Preliminary and Regional Reports

Promising Olive Cultivars for Oil Production in Hawaii

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SUMMARY. To determine promising olive (*Olea europaea*) cultivars for oil production in Hawaii, seven trees each of 10 cultivars (Arbequina, Arbosana, Coratina, Frantoio, Koroneiki, Leccino, Mission, Moraiolo, Pendolino, and Taggiasca) were planted in Feb. and July 2011 at the Lalamilo Experiment station on Hawaii Island (lat. 20.0176°N, long. 155.6827°W, elevation 2700 ft). In addition, two trees each of these 10 cultivars were planted in June 2011, with the exception of Arbequina, which was planted in July 2012, at the Maui Agricultural Research Center in Kula, Maui (lat. 20.7564°N, long. 156.3289°W, elevation 3100 ft). At Lalamilo, after ≈2 years of growth in the field (2013), three cultivars of olives (Arbequina, Arbosana, and Koroneiki) flowered, fruited, and produced oil yields of greater than 20%. These same cultivars flowered and fruited in 2014 and 2015. There was no significant difference among cultivars in fresh weight fruit yield averaged over 2 years (2013 and 2014), ranging from 2.14 to 2.45 kg/tree. During December to March, calculation of chilling hours below 12.5 °C was 141 hours during 2012–13 and 161 hours during 2013–14. The other seven cultivars did not flower and fruit during these 2 years of growth at Lalamilo, perhaps due to a greater requirement for chilling hours. At Kula, after 3 years of growth (2015), nine cultivars of olives with the exception of Moraiolo flowered and fruited. Mean fresh weight fruit yield in 2015 ranged from 0.25 to 22.06 kg/tree for various cultivars grown in Kula, Maui. In 2013, the oil from three cultivars grown at Lalamilo was analyzed for free fatty acids (FFA), peroxide value (PV), ultraviolet absorption for conjugated double bonds, 1,2-diacylglycerol (DAG), and pyropheophytins (PPP). Oil quality was within the range of extra-virgin olive oil. There is a need to investigate further the effects of temperature and management on flowering and fruiting of olive cultivars grown in Hawaii at various elevations. In particular, ‘Arbequina’, ‘Arbosana’, and ‘Koroneiki’ appear to have a lower requirement for chilling hours than other cultivars tested.

Olives are grown throughout the Mediterranean basin, and the best production areas are characterized by mild, rainy winters and long, warm, and dry summers. Traditional olive orchards are low density (≈100 trees/ha) and rainfed (Gomez-del-Campo, 2013; Naor et al., 2013).

Plantings of olives have spread outside the Mediterranean region, into countries such as Angola, Australia (northern Victoria province),

northwest Argentina, California, and Texas (Aybar et al., 2015; De Melo-Abreu et al., 2004; Mailer and Ayton, 2011; Malik and Bradford, 2006; Sahli et al., 2012; Trentacoste et al., 2010). In Hawaii, olives have been cultivated during most of the 20th century and are naturalized in dry to mesic areas on Hawaii Island (Wagner et al., 1990).

Temperature is the most important environmental factor that influences olive flowering and fruit set. In

the absence of winter chilling or hours below 7.2 °C, no flowers were produced in several olive cultivars (Hartmann and Porlingis, 1957). In Hawaii, which is located in the tropics, a higher elevation is associated with cooler temperatures. On Hawaii Island, a planting of ‘Arbequina’ at an elevation of 1000 ft did not produce any flowers (D. McKanna, personal communication).

There are three stages in olive flower production: 1) floral buds are initiated at the end of summer or early autumn, 2) floral bud dormancy during the winter cold period, and 3) bud burst and flower structure development until anthesis (full bloom) (Fabbri and Benelli, 2000; Fernandez-Escobar et al., 1992). Rallo and Martin (1991) showed that 7.2 °C is sufficient to complete chilling requirements of ‘Manzanillo’ in a growth chamber following 800 h below 7.2 °C in the field, whereas 12.5 °C allowed completion of chilling requirements and subsequent growth of floral bud. In addition, flower formation has been shown to be inhibited by high daytime temperatures (≥24 °C), and it was suggested that the lack of flowering of ‘Arbequina’ in Weslaco, TX, was due to too many hours of high temperature (Malik and Bradford, 2006).

Cultivar selection is critical for successful fruit and oil production, because cultivars differ in the chilling requirement to break floral bud dormancy (De Melo-Abreu et al., 2004; Hartmann and Porlingis, 1957; Orlandi et al., 2004; Sahli et al., 2012). In central Italy and southern Spain, Orlandi et al. (2004) found that Italian cultivar Ascolana required 1848 h below 7.2 °C to reach budburst, whereas Spanish cultivar Picudo required 997 h. In northwest Argentina, at almost all sites (elevations ranging from 350 to 1200 m above sea level) and in all years, ‘Arbequina’ flowered normally (Aybar et al., 2015). In contrast, Leccino and Frantoio did not flower normally, indicating a need for selection of other cultivars better suited to the chilling hours found in northwest Argentina (Aybar et al., 2015).

Factors affecting olive oil yield include fruit number, average fresh fruit weight, and fruit oil concentration. Fruit oil concentration increases typically from early fall until harvest.

In Spain, oil content of 'Arbequina' and eight new cultivars showed greatly increased oil content between September and December (Leon et al., 2013). In Argentina, fruit oil concentration of 'Arbequina' increased rapidly between 50 and 150 d after full bloom (Trentacoste et al., 2010).

An index of fruit color [maturity index (MI)] is used widely to decide on the best time to harvest olives (Trentacoste et al., 2010). Depending on the cultivar and desired flavor characteristics of the oil, a fruit MI between 2.5 and 4.5 is used (Vossen, 2005): 0 = deep green color, 1 = yellow or yellow-green skin color, 2 = yellow-green with less than 1/2 of fruit with reddish spots and violet skin color, 3 = red to purple skin color on more than 1/2 of fruit, 4 = light purple to black skin color with white-green flesh color, 5 = black skin color and violet flesh color less than 1/2 way to the pit, 6 = black skin color and violet flesh color almost to the pit, and 7 = black skin color and dark flesh color all the way to the pit. In 'Arbequina' grown in Argentina, a fruit MI of 2.5 optimized both oil yield and oil quality (Trentacoste et al., 2010).

Oil production increases with irrigation, mostly due to increased crop load (Naor et al., 2013). There are two periods of growth when trees are most sensitive to drought stress: 1) in the spring between budburst and fruit drop (≈ 5 –6 weeks after budburst) and 2) from the end of

summer and early fall until harvest when oil is being synthesized in the fruit (Gomez-del-Campo, 2013). Summer is the period when irrigation water can be conserved with the least reduction in fruit and oil production (Gomez-del-Campo, 2013). In Golan Heights, Israel, irrigation at a crop coefficient (K_c) of 0.75 to 1.0 resulted in maximum oil yield in an orchard of 6-year-old 'Koroneiki' trees (Naor et al., 2013). Maximum fruit yield in a fully irrigated 'Arbequina' orchard (10–11 years after planting) in Argentina at a spacing of 417 trees/ha was reported to be 60 kg/tree ($25 \text{ t} \cdot \text{ha}^{-1}$) with an oil yield of $3.8 \text{ t} \cdot \text{ha}^{-1}$ (Trentacoste et al., 2010). Vossen (2005) reported that mature, irrigated orchards in north and central coasts of California at a spacing of 180 trees/acre produced an average fruit yield of 2.5 tons/acre (31 kg/tree or $5.6 \text{ t} \cdot \text{ha}^{-1}$) and an oil yield of 45 gal/ton ($1.0 \text{ t} \cdot \text{ha}^{-1}$). In northern Victoria province, Australia, fruit yield in fully irrigated 'Paragon' orchards grown for 9 to 11 years after planting at a spacing of 250 trees/ha ranged from 28 to 42 kg/tree (7 to $10.5 \text{ t} \cdot \text{ha}^{-1}$) and oil yield ranged from 4.8 to 5.8 kg/tree (1.2 to $1.45 \text{ t} \cdot \text{ha}^{-1}$) (Mailer and Ayton, 2011).

Consumption of all salad and cooking oils in the United States has increased steadily from 15.4 lb per capita in 1970 to 33.7 lb per capita in 2000 (Barrio and Carman, 2005). Demand in the United States for olive oil is growing due to its health benefits. For example, olive oil has been reported to have a protective effect against coronary heart disease, various cancers, and age-related cognitive decline due to its high content of monounsaturated fatty acids and polyphenols (Dag et al., 2009).

There is a potential market for high value, boutique olive oil produced in Hawaii. However, there is little information on olive cultivars best suited for oil production in Hawaii or best management practices to maximize oil production. In addition, there is a need for more information on the minimum chilling requirements to break winter dormancy of floral buds of various olive cultivars grown in Hawaii. The objective of these field trials conducted in Lalamilo, Hawaii Island, and Kula, Maui, was to determine olive cultivars best suited for oil production.

Materials and methods

PLANTING AT LALAMILO. Ten olive cultivars were selected for oil production, based partly on recommendations by P. Vossen from the University of California, Davis (UCD), and partly on availability through plant nurseries in California and Hawaii (Table 1). The cultivars recommended for oil production by Mr. Vossen were Arbequina, Arbosana, Frantoio, Koroneiki, Leccino, Mission, Pendolino, and Moraiolo.

Olive cultivar Arbequina was obtained from Kealakekua Bay Farm Management (Kailua-Kona, HI) in pots that were 2.5 inches diameter, 10 inches depth, and 40 inches³ volume (D40L Deepot cells; Stuewe & Sons, Tangent, OR). Cultivars Arbosana, Frantoio, Koroneiki, Leccino, and Mission were obtained from Duarte Nursery (Hughson, CA) in similar sized pots. These cultivars were large enough to transplant into the field immediately. Four cultivars obtained from McEvoy Ranch (Petaluma, CA) were replanted in 1-gal pots with potting medium containing perlite and peatmoss (Sunshine Mix #2; Sun Gro Horticulture, Agawam, MA).

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
10	%	$\text{g} \cdot \text{L}^{-1}$	0.1
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
16.3871	inch ³	cm^3	0.0610
0.4536	lb	kg	2.2046
1.6093	mph	$\text{km} \cdot \text{h}^{-1}$	0.6214
7.4892	oz/gal	$\text{g} \cdot \text{L}^{-1}$	0.1335
1	ppm	$\mu\text{g} \cdot \text{g}^{-1}$	1
2.3385	qt/acre	$\text{L} \cdot \text{ha}^{-1}$	0.4276
2.2417	ton(s)/acre	$\text{t} \cdot \text{ha}^{-1}$	0.4461
$(^{\circ}\text{F} - 32) \div 1.8$	$^{\circ}\text{F}$	$^{\circ}\text{C}$	$(^{\circ}\text{C} \times 1.8) + 32$

and grown in the greenhouse for ≈5 months until ready for transplanting.

Six cultivars of olive trees were planted in a randomized complete block design on 24 Feb. 2011 at the Lalamilo Experiment Station (lat. 20.0176°N, long. 155.6827°W) (Table 1). They were planted at a spacing of 10 ft apart in single rows along dirt roads. Spaces were left for the four remaining cultivars (Taggiasca, Coratina, Pendolino, and Moraiolo), that were planted on 13 July 2011 (Table 1). One tree of each cultivar was placed in a block that was repeated seven times in a randomized complete block design. After planting, mulch was placed around the trees (but away from the trunk) to control weeds.

LALAMILO SITE INFORMATION. The Lalamilo Experiment station is located on Hawaii Island at 2700 ft elevation. Air temperatures were recorded hourly at the Lalamilo station. The soil series is the Waimea series (medial, amorphous, isothermic, and Humic Haplustands) [Ikawa et al., 1985; U.S. Department of Agriculture (USDA) and UCD, 2015]. Soil at

Lalamilo is considered a “light soil,” because it is a volcanic ash soil.

Five soil samples were taken at the Lalamilo Experiment Station on 14 Oct. 2005. Samples were sent to the University of Hawaii Agricultural Diagnostic Service Center (ADSC). Soil pH was determined using the saturated paste method; extractable phosphorus (P) was determined using the modified Truog method; soil cations [potassium (K), calcium (Ca), and magnesium (Mg)] were extracted using ammonium acetate (1 M, pH 7.0) and determined using inductively coupled plasma emission spectrophotometry (Optima 7000DV Spectrometer; PerkinElmer, Waltham, MA) (Hue et al., 2000). Mean results of the analysis of four soil samples taken in a field at Lalamilo Experiment Station in 2005 are shown in Table 2. Based on Yost and Uchida (2000), soil pH was adequate, whereas, extractable P, K, Ca, and Mg were all high.

IRRIGATION AT LALAMILO. Drip irrigation lines were installed with one emitter (DIG button dripper, 0.5 gal/h; DIG Corp., Vista, CA)

placed ≈1 ft away from the trunk. Plants were irrigated starting 24 Feb. 2011 at 1.0 gal per application three times per week. Then, to avoid pythium root rot (*Pythium* sp.) and salt damage (Miyasaka and Hamasaki, 2012), on 1 Feb. 2012, the irrigation rate was changed to 3 gal applied once per week. Irrigation was turned off on 29 Jan. 2013, and resumed on 6 May 2014. A second emitter was placed 12 inches away from the trunk for the three cultivars that flowered and fruited, resulting in a doubling of irrigation rate for these trees.

WIND PROTECTION GUARDS AT LALAMILO. The Lalamilo station is in a windy area located between two mountain ranges (Mauna Kea and Kohala). According to the National Renewable Energy Laboratory (True Wind Solutions and National Renewable Energy Laboratory, 2004), wind speed at Lalamilo station at 50 m height ranged from 16.8 to 19.7 mph. This is an excellent to outstanding resource for wind power, but could be damaging to young trees.

To protect young plants from wind damage, shade cloth cages were constructed as follows. Weed mat (4 ft wide) was cut with a hole in the center and each tree inserted into the center of the mat on 27 May 2011. During May to June 2011, one T-post was installed next to each planted tree; a wire cage (3 ft diameter by 4 ft high) was secured to the T-post, and shade cloth (47% shade) placed around the wire cage. After the second planting, the young trees were protected immediately with the shade cloth cages.

FERTILIZATION AT LALAMILO. On 28 Feb. 2011, trees were fertilized in a ring ≈6 inch radius from the tree trunk with 100 g/tree of slow-release fertilizer (Apex 16N-2.6P-9.1K, release rate of 7–8 months at 70 °F; J.R. Simplot Co., Lathrop, CA). On 19 Oct. 2011, trees were fertilized with the same amount of fertilizer immediately next to the tree trunk, placing fertilizer through the hole in the weed mat. On 24 Jan. 2012, this fertilizer was removed due to concerns about high salt content. On 23 Mar. 2012, another slow-release fertilizer was applied at 100 g/tree (Nutricote 13N-5.7P-10.8K, Sun Gro Horticulture) at a radius of 2 ft away from tree trunk, outside the weed mat. Then,

Table 1. Ten olive cultivars planted at Lalamilo Experiment station on Hawaii Island, their country of origin, source of planting materials and planting date.

Cultivar	Country of origin	Nursery ^a	Planting date
Arbequina	Spain	Kealakekua	24 Feb. 2011
Arbosana	Spain	Duarte	24 Feb. 2011
IRTA i-43 PP18598 ^y			
Taggiasca	Italy	McEvoy	13 July 2011
Frantoio	Italy	Duarte	24 Feb. 2011
Koroneiki	Greece	Duarte	24 Feb. 2011
IRTA i-38 PP18599 ^y			
Leccino	Italy	Duarte	24 Feb. 2011
Mission	California	Duarte	24 Feb. 2011
Coratina	Italy	McEvoy	13 July 2011
Pendolino	Italy	McEvoy	13 July 2011
Moraiolo	Italy	McEvoy	13 July 2011

^aDuarte = Duarte Nursery (Hughson, CA), Kealakekua = Kealakekua Bay Farm Management (Kailua-Kona, HI), McEvoy = McEvoy Ranch (Petaluma, CA).

^yIRTA i-43 PP18598 is a clone from a selected ‘Arbosana’ tree and IRTA i-38 PP18599 is a clone from a selected ‘Koroneiki’ tree (Tous et al., 2011).

Table 2. Results of soil analysis at Lalamilo Experiment Station on Hawaii Island and at Maui Agricultural Research Center at Kula, Maui.

Location	pH ^z	Phosphorus (μg·g ⁻¹) ^y	Potassium (μg·g ⁻¹) ^x	Calcium (μg·g ⁻¹)	Magnesium (μg·g ⁻¹)
Lalamilo	6.2	214	821	5,356	686
Kula	6.1	46	403	2,356	318

^zSoil pH was measured using the saturated paste method (Hue et al., 2000).

^yExtractable phosphorus was measured using the modified Truog procedure (Hue et al., 2000); 1 μg·g⁻¹ = 1 ppm.

^xExtractable soil cations (potassium, calcium, and magnesium) were extracted using ammonium acetate (1 M, pH 7.0) as the extracting solution and measured using inductively coupled plasma emission spectrophotometer (Hue et al., 2000).

on 19 Aug. 2013 and 6 May 2014, 100 g each of slow-release fertilizer (Apex 12N–1.7P–10.0K, release rate 3–4 months at 70 °F), soluble Mg fertilizer (K Mag 0N–0P–22K–10.8Mg; Mosaic Co., Plymouth, MN), soluble Ca fertilizer (gypsum 0N–0P–0K–22Ca) were applied outside the weed mat.

PEST MANAGEMENT AT LALAMILO. During 2014 and 2015, ash whitefly (*Siphoninus phillyreae*) was observed to infest the olive trees. In 2015, insect growth regulators pyriproxifen (Knack; Valent U.S.A. Corp., Walnut Creek, CA) and buprofezin (Applaud; Nichino America, Wilmington, DE) were applied according to the label on 19 Aug. 2015 and 10 Sept. 2015, respectively.

PRUNING AND GROWTH MEASUREMENTS AT LALAMILO. On 13 Sept. 2012, protective shade cloth cages were removed (except for small trees that did not reach the tops of cages). Trees were pruned to a single main trunk for the first 2 to 3 ft of height. To prevent wind damage, trees were secured to the T-post.

On 27 Nov. 2012, heights and basal diameters of trees (4 inches above ground level) were measured. One-way analysis of variance (ANOVA) was conducted on these growth parameters using PROC GLM (SAS version 9.2; SAS Institute, Cary, NC). During 27 Jan. 2015 and 3 Feb. 2015, olive trees were pruned severely to open up the canopy as well as to train about four main scaffold branches.

FLOWERING AND HARVESTING AT LALAMILO. Flowers were observed on ‘Arbequina’, ‘Arbosana’, and ‘Koroneiki’ during Mar. to Apr. 2013, 2014, and 2015. On 16 Oct. 2013, 2 Oct. 2014, and 22 Oct. 2015, olives were harvested from three cultivars (Arbequina, Arbosana, and Koroneiki) in a onetime, annual harvest. Branches and stems were removed, as well as fruit that appeared offgrade. Fresh weights of good fruit were determined, and then 100 representative fruit were graded for color according to the maturity standard (Vossen, 2005). The other seven cultivars did not produce fruit, except for small yields (<1 kg) of two Mission trees during Oct. 2015.

Fresh weights of offgrade fruit were determined in 2013. A subsample was sent to the University of Hawaii’s ADSC to determine

whether any diseases or pests were responsible.

For individual trees, yields were averaged across 2 years (2013 and 2014) due to known alternate-bearing characteristics of olives (Martin et al., 2005), and were compared for treatment differences due to cultivar using one-way ANOVA. Statistical analysis was conducted using PROC GLM (SAS version 9.2). Data from 2015 was not included in this analysis, because most fruit had fallen off trees before harvest.

OLIVE OIL AT LALAMILO. Three olive cultivars were processed for olive oil on 18 Oct. 2013. Cooperator D. McKanna used a modified version of an olive oil press (First Press home olive oil press; The Olive Oil Source, Santa Ynez, CA). Oil yields were calculated, assuming a specific density of 0.91 (Vossen, 2005). Olive oil was shipped immediately in 2013 to the UCD Olive Center for chemical analysis of FFA, PV, ultraviolet absorption for conjugated double bonds, DAG, and PPP. In 2014, oil from the same three cultivars were processed for olive oil and shipped after storage for 2 months to UCD for chemical analysis and sensory evaluation.

PRELIMINARY PLANTING AT KULA. The Maui Agricultural Research Center at Kula, Maui, is located at ≈3100 ft elevation (lat. 20.7574°N, long. 156.3132°W). Maximum/ minimum air temperatures were recorded daily. The soil series is the Kula series, which is a Medial, amorphic, isothermic, and Humic Haplustand (Ikawa et al., 1985; USDA and UCD, 2016). This volcanic ash soil is considered to be “light soil.” A soil sample of a nearby field was taken on 31 Aug. 2015 and sent to the University of Hawaii ADSC for analysis as described earlier. Soil pH and extractable K are considered sufficient, whereas, extractable P, Ca, and Mg are considered to be low [Table 2 (Yost and Uchida, 2000)].

Two trees each of the same 10 cultivars that were described for the Lalamilo site were planted at the Kula Experiment Station on Maui at a spacing of 10 × 10 ft on 14 June 2011, with the exception of Arbequina, which were planted on 26 July 2012. Kula Station is located on the leeward side of Maui Island and wind

speed is low, ranging from 0 to 12.5 mph (True Wind Solutions and National Renewable Energy Laboratory, 2004), so we did not install wind protection guards.

Initially, irrigation was applied at 1 gal twice per week using two spot emitters placed ≈1 ft from trunk. After ≈1 year, irrigation was applied per tree at 4.2 gal/tree twice per week using multidrip emitters. Due to heavy fruit set in 2015, irrigation was increased to 10.4 gal/tree per week starting 10 Aug. 2015. Trees were fertilized twice per year with 100 g of slow-release fertilizer (Apex 16N–2.6P–9.1K) during spring and summer. Ash whiteflies infested the trees during Summer to Fall 2013, and buprofezin (Talus Insect Growth Regulator; SePRO Corp., Carmel, IN) was applied according to the label in Oct. 2013.

Height and basal stem diameter were measured on 14 Dec. 2012 after ≈1.5 years of growth for nine cultivars and 0.5 years of growth for Arbequina. One-way ANOVA was conducted on these two growth parameters using PROC GLM (SAS version 9.2). Flowering was observed during Spring 2014; however, the flowers turned brown and fell off. It was thought to be due to inadequate soil moisture and the irrigation was increased in 2015.

During Mar. to Apr. 2015, all cultivars flowered and set fruit, except for Moraiole. During Aug. to Oct. 2015, all trees with fruit were harvested when average MI appeared to be ≈3. All fruit was removed in a onetime harvest per tree, with the exception of one ‘Mission’ tree that was harvested on 20 Aug. 2015 and on 25 Sept. 2015, and one ‘Leccino’ tree that was harvested on 20 Aug. 2015 and on 28 Oct. 2015. One-way ANOVA was conducted on yield of nine cultivars using PROC GLM (SAS version 9.2).

Results and discussion

GROWTH OF OLIVE TREES AT LALAMILO. Fuller rose beetles (*Pantomorus cervinus*) were observed to damage young olive leaves during 2011. These are flightless, nocturnal beetles that feed on leaves, causing a notching of leaf margins.

During Jan. 2012, about five to eight olive trees that had been transplanted for less than 1 year showed

symptoms that ranged from minor (chlorosis of leaves) to moderate (leaf-tip burn and marginal necrosis) to severe (dieback). After soil analysis, it was found that the salinity levels were moderately high, perhaps due to slow-release fertilizer placed too close to the tree trunk (Miyasaka and Hamasaki, 2012). Foliar analysis revealed too low a level of calcium, an essential element that helps plants resist pathogens. Disease diagnosis of excavated roots showed a pythium rot, a disease that is considered to be a minor root rot. Perhaps, too frequent irrigation provided ideal, moist conditions for this pathogen. In summary, the problem was diagnosed to be primarily due to salt stress, exacerbated by low calcium, and too frequent irrigation. To solve this problem, the slow-release fertilizer was removed from near the trunk, irrigation scheduled only once per week to allow drying of the soil around the plant roots, and the fungicide mono and dipotassium salts of phosphorous acid (Fosphite; JH Biotech, Ventura, CA) was applied at the rate of 1.1 qt/acre a.i. in 100 gal of water to control pythium rot.

On 27 Nov. 2012, cultivars differed significantly in height and basal trunk diameter (Table 3). ‘Leccino’ was the tallest and had the greatest trunk basal diameter. ‘Coratina’ was the shortest and ‘Moraiolo’ had the smallest basal diameter. Not surprisingly, cultivars planted earlier had greater heights and tended to have greater basal diameters than cultivars planted later. As of 27 Nov. 2012, one tree each of ‘Arbosana’, ‘Pendolino’, and ‘Taggiasca’ had died, as well as two trees of ‘Coratina’. The remaining trees appeared to be growing well.

During July 2014, ash whitefly was observed to infest the olive trees. The whiteflies excreted honeydew, and leaves and fruit became sticky and in some cases, discolored by sooty mold. Wild and ornamental olive trees in the area were similarly infested. By Sept. 2014, ash whitefly infestation levels were still high and insecticidal control was being considered but was not applied because of the upcoming harvest in 2014. Ash whiteflies became a problem again in 2015 and application of insect growth regulators (pyriproxifen and buprofezin) during Aug. to Sept. 2015 appeared to control the pests.

FLOWERING AND FRUITING AT LALAMILO. Figures 1 and 2 show maximum and minimum air temperatures during Dec. 2012 through Mar. 2013, as well as during Dec. 2013 through Mar. 2014. Chilling hours to break dormancy have been calculated previously as the number of days from when mean daily temperature dropped below 7.2 °C until the first reproductive budburst (Orlandi

et al., 2004). However, the lowest minimum temperature recorded at Lalamilo during this 2-year period was 47 °F, which is above that reported to be required for breaking the dormancy of buds.

Perhaps, the more relevant temperature in this tropical agro-environment is 12.5 °C, which was reported by Rallo and Martin (1991) to be sufficient to complete the chilling

Table 3. Time after transplanting, heights, and basal diameters of 10 cultivars of olive trees grown at Lalamilo Experiment Station on Hawaii Island measured on 27 Nov. 2012.

Cultivar	Time after transplanting (mo.)	Ht [mean ± SE (m)] ^z	Basal diam [mean ± SE (cm)] ^z
Arbequina	22	2.08 ± 0.17 cd ^y	4.3 ± 0.38 cd
Arbosana	22	2.36 ± 0.31 bc	5.2 ± 0.54 bc
Coratina	17	1.68 ± 0.20 d	3.7 ± 0.48 de
Frantoio	22	2.37 ± 0.09 bc	6.4 ± 0.31 a
Koroneiki	22	2.75 ± 0.13 ab	5.8 ± 0.46 ab
Leccino	22	2.90 ± 0.34 a	6.8 ± 0.55 a
Mission	22	2.05 ± 0.18 cd	3.9 ± 0.32 de
Moraiolo	17	1.82 ± 0.19 d	2.9 ± 0.74 e
Pendolino	17	1.73 ± 0.25 d	4.4 ± 0.30 cd
Taggiasca	17	1.77 ± 0.17 d	3.1 ± 0.41 e
<i>P</i> > <i>F</i>			
Cultivar		<0.0001	<0.0001
Block		0.0006	0.002

^z1 m = 3.2808 ft, 1 cm = 0.3937 inch.

^yThe same letters in a column indicate no significant differences between means at *P* ≤ 0.05 using the Waller-Duncan k-ratio test.

Fig. 1. Maximum and minimum air temperatures at Lalamilo Experiment station on Hawaii Island during Dec. 2012 and Jan. to Mar. 2013. The lower line is drawn at 54.5 °F, the temperature reported by Rallo and Martin (1991) to be sufficient for chilling and bud development. The upper line is drawn at 75.2 °F, the temperature suggested as inhibitory to flowering by Malik and Bradford (2006); (°F - 32) ÷ 1.8 = °C.

Fig. 2. Maximum and minimum air temperatures at the Lalamilo Experiment station on Hawaii Island during Dec. 2013 and Jan. to Mar. 2014. The lower line is drawn at 54.5 °F, the temperature reported by Rallo and Martin (1991) to be sufficient for chilling and bud development. The upper line is drawn at 75.2 °F, the temperature suggested as inhibitory to flowering by Malik and Bradford (2006); $(^{\circ}\text{F} - 32) \div 1.8 = ^{\circ}\text{C}$.

requirement and for subsequent growth of floral buds. Similarly, rather than relying on a single threshold temperature of 7.2 °C, De Melo-Abreu et al. (2004) calculated chilling units using temperatures ranging between 0 and 20 °C; 1 h at a temperature of 7.3 °C was calculated as 1 chilling unit, whereas, 1 h at a temperature of 12.5 °C was calculated as 0.4 chilling units. Figures 1 and 2 show numerous days between December and March when minimum temperatures fell below 54.5 °F. Based on hourly measurements of air temperature, chilling hours below 54.5 °F were calculated to be 141 h between Dec. 2012 and Mar. 2013, and 161 h during these months in 2013–14. In Spain, De Melo-Abreu et al. (2004) calculated that ‘Arbequina’ required 339 chilling units for budbreak. In Tunisia, Sahli et al. (2012) calculated that ‘Chemlali’ required 125 chilling units to break bud dormancy. It is not possible to compare our measured chilling hours below 12.5 °C with calculated required chilling amounts by De Melo-Abreu et al. (2004) or Sahli et al. (2012), due to differences in calculations of chilling units by each researcher.

The other critical temperature in this tropical agro-environment is

24 °C, above which olive flowering was suggested to be inhibited by Malik and Bradford (2006). The number of days when maximum temperatures at Lalamilo exceeded 75.2 °F were low during 2012–13, but much greater during 2013–14 (Figs. 1 and 2).

During Mar. to Apr. in 2013, 2014, and 2015, trees of three cultivars (Arbequina, Arbosana, and Koroneiki) were observed to flower at Lalamilo. In June 2014, a second flowering was observed on ‘Koroneiki’. The other seven cultivars did not flower or produce fruit consistently during 2013 to 2015, perhaps indicating that their requirement for chilling hours was greater than those of these three cultivars. Alternatively, ‘Arbequina’, ‘Arbosana’, and ‘Koroneiki’ have been reported to be precocious (bearing fruit within 3 years after planting and reaching maximum yields within 5 years after planting) in a high-density system (De la Rosa et al., 2007). It is possible that the other seven cultivars may begin to bear fruit in later years.

Not all trees of these three cultivars (Arbequina, Arbosana, and Koroneiki) flowered each year. On 16 Oct. 2013, five trees each of ‘Arbequina’ and ‘Arbosana’ produced fruit and were harvested in a onetime

harvest, along with six trees of ‘Koroneiki’ that had produced fruit. On 2 Oct. 2014, five trees of ‘Arbequina’, three trees of ‘Arbosana’, and six trees of ‘Koroneiki’ produced fruit and were harvested in a onetime harvest. On 23 Oct. 2015, two trees each of ‘Arbequina’, ‘Arbosana’, and ‘Koroneiki’ produced fruit and were harvested; however, the yield data were not analyzed statistically, because substantial numbers of fruit had been observed to drop earlier.

Interestingly, the same trees did not flower and produce fruit each year. Two ‘Arbequina’ trees with moderate yields in 2014, did not bear in 2013 and two trees with moderate yields in 2013 did not bear in 2014. Similarly, two ‘Arbosana’ trees that had high yields in 2013 did not bear fruit in 2014, and one tree that did not bear fruit in 2013, produced a low yield in 2014. These results were not surprising, because olives are well-known to be alternate-bearing (Martin et al., 2005). Other possible explanations for reduced yields are abiotic stresses (excess salinity) or biotic stresses (pythium rot or ash whiteflies).

Fresh weight fruit yields per tree and oil volume per tree for ‘Arbequina’, ‘Arbosana’, and ‘Koroneiki’ are shown in Table 4. Due to the alternate-bearing characteristics of olives, it was decided to average yields over 2 years before conducting statistical analysis. No significant difference among the three cultivars was found in fruit yields averaged over 2 years. Fresh fruit yields ranging from 2.14 to 2.45 kg/tree of trees grown at Lalamilo were low compared with yields reported for ‘Arbequina’, ‘Arbosana’, and ‘Koroneiki’ grown for 3 years after planting in Spain of 8.43, 8.69, and 10.50 kg/tree, respectively (De la Rosa et al., 2007).

The offgrade fruit in 2013 that had been sent to ADSC for disease analysis did not show evidence of pathogenic activity, other than secondary microorganisms. Apparently, bruising of fruit during harvest was responsible for most of the offgrade appearance of fruit. Shriveled ‘Koroneiki’ fruit were observed on one tree with a high crop load in 2013, indicating that the tree was water stressed.

‘Arbosana’ had a low mean fruit MI in 2013 (Table 4), due to fruit from two trees that were much greener than those of the other three trees of the same cultivar. This index should be between 2.5 and 4.5 (Vossen, 2005) for most cultivars. One possible explanation for this low fruit MI is a second flowering; we have observed flowering in the presence of developing fruit similar to that reported by Malik and Bradford (2006). In 2015, we harvested later in Oct. in an attempt to increase fruit MI; however, we found that mature fruit fell off trees in large quantities and as a result, usable harvest data were not collected. Perhaps, the windy conditions in Lalamilo resulted in mature fruit falling more readily off trees, making it difficult to increase fruit MI through later harvests.

OLIVE OIL YIELD AND QUALITY AT LALAMILO. Percentage yield of olive oil was calculated (Table 4) based on 0.91 specific density of olive oil (Vossen, 2005). Oil yield in 2013 was above the minimum required for profitable production (Vossen, 2005), ranging from 21% to 24% (Table 4). Oil yields reported in the literature was 15.2% in Argentinian orchards (Trentacoste et al., 2010), 13.8% to 17.0% in Australian orchards (Mailer and Ayton, 2011), and 17.9% in California orchards (Vossen, 2005). Oil yield at Lalamilo in 2014 was considerably lower compared with 2013, probably due to problems during processing and is not reported here.

Results of chemical analysis of olive oil in 2013 are shown in Table 5. Frankel et al. (2010) provided an explanation for the quality analysis

conducted by the UCD Olive Center. FFA are formed by hydrolysis of the triacylglycerols in oils during extraction, processing, and storage. An elevated level of FFA indicates hydrolyzed, oxidized and/or poor-quality oil. Peroxides are primary oxidation products that are formed when oils are exposed to oxygen, producing undesirable flavors and odors. An elevated level of PV indicates oxidized and/or poor quality oil. Conjugated double bonds are formed from natural nonconjugated unsaturation in oils upon oxidation. An elevated level of ultraviolet absorbance indicates oxidized and/or poor quality oil. During the breakdown of triacylglycerols, DAGs are formed. Fresh “extra-virgin” olive oil contains a high proportion of 1,2-DAGs to 1,2- and 1,3-DAGs, whereas olive

Table 4. Average fresh weight of olive fruit per tree during 2013 and 2014 harvests, annual average fresh weight of fruit averaged over 2 years, oil volume per tree in 2013, fruit maturity index (MI) based on color in 2013, and oil yield in 2013.

Cultivar	2013 Fresh wt (kg/tree) ^z	2014 Fresh wt (kg/tree)	2013–14 Avg fresh wt [mean ± SE (kg/tree)] ^y	2013 Oil vol (L/tree) ^z	2013 MI (2.5–4.5 scale) ^y	2013 Oil yield (%) ^x
Arbequina	1.35	3.55	2.45 ± 1.19 a ^w	0.31	3.5	22
Arbosana	3.50	1.24	2.37 ± 0.74 a	0.47	2.1	21
Koroneiki	1.75	2.53	2.14 ± 0.73 a	0.41	3.3	24
<i>P > F</i>						
Cultivar			0.96			
Block			0.19			

^z1 kg = 2.2046 lb, 1 L = 0.2642 gal.

^yMI of 2.5 to 4.5 is considered to be mature, depending on cultivar and flavor desired (Vossen, 2005): 0 = deep green color, 1 = yellow or yellow-green skin color, 2 = yellow-green with less than 1/2 of fruit with reddish spots and violet skin color, 3 = red to purple skin color on more than 1/2 of fruit, 4 = light purple to black skin color with white-green flesh color, 5 = black skin color and violet flesh color less than 1/2 way to the pit, 6 = black skin color and violet flesh color almost to the pit, and 7 = black skin color and dark flesh color all the way to the pit.

^xOil yield calculated based on specific density of olive oil of 0.91 (Vossen, 2005).

^wThe same letters in a column indicate no significant differences between means at $P \leq 0.05$ using the Waller–Duncan k-ratio test.

Table 5. Olive oil quality from one sample each of three cultivars (Arbequina, Arbosana, and Koroneiki) harvested in 2013 and analyzed for free fatty acids (FFA), peroxide value (PV), K value of ultraviolet absorption at 232 nm [K232 (ultraviolet absorption for conjugated double bonds)], K value of ultraviolet absorption at 268 nm (K268), increase of ultraviolet absorption due to oxidation products (ΔK), 1,2-diacylglycerol (DAG), and pyropheophytins (PPP). Standards for extra-virgin olive oil are shown for each analysis based on the U.S. Department of Agriculture (USDA) and Australian Olive Association (AOA).

Test	Cultivar			USDA limits ^z	AOA limits ^z
	Arbequina	Arbosana	Koroneiki		
FFA (% as oleic acid) ^y	0.24	0.18	0.22	≤0.8	≤0.8
PV (meq/kg oil) ^y	8.2	3.7	10.5	≤20	≤20
K232 ^x	1.73	1.71	1.47	≤2.5	≤2.5
K268 ^x	0.08	0.09	0.14	≤0.22	≤0.22
ΔK^x	0.001	0.001	0.002	≤0.01	≤0.01
DAG (% of total 1,2 and 1,3 diacylglycerols) ^w	96.6	98.3	94.9	—	≥40
PPP (% of total pheophytins) ^y	0.0	0.0	0.56	—	≤15

^zUSDA standards for olive oil and AOA standards are from Frankel et al. (2010).

^yFFA and PV were analyzed using analytical titration (Frankel et al., 2010), milliequivalent (meq) is chemical activity of an element relative to activity of 1 mg of hydrogen, where meq = mg × valence/molecular weight and 1 meq/kg = 0.4536 meq/lb.

^xultraviolet absorption for conjugated double bonds was analyzed using ultraviolet spectrophotometry (Frankel et al., 2010); $K = D/(C \times S)$, where D is absorption at a particular wavelength, C is solution concentration (grams per liter), and S is cuvette thickness (centimeters); $\Delta K = K_{268} - [(K_{262} + K_{274})/2]$ where K is calculated at 268, 262, and 274 nm, respectively; 1 g·L⁻¹ = 0.1335 oz/gal = 0.1%, 1 cm = 0.3937 inch.

^wDAGs were analyzed using gas chromatography (Frankel et al., 2010).

^yPPP were analyzed using high performance liquid chromatography (Frankel et al., 2010).

oil from poor quality fruit and refined olive oil have elevated levels of 1,3-DAGs. The ratio of 1,2-DAGs to 1,3- and 1,3-DAGs is an indicator for oil that is hydrolyzed, oxidized, of poor quality, and/or adulterated with refined oil. Chlorophyll pigments break down to pheophytins and then to PPP upon thermal degradation of olive oils. An elevated level of PPP is an indicator for oil that is oxidized and/or adulterated with refined oil.

Based on analyzed levels of FFA, PV, ultraviolet, DAGs, and PPP, it appears that all three cultivars produced oil that met all analytical criteria (Frankel et al., 2010) (USDA and Australian Olive Association) for acceptable “extra-virgin” olive oil in 2013. Oil from each cultivar was sent to UCD Olive Center for analysis in 2014. However, results are not reported here due to oxidation problems caused by improper storage of olive oil for 2 months before shipping.

TREE GROWTH AND YIELD AT KULA. In Dec. 2012, all planted trees were alive in Kula, Maui. Tree height differed significantly with ‘Arbosana’ the tallest and ‘Arbequina’ the smallest (Table 6). It was not surprising that ‘Arbequina’ was the shortest tree, since it was planted 13 months later than the other nine cultivars. No significant differences were found for basal trunk diameter, with an overall average of 5.2 cm. Heights and basal diameters of trees grown at Kula, Maui, at 18 months after planting (with the exception of ‘Arbequina’) were similar to those grown at Lalamilo, Hawaii Island at 17 or 22 months after planting.

All olive cultivars flowered and set fruit in Kula in 2015, except for Moraiolo (Table 6). No significant differences in fresh weight fruit yield per tree were found among cultivars with yields ranging from a high of 22.06 kg/tree for Koroneiki to a low of 0.25 kg/tree for Arbequina. This lack of significant differences among cultivars was probably due to high variability, since only two trees were planted per cultivar. For example, one tree of ‘Leccino’ yielded 1.52 kg fresh weight, whereas, the second tree of ‘Leccino’ had a yield of 14.86 kg, almost 10 times greater than that of the first tree.

Compared with three cultivars that produced fruit at Lalamilo, ‘Arbosana’ and ‘Koroneiki’ produced much higher yields at Kula, whereas

‘Arbequina’ produced lower yields at Kula, probably due to its late planting date. Fresh fruit yields of Arbosana and Koroneiki at Kula were within the range of yields of the same cultivars grown for 3 years after planting in Spain (De la Rosa et al., 2007).

Figure 3 shows maximum and minimum air temperatures at Kula, Maui. Minimum air temperatures

during Dec. 2014 through Mar. 2015 were mostly below 54.5 °F, the temperature reported by Rallo and Martin (1991) to be sufficient for chilling and bud development. Very few maximum air temperatures exceeded 75.2 °F, the temperature suggested as inhibitory to flowering by Malik and Bradford (2006). Hourly air temperatures were not

Table 6. Time after planting, height of olive trees measured on 14 Dec. 2012, and fresh weight (FW) of fruit per tree averaged over two trees during 2015 harvest at Kula, Maui.

Cultivar	Time after planting (mo.) ^z	Ht [mean ± SE (m)] ^y	Fruit FW [mean ± SE (kg/tree)] ^y
Arbequina	5	0.3 ± 0.03 d ^x	0.25 ± 0.20 a
Arbosana	18	2.8 ± 0.03 a	6.06 ± 2.64 a
Coratina	18	1.8 ± 0.56 abc	1.05 ± 0.55 a
Frantoio	18	2.3 ± 0.18 abc	1.23 ± 1.09 a
Koroneiki	18	2.6 ± 0.29 ab	22.06 ± 14.00 a
Leccino	18	2.5 ± 0.67 ab	8.19 ± 6.67 a
Mission	18	2.3 ± 0.34 abc	0.74 ± 0.06 a
Moraiolo ^w	18	1.2 ± 0.47 cd	
Pendolino	18	1.4 ± 0.02 bcd	4.71 ± 3.91 a
Taggiasca	18	2.0 ± 0.23 abc	1.57 ± 0.97 a
<i>P > F</i>			
Cultivar		0.02	0.21
Block		0.50	0.19

^zNine cultivars were planted on 14 June 2011 with the exception of Arbequina, which was planted on 26 July 2012.

^y1 m = 3.2808 ft, 1 kg = 2.2046 lb.

^xThe same letters in a column indicate no significant differences between means at $P \leq 0.05$ using the Waller-Duncan k-ratio test.

^w‘Moraiolo’ did not flower and produce fruit.

Fig. 3. Maximum and minimum air temperatures at the Maui Agricultural Research Center in Kula, Maui, during Dec. 2014 and Jan. to Mar. 2015. The lower line is drawn at 54.5 °F, the temperature reported by Rallo and Martin (1991) to be sufficient for chilling and bud development. The upper line is drawn at 75.2 °F, the temperature suggested as inhibitory to flowering by Malik and Bradford (2006); (°F – 32) ÷ 1.8 = °C.

recorded at Kula, so it is not possible to calculate actual chilling hours to compare with Lalamilo. However, it is readily apparent that air temperatures at Kula (Fig. 3) were cooler than those at Lalamilo (Figs. 1 and 2).

Conclusions

Based on harvest data from 2013 to 2015, olive cultivars Arbequina, Arbosana, and Koroneiki appear to grow well in the tropical but high elevation agro-environment of Lalamilo Experiment station in Waima, Hawaii Island (elevation 2700 ft). In 2013, after only 2 years of growth, they flowered, fruited, and produced a high quality “extra-virgin” olive oil. The lack of flowering and fruit production of the other seven cultivars at Lalamilo could be due to a greater requirement for chilling hours. At a preliminary trial of olives in Kula, Maui (elevation 3100 ft), all cultivars flowered and fruited after 3 years of growth, except for Moraiolo. Although only two trees per cultivar were planted at Kula, much higher yields were found for Koroneiki and Arbosana, perhaps indicating that temperatures were more suitable for breaking bud dormancy at this higher elevation. There is a need to determine chilling requirements for various olive cultivars, so that recommendations for suitable geographic locations could be made for planting of olive orchards in Hawaii. In addition, further studies of orchard management (tissue analysis to determine fertilizer requirements, optimum irrigation, and pruning for improved light interception) need to be conducted to maximize olive oil production and quality for promising olive cultivars grown in Hawaii.

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