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NURSERY RESPONSE OF *ACACIA KOA* SEEDLINGS TO CONTAINER SIZE, IRRIGATION METHOD, AND FERTILIZATION RATE

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□ *Planting koa (*Acacia koa *A. Gray) in Hawai'i, USA aids in restoration of disturbed sites essential to conservation of endemic species. Survival and growth of planted seedlings under vegetative competition typically increases with initial plant size. Increasing container size and fertilizer rate may produce larger seedlings, but high fertilization can lead to surface and groundwater pollution and relatively low fertilizer use efficiency. Subirrigation systems may help mitigate this problem. Our study objective was to evaluate koa seedling growth with overhead or subirrigation over a range of container volumes (50 to 656 mL) and fertilizer rates (0 to 9.6 kg·m^{-3}). Increasing container volume from 50 to 656 mL yielded koa seedlings with 200% more height and stem diameter growth. Subirrigation resulted in less nutrient leaching losses and yielded seedlings of similar vigor as overhead irrigated seedlings. Subirrigation helps optimize fertilizer delivery, which may improve fertilizer use efficiency and reduce environmental contamination.*

Keywords: controlled-release fertilizer, electrical conductivity, forest restoration, leaching, photosynthesis, subirrigation

INTRODUCTION

Hawai'i has the most critically endangered species within the United States, due primarily to competition from introduced species and habitat fragmentation-degradation (Balis-Larsen and Motivans, 2003). One habitat that has been substantially degraded through anthropogenic activities is the endemic, montane koa (*Acacia koa* A. Gray) forest (Scowcroft and Jeffrey, 1999). With its demise, many species, especially birds, have become

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threatened, endangered, or extinct (Maxfield, 2003). In addition to its ecological importance, koa is valuable for specialty, value-added wood products, such as bowls, furniture, picture frames, and flooring, contributing to the state's $US 30 million forest industry (Yanagida et al., 2004).

For these reasons, interest in planting koa has increased (Pejchar and Press, 2006). Under optimum conditions, koa can grow up to 2.2 m·year^{-1} (Cole et al., 1996), but on disturbed tropical sites, the success of outplanted tree seedlings is particularly limited by grass competition (Holl et al., 2000). On many sites on the Island of Hawai'i, the introduced invasive kikuyu grass (*Pennesitum clandestinum* Hochst. ex Chiov.) (Motooka et al., 2003) poses such a challenge to koa reforestation; its dense, thick mats of rhizomes impede seedling survival and growth (Jeffrey and Horiuchi, 2003).

In temperate forest regeneration, larger nursery-grown seedlings generally perform better than smaller seedlings when outplanted on sites with severe competition (Jobidon et al., 2003; South and Mitchell, 1999). Larger stock can be produced by increasing container size, fertilization level, and/or irrigation frequency (Endean and Carlson, 1975; Lamhamedi et al., 1996; Scarratt, 1972; Timmer and Miller, 1991). In Hawai'i, however, restricted water availability may limit options for nursery stock production (Dumroese et al., 2006).

In Hawai'i and elsewhere, overhead irrigation, because of relatively low installation cost, is the most common form of irrigation in forest and conservation nurseries (Landis et al., 1989). Overhead irrigation, however, is generally inefficient, with 49–83% of applied water discharged from the nursery (Dumroese et al., 1995). This wasted water contains appreciable amounts of fertilizer with potential to contaminate water sources (Dumroese et al., 1995; Juntunen et al., 2002; Molitor, 1990).

Subirrigation, a closed system, may improve irrigation efficiency and thereby reduce nursery water use and fertilizer runoff (Davis et al., 2008; Dumroese et al., 2006, 2007). Water circulates from a reservoir into an application tank where capillary action causes upward water movement into growing medium (Coggeshall and Van Sambeek, 2002). When irrigation is complete, unused water drains back to the reservoir for later recirculation. Subirrigation reduced water use 86% compared to overhead irrigation for food crops (Ahmed et al., 2000) and, in a Hawaiian nursery, identical crops of *Metrosideros polymorpha* Gaudich were produced with half the water of overhead irrigated plants (Dumroese et al., 2006).

Although several studies have shown that seedlings of a variety of species can be produced with equal or better size and biomass allometry using either irrigation method, (Bumgarner et al., 2008; Davis et al., 2008; Dumroese et al., 2006; Pinto et al., 2008), biological mechanisms to explain observed morphological responses under varying irrigation techniques are lacking. For example, compared to morphology, which reflects all inputs across the growing season, net photosynthetic assimilation (A) provides a clear depiction of seedling physiological status at a given time.

Thus, in an effort to improve koa seedling production efficiency during nursery culture, a study was initiated to evaluate seedling development and substrate electrical conductivity with overhead or subirrigation across a range of container volumes and fertilizer rates. We hypothesized that: 1) larger containers would yield larger koa plants; 2) higher fertilizer rates would increase koa seedling size; 3) subirrigation would be equally effective in promoting koa growth as conventional overhead irrigation; and 4) subirrigation would yield higher resource use efficiency than conventional overhead irrigation.

MATERIALS AND METHODS

Our experiment was conducted under operational conditions at an open-growing compound at the Hawai'i Division of Forestry and Wildlife Kamuela (Waimea) State Tree Nursery, 4 km south of Kamuela on the Island of Hawai'i, USA (20° 00′ 24″ N, 155° 40′ 38″ W). To test the hypothesis that increasing container volume would yield larger koa seedlings, we used four container types: Hawai'i "dibble tube", Ray Leach "Cone-tainer" SC-10, Deepot D-16, and Deepot D-40 (see Table 1 for characteristics). To test our hypothesis that increasing fertilizer rates would improve koa growth, we mixed a 2 parts *Sphagnum* peatmoss (Pro-Mix, Premier Horticulture, Dorval, QC, Canada) to 1 part perlite (v:v) medium and amended it with four levels of controlled release fertilizer: 0, 4.8 (the "medium" rate on the fertilizer label and current nursery standard), 7.2, and 9.6 $kg \cdot m^{-3}$ Osmocote Plus® 15 nitrogen (N): 9 phosphorus pentoxide (P_2O_5): 12 potassium oxide (K_2O) (5 to 6 mo longevity at 21°C; Scotts Co., Marysville, OH, USA). These rates reflect the decompressed volume of the medium. To test the hypothesis that subirrigation and overhead irrigation would yield similar koa seedlings, we used 2.44 m × 1.22 m × 11.5 cm subirrigation trays (Spencer-Lemaire, Edmonton, Alberta, Canada). Each tray had a 283 L water reservoir connected

TABLE 1 Characteristics of containers used to grow *Acacia koa*

	Diameter (cm)	Depth (cm)	Volume (mL)	Density (cavities m^{-2})
Hawaii dibble tube[a]	2.5	12	50	449
Ray Leach "Cone-tainer" SC-10[b]	3.8	21	164	528
Deepot-16 (D-16)[b]	5.0	18	262	269
Deepot-40 (D-40)[b]	6.4	25	656	174

[a]Pacific Allied Products, Ltd., Kapolei, HI, USA
[b]Stuewe and Sons, Inc., Tangent, OR, USA

to a submersible pump and timer. Each tray, pump, and timer served as a replicate. The overhead irrigation treatment was the nursery standard: rotating nozzles on risers on 6.6 m × 5.3 m spacing. All seedlings were irrigated every other day.

In early November 2005, we transplanted germinating (seven days following the usual hot water soak) koa seeds of a local source (Puʻu Waʻawaʻa) into a four container × four fertilizer rates × two irrigation systems × three replication completely randomized block design. Within each container–fertilizer–irrigation–replication combination, we sowed at least 200 seeds.

After three months of growth (February 2006), we selected seedlings from the centermost portions of container trays to avoid edge effects. We measured root-collar diameter (RCD) and shoot height on four seedlings within each container–fertilizer–irrigation–replication combination (384 seedlings). Three Deepot -16 containers were randomly selected from each fertilizer–irrigation–replication combination (72 containers) and, one hour after irrigating the containers to field capacity to ensure accurate data collection (Scoggins and van Iersel, 2006), measured electrical conductivity (EC) at 3 depths (1, 5, and 10 cm) using a Field Scout EC meter (Spectrum Technologies, Inc., Plainfield, IL, USA).

To test the effects of fertilizer and irrigation system net photosynthetic assimilation we randomly selected three seedlings from each fertilizer–irrigation–replication combination (72 seedlings) and from each container–irrigation–replication combination within the 7.2 $kg\cdot m^{-3}$ fertilizer rate. We measured net photosynthetic assimilation (A) using a LI-6400 infrared gas analyzer and conifer chamber (LI-6400-05, Li-Cor, Inc., Lincoln, NE, USA) with a controlled carbon dioxide (CO_2) mixer unit. Measurements were conducted between 10:00 and 14:00 on successive clear days where ambient photosynthetically active radiation exceeded 1500 $\mu mol\cdot m^{-2}\cdot s^{-1}$. The leaf temperature within the chamber was maintained at approximately 24°C, reference carbon dioxide (CO_2) concentration of 400 $\mu mol\cdot m^{-2}\cdot s^{-1}$, relative humidity between 55–60%, and flow rate at 500 $\mu mol\cdot s^{-1}$. Following enclosure in the chamber, data was logged when a leaf reached a steady-state value (coefficient of variations of CO_2 and water within the chamber was <0.25%). Following measurement, leaves were excised and the portion contained within the conifer chamber measured for leaf area using an LI-3000A leaf area meter (Li-Cor, Inc.); values for A were then corrected for leaf area. The samples were oven dried at 70°C for > 72 hrs and analyzed for N concentration using a LECO CNS 2000 elemental analyzer (LECO Corp., St. Joseph, MI, USA).

We used analysis of variance (PROC GLIMMIX; SAS Institute Inc., Cary, NC, USA) with two model statements to analyze data. The first model examined effects of container type, fertilizer rate, irrigation method, and replication (included as a random effect) on height, root-collar diameter, net photosynthetic assimilation (A), and foliar N concentration. The second tested effects of fertilizer rate, irrigation method, and replication (included as a random effect) for the Deepot-16 containers on electrical conductivity (EC) at three depths. Models were considered significant when $P < 0.05$. Regression analysis was completed with SigmaPlot 10 (Systat Software Inc., Chicago, IL, USA).

RESULTS

Irrigation method had no effect on seedling height ($P = 0.9877$) or RCD ($P = 0.81$); average seedling height was 18.2 cm with a RCD of 3.15 mm. Seedling height and RCD were, however, significantly affected by container and fertilizer rate ($P < 0.0001$). Seedlings were taller as container size increased (Figure 1A); each container type yielded seedlings that were significantly taller. For RCD, dibble seedlings had significantly thinner stems (2.19 ± 0.14 mm; mean ± standard error) than SC-10 and D-16 seedlings (3.06 ± 0.14 and 3.32 ± 0.14 mm, respectively), which were not significantly different themselves but significantly different than D-40 seedlings (4.00 ± 0.14 mm). With fertilizer rate, height was significantly enhanced by fertilizer addition, but no additional benefit was observed when fertilizer rate increased from 4.8 to 9.6 kg·m^{-3} (Figure 1B). RCD followed the same pattern: non-fertilized

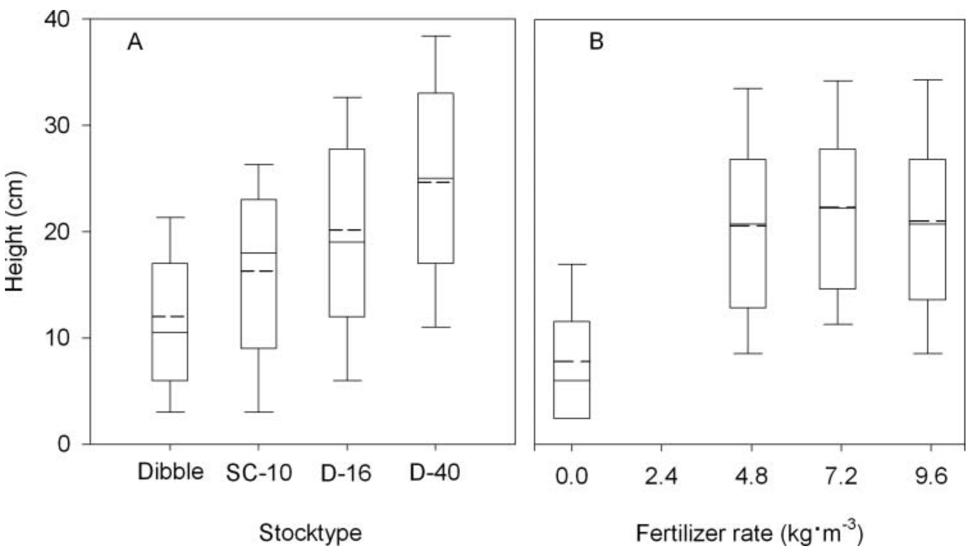

FIGURE 1 Box plots for heights of 12-week-old koa seedlings A) grown in four different containers (see Table 1) filled with substrate amended with 4.8 kg·m^{-3} Osmocote Plus® 15N:9P_2O_5:12K_2O controlled-release fertilizer (5 to 6 mo longevity at 21°C), and B) grown in Deepot-16 containers with four different rates of Osmocote Plus® 15N:9P_2O_5:12K_2O controlled-release fertilizer (5 to 6 mo longevity at 21°C). For each plot, boxes indicate the 25th and 75th percentiles, solid line is the median, dashed line is the mean, and whisker bars indicate the 10th and 90th percentiles.

seedlings had a mean RCD of 1.83 ± 0.14 mm, significantly less than fertilized seedlings. Fertilized seedlings had an average diameter of 3.58 mm and were not significantly different. We detected no discernable patterns to any interactions (data not shown).

Irrigation method significantly ($P = 0.0230$) affected substrate electrical conductivity (EC). Subirrigated containers had 410% higher EC levels than those irrigated from above (0.82 vs. 0.20 dS·m^{-1}). Fertilizer rate also significantly affected EC levels ($P < 0.0001$), with values generally increasing as fertilizer rate increased. EC for 0, 4.8, 7.2, and 9.6 kg·m^{-3} was 0.08, 0.39, 0.88, and 0.70 dS·m^{-1}, respectively. The two lowest rates were not significantly different; the two highest rates were not significantly different; the 4.8 and 9.6 kg·m^{-3} were not significantly different. Depth within the container significantly affected EC ($P = 0.0062$); values at 1 and 10 cm were not significantly different and averaged 0.40 dS·m^{-1}, significantly less than the 0.73 dS·m^{-1} measured at 5 cm. Irrigation method and fertilizer rate significantly interacted to affect EC values ($P = 0.0004$), as did irrigation method and depth ($P = 0.0036$). At 0 kg·m^{-3} EC values were low regardless of irrigation method. As fertilizer rate increased, EC with overhead irrigation remained low, whereas with subirrigation values were 300% to 600% greater as fertilizer increased from 4.8 to 9.6 kg·m^{-3} (Figure 2A). A similar trend was observed for depth: EC values at all depths were very low after overhead irrigation, whereas ECs were 300% to 600% greater at 1, 5, and 10 cm of depth after subirrigation, peaking at 1.25 dS·m^{-1} at the 5-cm depth (Figure 2B).

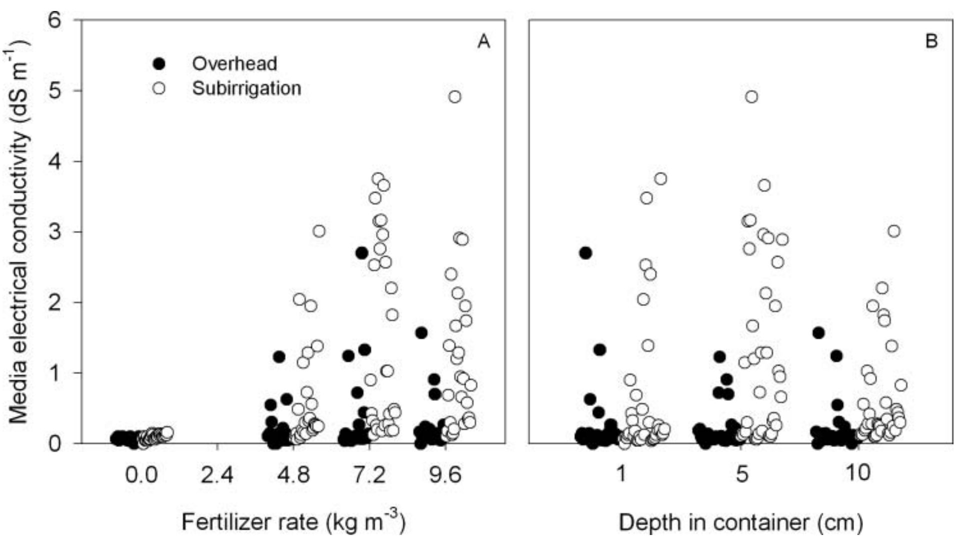

FIGURE 2 Scatter plots for substrate electrical conductivity in Deepot-16 containers (see Table 1) amended with A) four rates (0, 4.8, 7.2, and 9.6 kg·m^{-3}) of Osmocote Plus® 15N:9P_2O_5:12K_2O controlled-release fertilizer (5 to 6 mo longevity at 21°C) or B) for all rates at 1, 5, and 10 cm depths after 12 weeks of growing koa with overhead (black) or subirrigation (white). Although measured at discrete rates and depths, data were adjusted along the X-axis to reduce overplotting.

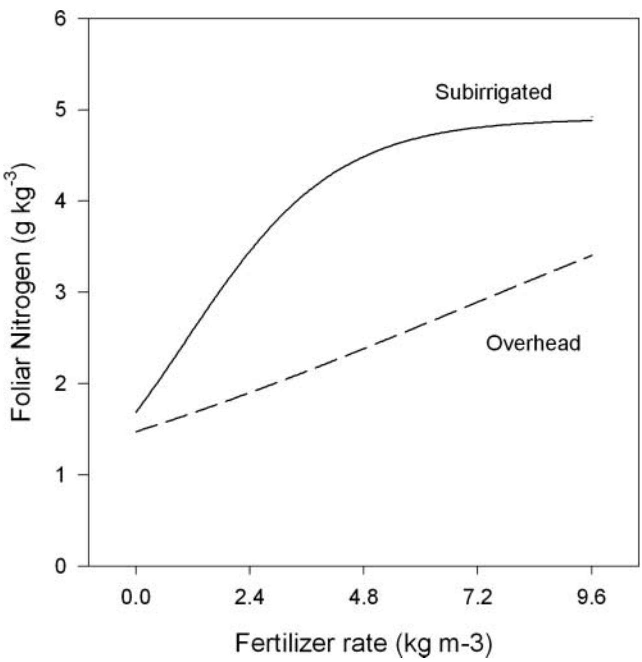

FIGURE 3 Regression analysis showing the significant interaction of irrigation and fertilizer rate on foliar nitrogen concentration of 12-week-old koa seedlings grown in substrate amended with four rates (0, 4.8, 7.2, and 9.6 kg·m^{-3}) of Osmocote Plus® 15N:9P_2O_5:12K_2O controlled-release fertilizer (5 to 6 mo longevity at 21°C). Both sigmoidal curves were best described by $f = a/(1 + \exp(-(x-x_o)/b))$; $R^2 = 0.8759$ for subirrigation (solid line) and 0.6864 for overhead irrigation (dashed line).

Fertilizer rate significantly affected foliar N concentration ($P < 0.0001$). Foliar N concentrations for 4.8, 7.2, and 9.6 kg·m^{-3} were 35.6 ± 3.4, 36.9 ± 3.1, and 42.1 ± 2.6 g·kg^{-1}, respectively, not significantly different from each other, but significantly greater than the 0 kg·m^{-3} control (15.5 ± 1.0 g·kg^{-1}). In addition, subirrigated seedlings had 56% more N ($P = 0.0511$) than those irrigated overhead (39.7 ± 2.7 g·kg^{-1} vs. 25.4 ± 1.6 g·kg^{-1}). Fertilizer rate and irrigation method significantly interacted to affect foliar N concentrations ($P = 0.0233$). In general, foliar N was low and similar when fertilizer rate was 0 kg·m^{-3}, but with increasing rates of fertilizer, subirrigated seedlings had higher foliar N concentrations (Figure 3). Container size significantly affected foliar N concentration ($P = 0.0045$). The two smallest containers (dibble and SC-10) had similar N concentrations (21.3 ± 1.7 and 28.9 ± 3.6 g·kg^{-1}, respectively). SC-10 containers yielded similar values to Deepot-16 (33.7 ± 2.8) and Deepot-40 (35.4 ± 3.4) containers, and both Deepots had higher N concentrations than the dibble tubes. Irrigation method ($P = 0.0642$) and the irrigation method x container interaction ($P = 0.0551$) showed similar trends; foliar N concentrations tended to be higher with subirrigation (data not shown).

Net photosynthetic assimilation (A) was unaffected by irrigation ($P = 0.5589$) but significantly affected by fertilization ($P = 0.0011$). As with foliar N concentrations, A values for seedlings receiving ≥ 4.8 kg·m^{-3} were not significantly different from each other (averaged 16.7 μmol·m^{-2}·s^{-1}), but were significantly greater than the 0 kg·m^{-3} control (8.1 $\pm$ 0.6 μmol·m^{-2}·s^{-1}). Container size significantly affected A as well ($P = 0.0184$), following a similar pattern as with foliar N concentration. The two smallest containers (dibble and SC-10) had similar A (9.7 $\pm$ 1.1 and 12.3 $\pm$ 1.2 μmol·m^{-2}·s^{-1}, respectively). The SC-10 containers yielded similar values to D-16 (14.1 $\pm$ 1.2) and D-40 (15.6 $\pm$ 1.3) containers, and both Deepots yielded significantly higher A than dibble tubes.

DISCUSSION

Our first hypothesis that larger containers would yield larger koa plants was confirmed. Within each fertilizer rate, koa seedlings generally grew larger as container volume increased. This relationship has been shown for a variety of species (Pinto et al., 2008; Scarratt, 1972). We also confirmed our hypothesis that more fertilizer would increase koa size. Not surprisingly, koa growth increased dramatically between the 0 and 4.8 kg·m^{-3} CRF rates. We detected no additional height or RCD growth as fertilizer rate increased from 4.8 kg·m^{-3}, suggesting that plants were in luxury consumption. In another study with the same containers and fertilizer, no additional growth was observed when the rate exceeded 2.3 kg·m^{-3} (Dumroese et al., 2009). Together, these studies suggest that CRF rates of 2.3 to 4.8 kg·m^{-3} (345 to 700 g N·m^{-3}) provide sufficient N for a typical 12-week growing regime used in Hawai‘i regardless of container volume. Defining sufficient fertility for nursery tree seedlings is paramount to producing high quality seedlings (Salifu and Jacobs, 2006). In addition, if nursery inoculation of the leguminous koa with N-fixing bacteria is desired, these rates would promote formation of appreciable *Bradyrhizobium* nodules (Dumroese et al., 2009).

Subirrigation had no affect on koa height or RCD growth, which confirmed our third hypothesis that growth would be similar between the two irrigation methods. Studies with several deciduous hardwood tree species of the eastern United States (Bumgarner et al., 2008; Coggeshall and Van Sambeek, 2002; Davis et al. 2008) also showed that plant growth with subirrigation was equal to, or exceeded, that of overhead irrigation. This was also the case for the tropical hardwood *M. polymorpha* (Dumroese et al., 2006) as well as the herbaceous *Echinacea pallida* (Nutt.) (Pinto et al., 2008).

Regardless of irrigation method, mean A for our seedlings was 14.5 μmol·m^{-2}·s^{-1}, similar to values reported for koa by Walters and Bartholomew (1984) and Gleason and Ares (2004). Under our nursery scenario, seedlings had high moisture availability regardless of irrigation treatment. Our results concur with those of Ares and Fownes (1999) who found that larger koa plants growing with high moisture availability had similar *A*. Among fertilizer rates > 4.8 $kg \cdot m^{-3}$ *A* was, however, 16% greater, averaging 16.8 $\mu mol \cdot m^{-2} \cdot s^{-1}$. This may be attributable to the higher N concentration in our fertilized seedlings (>35 $g \cdot kg^{-1}$) compared with values of 29 $g \cdot kg^{-1}$ reported by Gleason and Ares (2004), and as observed with *Q. rubra* L. (Salifu et al., 2008) and *Retama sphaerocarpa* (L.) Boiss. (Villar-Salvador et al., 2008).

In this study, EC values were greater in subirrigated containers than in overhead irrigated containers. Similar results were reported for *Q. rubra* (Bumgarner et al., 2008; Davis et al., 2008), *M. polymorpha* (Dumroese et al., 2006), and *E. pallida* (Pinto et al., 2008). Higher EC values with subirrigation are likely a result of high leaching associated with overhead irrigation. Less leaching results in higher plant nutrient availability and improved fertilizer use efficiency (e.g., Tyler et al., 1996; Yelanich and Biernbaum, 1994), thereby confirming our last hypothesis. Toxic levels of salts may accumulate in the upper portion of the plug with subirrigation (Klock-Moore and Broschat, 2001). Davis et al. (2008) showed that application of clear water could effectively leach salts downward, alleviating this tendency. Because seedlings in our study were grown outdoors, periodic rainfall likely contributed to leaching. Even so, other studies of subirrigated native plants have yet to show detrimental salt accumulation in the upper portions of the root plug (Dumroese et al., 2006; Pinto et al., 2008). In this study, EC at the 5 cm depth in the medium of subirrigated koa averaged 1.25 $dS \cdot m^{-1}$, indicating relatively low residual fertilizer (Jacobs and Timmer, 2005), but nearly 600% that of the overhead irrigated crop. Albeit low, this fertilizer could be a useful nutrient reserve for plant use during establishment, which may help compensate for inherently N deficient volcanic soils typical of koa restoration sites (Vitousek and Farrington, 1997).

Producers of native plants for restoration must balance resource inputs (e.g., water and nutrients) with nursery efficiency (i.e., plant growth per unit time) while decreasing potential environmental impacts (e.g., nutrient loss in waste water and subsequent contamination of water resources). Based on results of this study and Dumroese et al. (2009), relatively low rates of N (0.35 to 0.72 $kg \cdot m^{-3}$) are sufficient to maximize koa height growth and net photosynthetic assimilation during nursery production in a variety of container sizes. Moreover, subirrigation offers a satisfactory alternative for producing nursery stock without potential environmental degradation caused by nutrient leaching.

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