typical super high-density olive oil orchard and straddle harvester.**

![Image of high-density olive orchard](image2.png)

**Fig. 11 - Nine-year-old high density, 490 tree/ha, trellised ‘Manzanillo’ table olive hedgerow planting.**

**Table 2 - Annual and cumulative yield (tons per acre) produced by three different training treatments versus conventionally pruned trees in a nine year old ‘Manzanillo’ orchard**

<table>
<thead>
<tr>
<th>Year</th>
<th>2004 4th (Mg ha⁻¹)</th>
<th>2005 5th (Mg ha⁻¹)</th>
<th>2006 6th (Mg ha⁻¹)</th>
<th>2007 7th (Mg ha⁻¹)</th>
<th>2008 8th (Mg ha⁻¹)</th>
<th>2009 9th (Mg ha⁻¹)</th>
<th>Cumulative Yield (Mg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>9.16</td>
<td>3.92</td>
<td>6.92</td>
<td>14.31</td>
<td>13.35</td>
<td>7.75</td>
<td>54.79</td>
</tr>
<tr>
<td>Free-standing</td>
<td>8.20</td>
<td>3.38</td>
<td>5.06</td>
<td>14.34</td>
<td>11.29</td>
<td>9.56</td>
<td>51.99</td>
</tr>
<tr>
<td>Trellised, woven</td>
<td>9.43</td>
<td>3.76</td>
<td>2.28</td>
<td>13.60</td>
<td>13.17</td>
<td>4.97</td>
<td>50.04</td>
</tr>
<tr>
<td>Trellised, tied</td>
<td>8.02</td>
<td>7.73</td>
<td>3.94</td>
<td>16.82</td>
<td>10.13</td>
<td>9.83</td>
<td>56.47</td>
</tr>
<tr>
<td>Average</td>
<td>8.71</td>
<td>4.70</td>
<td>5.11</td>
<td>14.76</td>
<td>12.39</td>
<td>8.04</td>
<td>53.27</td>
</tr>
</tbody>
</table>

No significant differences.
The next step in this ongoing research program will be to determine if the canopy contact harvesters and trunk shaking harvesters will have higher final efficiencies in high-density hedgerow orchards, or in conventional orchards that have been topped, hedged and skirted to produce a modified hedgerow. These trials will be conducted in 2010. At that time we also hope to determine the field operating parameters of ground speed, hectares per hour, tons per hour and cost per ton and per hour to harvest the olives. The final project goal is an online interactive harvest calculator which will allow growers to enter their orchard parameters to determine if hand harvest or machine harvest produces a better net return.

7. Conclusions

Interestingly, though olives are one of the world’s oldest continuously produced tree crops the technology of production has remained unchanged through even the industrial revolution, a revolution that had a greater impact on agriculture than any other sector. Now however, the changes in olive orchard development and olive harvesting technology are bringing this traditional crop into the twenty first century. Within ten years all truly commercial table and oil olives will be mechanically harvested. The research has been an ongoing process of developing and evaluating picking technologies, defining, and ranking the limiting factors, and pursuing both simultaneously. For table olives two picking technologies have been developed; trunk shakers and picking heads. The most limiting factor, fruit damage, has been eliminated. Now viable harvesting machines must be developed for both picking technologies and the orchards densities best suited to these harvest technologies must be defined. It appears these new orchards will be hedgerows, with or without trelises, and may be mechanically pruned. The specific tree densities and how these orchards will be pruned to produce an economic return with the current cultivars will be determined as these orchards mature.

References


LEE S. H., GIAMARDA I.J., FERGUSON L., 2009 - Sensory characteristics and consumer acceptance of mechanically harvested California black olives. - Department of Food Science and Technology, University of California, Davis, USA, http://groups.ucanr.org/olive_harvest/Statewide_Olive_Days/.


