

Article

Nursery Cultural Techniques Facilitate Restoration of *Acacia koa* Competing with Invasive Grass in a Dry Tropical Forest

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Abstract: Anthropogenic activity has caused persistent and prominent losses of forest cover in dry tropical forests. Natural regeneration of forest trees in grazed areas often fails due to lack of seed sources and consumption by ungulates. To address this, the effective restoration of such sites often requires fencing and outplanting nursery-grown seedlings. In the degraded, dry forests of tropical Hawaii, USA, an additional challenge to restoration of native forest trees is the introduced kikuyu grass (*Cenchrus clandestinus*). This invasive, rapidly growing rhizomatous plant forms deep, dense mats. We studied the use of nursery cultural techniques to facilitate the establishment of koa (*Acacia koa*) seedlings outplanted amidst well-established kikuyu grass on a volcanic cinder cone on the dry, western side of Hawaii Island. Seedlings were grown four months in three container sizes (49, 164, 656 cm³) and with four rates (0, 4.8, 7.2, and 9.6 kg m⁻³) of 15–9–12 (NPK) controlled-release fertilizer incorporated into media prior to sowing. After 16 months in the field, seedling survival was > 80% for all treatments with two exceptions: the non-fertilized 49 cm³ (78%) and 164 cm³ (24%) containers. After 10 years, only these two treatments had significantly lower survival (35% and 10%, respectively) than the other treatments. One year following planting, none of the non-fertilized seedlings had transitioned to phyllodes from juvenile true leaves, regardless of container size. For the fertilized 656 cm³ container treatment, 78%–85% of seedlings had phyllodes, with mean values increasing by fertilizer rate. Phyllodes are known to confer greater drought resistance than true leaves in koa, which may help to explain the improved survival of fertilized trees on this relatively dry site. Overall, nursery fertilization was more influential on seedling height and diameter response than container size after outplanting. However, the largest container (656 cm³) with the addition of fertilizer, produced significantly larger trees than all other treatments during the early regeneration phase; early growth differences tended to fade at 10 years due to inter-tree canopy competition. Although koa is able to fix atmospheric nitrogen through rhizobium associations, our data confirm the importance of nursery fertilization in promoting regeneration establishment. Nursery cultural techniques may play an important role in forest restoration of dry tropical sites invaded by exotic vegetation.

Keywords: competing vegetation; controlled-release fertilizer; forest restoration; heteroblasty; koa; nursery stocktypes; outplanting; reforestation

1. Introduction

Human-driven land use change, such as conversion of forest into pasture for cattle production, has caused prominent losses of forest cover worldwide [1,2]. However, a decline in the profitability of ranching in some regions, combined with governmental cost-share programs and tax incentives for conservation, have increased interest in restoring abandoned grazing lands to native forests [3,4]. Natural regeneration of forest trees in such areas is difficult to achieve due to lack of naturally available seed, difficult germination conditions due to vegetative competition, and consumption of germinated seeds and young seedlings by ungulates. Therefore, fencing and artificial reforestation through the outplanting of nursery-grown seedlings is often required. The successful restoration of grazed sites by tree planting is inhibited by myriad factors, including costs, seasonal drought, competition from invasive species, such as non-native grasses [5–8], and increased fire susceptibility caused by inflammable introduced grasses [9,10].

To successfully restore forest sites degraded by grazing, the conceptual framework provided by the Target Plant Concept (TPC) may be used to (1) identify important limiting factors on the outplanting site, and (2) develop plant materials (i.e., stocktypes) and site preparation methods to increase the likelihood of outplanting success [11–13]. Mechanical and chemical site preparation can alleviate harsh soil conditions and reduce vegetative competition to improve seedling establishment success and accelerate regeneration trajectories [7,14,15], but targeting optimal stocktypes to overcome specific site limiting factors may achieve a similar result, even without site preparation [7,16,17]. For example, taller seedlings are more competitive on sites with high vegetative competition that limit light [18–22], and seedlings with large root systems [16,23,24], and balanced shoot-to-root ratio to reduce transpirational demand [25,26] may perform better on drought-prone sites. Nursery fertilization regimes may also be adjusted to optimize nutrient levels in seedlings, often through inducing luxury nutrient consumption [27–30]. Thus, through the manipulation of cultural conditions (e.g., container volume or configuration; fertilization or irrigation regimes), forest nurseries can produce a wide variety of stocktypes tailored to perform well on a given outplanting site [13,31–34]. Nursery studies have routinely measured plant morphological and physiological quality following the nursery cultivation period, but relatively fewer such trials have tracked subsequent seedling performance under field conditions [13,35,36].

Within the United States, Hawaii's native tropical forests have experienced severe habitat fragmentation and degradation due to excessive harvesting, conversion to pasturelands, and competition from introduced species [37,38]. More than half of the Hawaiian land area is either heavily (16%) or somewhat disturbed (36%) by non-native vegetation [39] and often passive natural regeneration is impeded [40]. Thus, forest restoration in Hawaii is usually accomplished via reconstruction projects [41], whereby ungulates are removed and native species outplanted [40]. In particular, the habitat of Hawaii's endemic, montane koa (*Acacia koa* A. Gray) forest has been severely depleted [42], causing many species, particularly forest birds, to become threatened, endangered, or extinct [43,44]. Beyond its ecological importance, old-growth koa has high economic value for specialty value-added wood products [45,46] and emerging markets for younger, small diameter koa have development potential [47]. As a leguminous species, koa and its symbiotic bacterial partner fix atmospheric nitrogen and grow rapidly under optimal conditions [48,49]. Planted koa may thus provide a means to quickly restore dominant native forest cover, enhance species richness [50], and recreate habitat of native forest birds [51]. This has generated unique interest and incentive for planting koa to restore habitat and meet multiple restoration objectives, including ecosystem and socioeconomic goals [52]. Large-scale native forest restoration of high-elevation pastures in Hawaii began in the 1970s and 1980s and typically involved planting koa to serve as nurse crops for underplantings of other native species [40,42].

The mesic, montane zones frequently targeted for koa restoration are mainly dominated by introduced kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) [40,53]. Kikuyu grass exhibits invasive behavior and produces dense, thick mats of rhizomes that inhibit successful natural tree regeneration [54], as well as survival and growth of outplanted koa [7,55]. Although site preparation techniques have been developed to help control kikuyu grass for koa restoration

plantings [7,56], this is still an emerging science [40], and few studies have examined the potential for nursery cultural treatments to promote koa seedling establishment in the absence of effective site preparation. Further, while some recent studies on koa reforestation and restoration have followed the basic premise of the TPC by tracking nursery treatments in the field [7,57], most trials have either reported results of nursery treatments in the absence of outplanting [58–60] or evaluated site preparation treatments without a nursery component [49,61,62]. Additionally, most koa reforestation studies, and those conducted under tropical conditions more broadly, have been limited in time frame to the first year or two after planting, with relatively few longer-term assessments. Long-term reforestation trials could be particularly insightful for koa because its leaves exhibit heteroblasty, involving transition from bipinnately compound, horizontally oriented true leaves to vertically oriented phyllodes [63]. These different leaf types have varying ecophysiological attributes related to light capture and drought resistance [64–69]. Thus, cultural treatments that affect this rate of transition may have important implications on koa growth and development beyond the establishment phase [49,62].

In a 10-year field trial, we evaluated the influence of nursery fertilization and container size on koa field performance after outplanting onto a site on the dry western slopes of Hawaii Island. The site was occupied exclusively by dense African kikuyu grass prior to planting and no site preparation was conducted. Specifically, we hypothesized that (i) koa produced in relatively large nursery containers would exhibit greater survival and height/diameter, as well as faster transition from juvenile true leaves to phyllodes, (ii) seedlings fertilized at higher treatment rates in the nursery would perform better within a given container type, and (iii) at least some of the treatment differences that occurred during the early establishment phase would be maintained through the end of the experiment.

2. Materials and Methods

2.1. Plant Material and Nursery Treatments

Koa seedlings were grown in an uncovered, outdoor compound at the Hawaii Division of Forestry and Wildlife Kamuela (Waimea) State Tree Nursery, 4 km south of Kamuela on Hawaii Island, USA (20.007017 N, 155.833607 W). Seeds from a local source (Pu'u Wa'awa'a) were collected in July 2005 from more than 20 trees. In early November 2005, we transplanted germinating (7 days following the usual hot water soak) koa seeds, and seedlings were grown for approximately 4 months (November 2005 to March 2006) under a combination of different nutrition and container size treatments.

Three container types provided a range of sizes:

- Hawaii dibble tube: 49 cm³ volume, 2.5 cm diameter × 12 cm depth, and tray density of 449 containers m⁻² (Pacific Allied Products, Ltd., Kapolei, HI USA).
- Ray Leach “cone-tainer” SC-10: 164 cm³ volume, 3.8 cm diameter × 21 cm depth, and tray density of 528 containers m⁻² (Stuewe and Sons, Inc., Tangent, OR USA).
- Deepot 40 (D-40): 656 cm³ volume, 6.4 cm diameter × 25 cm depth, and tray density of 174 containers m⁻² (Stuewe and Sons, Inc., Tangent, OR USA).

Containers were filled with 2 parts *Sphagnum* peat moss (Pro-Mix, Premier Horticulture, Dorval, QC, Canada) mixed to 1 part perlite (v:v) medium and amended with four levels of controlled release fertilizer: 0, 4.8 (nursery standard), 7.2, and 9.6 kg m⁻³ of Osmocote Plus (15N:9P₂O₅:12K₂O; 5 to 6 month longevity at 21 °C; Scotts Co., Marysville, OH, USA). These rates reflect the decompressed volume of the medium. All seedlings were grown under operational irrigation conditions characterized by overhead irrigation applied every other day using rotating nozzles on risers on 6.6 m × 5.3 m spacing.

2.2. Outplanting Site and Experimental Design

Seedlings were hand-planted with tree spades on the Pu'u Wa'a Wa'a cinder cone within the Pu'u Wa'a Wa'a Forest Reserve on Hawaii Island, USA. The site is on the leeward, dry western slopes of the island at an elevation of 1200 m (19.773524 N, 155.833607 W). The cone was deforested during the previous century and grazed by cattle, sheep, and goats [70]. Since 2003, some parcels have been fenced and planted to restore native trees. The study was conducted on approximately 0.4 ha within a 36-ha fenced area free from grazing and in need of reforestation. The soil is classified as a medial, amorphic, isothermic Pachic Haplustands of the Waawaa series consisting of a medial silt loam A-horizon above a medial silty clay loam B-horizon. These productive soils are deep (> 2 m), slightly acidic to neutral in pH, well-drained with moderate soil water storage, and have an estimated CEC at a pH of 7 of 83.3 meg 100 g⁻¹ at 0–30 cm depth [71].

This region is arid and within the lower range of annual precipitation requirements for koa [72]. Mean annual rainfall for the Waawaa soil series is about 560 mm and mean annual air temperature is about 20 °C [71]. From 2004 through 2014, August was the warmest month (21.3 °C) and February was the coolest (17.9 °C). According to a nearby Remote Automated Weather Station (RAWS) station at the base of the cone, average annual precipitation during 2005 through 2013 was 326 ± 57 mm, but this included extreme drought years during 2010 to 2012. Additionally, the top of the cone, where the study was located, receives more precipitation than much of the surrounding area. The mean annual precipitation recorded from 1978 to 2007 was 688 mm [73].

The site was occupied exclusively by dense African kikuyu grass prior to planting. No site preparation (e.g., mechanical or chemical; fertilization) or post-planting silvicultural management was conducted on the study site. Seedlings from the nursery treatments were outplanted in late-March 2006 on a 2 × 2 m spacing. The study was established in the nursery as a randomized complete block design (three container sizes × four fertilizer rates) replicated across three blocks. Each container size × fertilizer rate combination represented an individual nursery stocktype. When lifting from nursery containers, we selected seedlings from the centermost portions of container trays to avoid edge effects. In the field, we maintained the same randomized complete block design using 10 trees per treatment replication for a total of 360 seedlings. Each individual seedling represented a sampling unit and the experimental unit used in data analysis was the mean response for each treatment replication.

2.3. Measurements and Data Analysis

Immediately after outplanting (April 2006), initial measurements were taken for height and ground line diameter (GLD). Additionally, measurements were taken for survival, height, and GLD in August 2007 and May 2016. Diameter at breast height (DBH, 1.37 m above groundline) was assessed in May 2016. The presence of phyllodes was assessed in April 2007 (one year after outplanting).

Analysis of variance (ANOVA) was used for data analysis using SAS Software (SAS Institute, Inc., Cary, NC, USA). Tests for normality, constant variance, and linearity were performed with data transformations being applied when statistical assumptions were not met. One-way ANOVA was used because seedlings fertilized at different treatment rates (kg m⁻³) within a container treatment received different total fertilizer amounts. Additionally, absolute values for morphological response variables were used in the analyses. Relative growth measures may lead to faulty conclusions for a long-term study according to the variable interest law, which states that the growth of a plant during a unit of time is a percentage of the initial size of the plant at the beginning of that time. As the plant grows, however, this percentage will change in response, creating a varied percentage over time [74]. Thus, absolute values were used to capture seedling performance based on nursery cultural practices and to eliminate issues with variable growth patterns during the experiment. When significant ($p < 0.05$) treatment effects were detected, means separations were performed at $\alpha = 0.05$ using Fisher's LSD test. Results of transformed variables are described as back-transformations, in which the mid-point of the 95% confidence interval is used to estimate the mean.

3. Results

3.1. Survival

Seedling survival 16 months after outplanting (August 2007) was > 80% for most stocktypes, and only the 49 cm³ control (78%) and 164 cm³ control (24%) stocktypes were statistically different ($p < 0.001$) from some other treatments and each other (Figure 1). Ten years after outplanting (May 2016), tree survival had declined across all stocktypes, with the greatest reduction observed for the 49 cm³ control stocktype (78% at 16 months to 35% at 10 years). Ten-year survival ranged from 61% to 90% without significant differences among stocktypes, with the exception of the 49 cm³ control (35%) and 164 cm³ control (18%) stocktypes, which were statistically different ($p < 0.001$) from most other treatments but not themselves (Figure 1).

3.2. Phyllode Development

At the April 2007 measurement period (one year following planting), significant differences ($p < 0.0001$) occurred among nursery treatments in the percentage of seedlings that had transitioned from juvenile true leaves to mature phyllodes (Figures 1 and 2). None of the non-fertilized seedlings exhibited phyllodes, regardless of container size (Figure 1). Seedlings within the fertilized 49 cm³ container treatment combination exhibited a trend of declining phyllodes production (10%–44%) with increasing fertilizer rate. No clear trends were observed for the fertilized 164 cm³ container treatments although the highest fertilizer rate produced the greatest proportion of seedlings exhibiting phyllodes (59%). Among the fertilized 656 cm³ container treatments, 78%–85% of seedlings had phyllodes, with no difference among fertilizer rates.

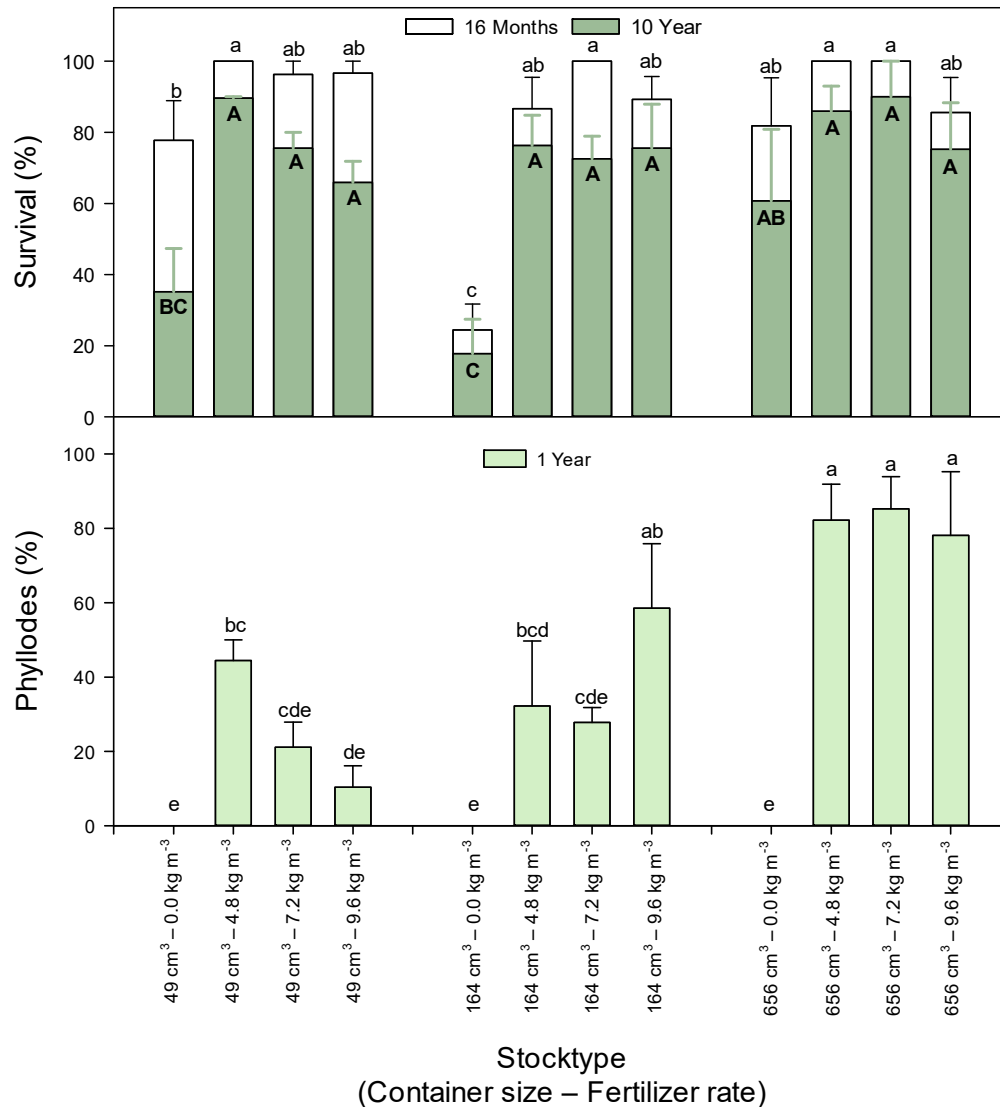


Figure 1. Mean ($\pm$ SE) percent survival of *Acacia koa* by stocktype treatment 16 months and 10 years post planting, and percentage of seedlings with phyllodes by stocktype treatment 1 year following outplanting. One-way ANOVA was performed independently for each response variable at each measurement period. Treatment mean values for survival at 16 months or phyllodes at 1-year post planting followed by different lowercase letters denote significant differences at $\alpha = 0.05$ using Fisher's LSD. Mean values for survival 10 years post planting followed by different uppercase letters denote significant differences at $\alpha = 0.05$ using Fisher's LSD.

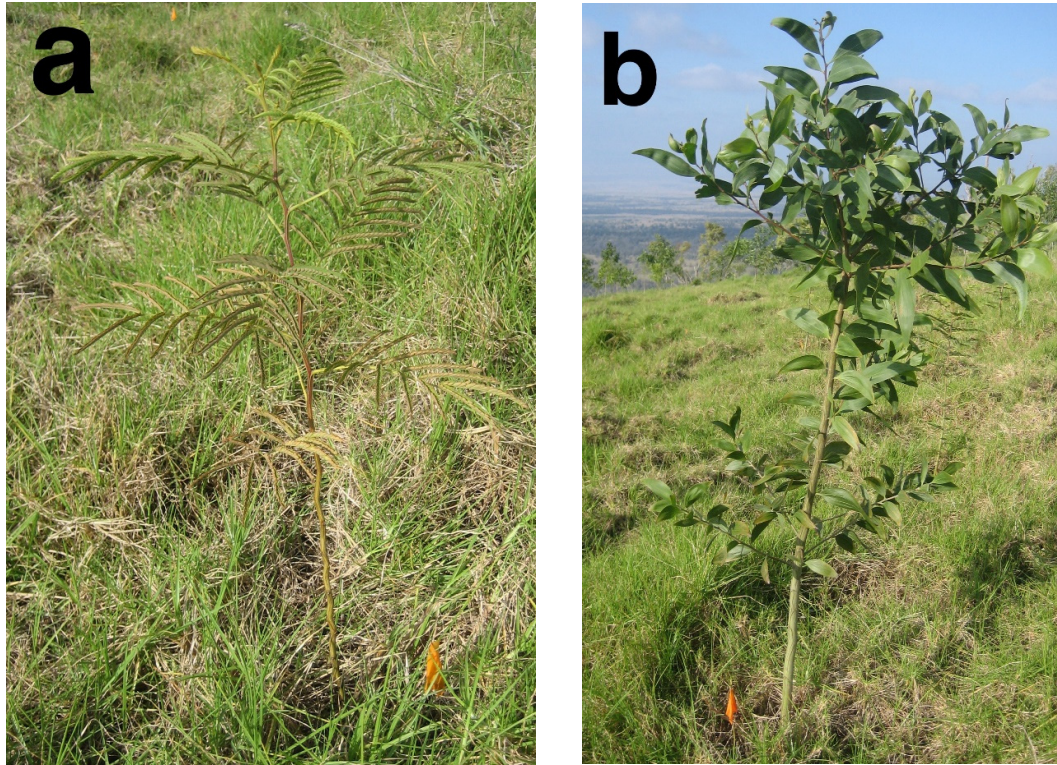


Figure 2. Examples of *Acacia koa* seedlings from different nursery treatments one year following planting exhibiting juvenile true leaves (a) and following transition to mature phyllodes (b).

3.3. Tree Growth

When outplanted (April 2006), nursery treatments of fertilizer and container size yielded a statistically significant ($p < 0.0001$) response for mean height and GLD. Seedlings grown with fertilizer and in the two largest containers (164 cm³ and 656 cm³) had greater height and GLD than seedlings grown without fertilizer and in the smallest container size (Figure 3). Among fertilized seedlings, the 7.2 and 9.6 kg m⁻³ rates resulted in significantly greater heights and GLDs compared to the low 4.8 kg m⁻³ rate, but only for the two larger container sizes. The tallest seedlings with the largest GLD at the time of planting were associated with the stocktype from the largest container (656 cm³), receiving the most fertilizer (9.6 kg m⁻³) (Figure 3). Mean height and GLD for this stocktype were significantly greater than all other stocktypes, with the exception of height when compared to the 656 cm³ 7.2 kg m⁻³ stocktype. Overall, nursery fertilization was more influential on seedling height and GLD response than container size (Figure 3).

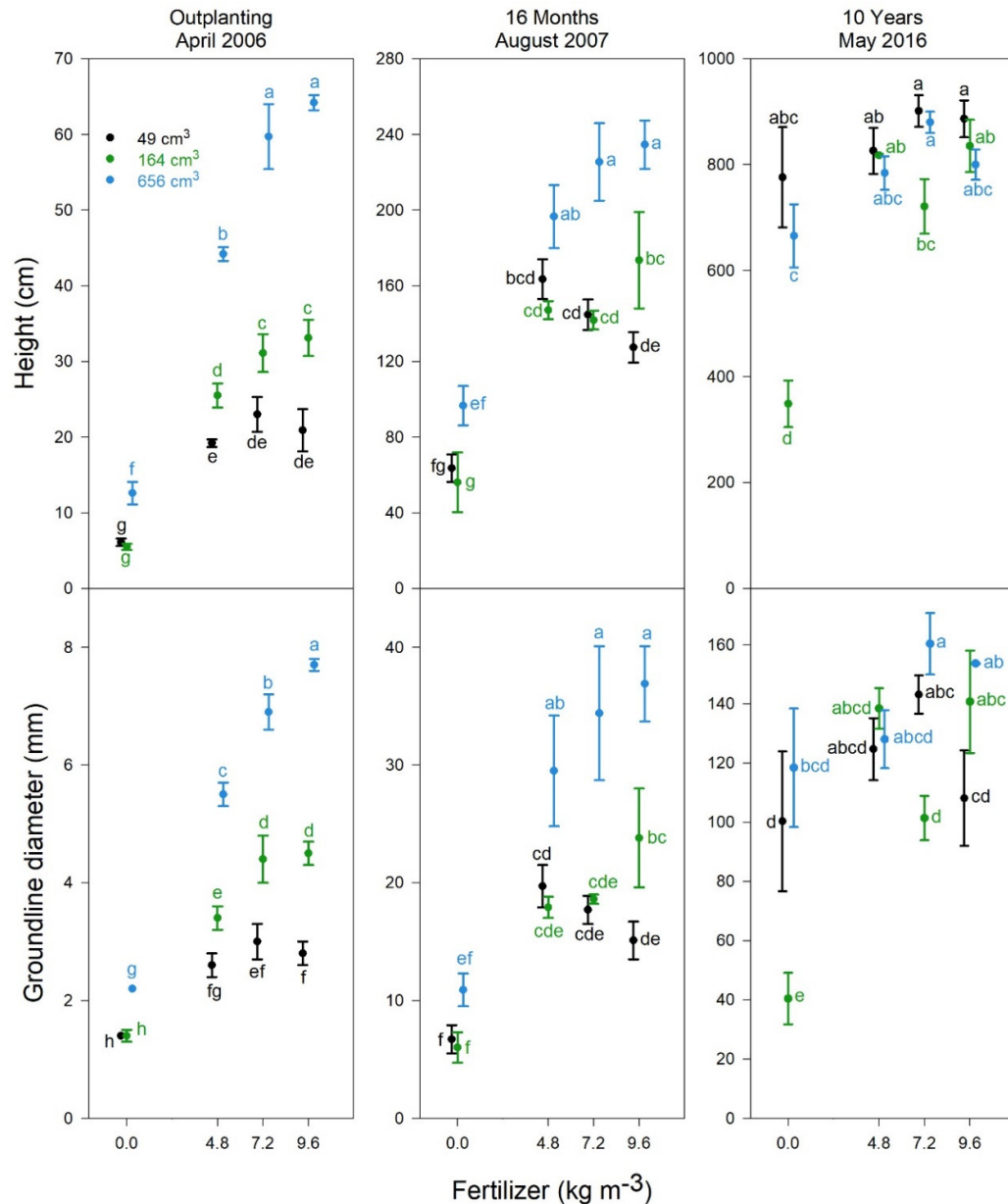


Figure 3. Mean ($\pm$ SE) height and groundline diameter response of *Acacia koa* by stocktype treatment. One-way ANOVA was performed independently for each response variable at each measurement period. Treatment mean values followed by different letters denote significant differences at $\alpha = 0.05$ using Fisher's LSD. Values at each fertilizer rate are staggered to improve clarity among container volumes.

Sixteen months later (August 2007), container size and fertilization continued to significantly ($p < 0.0001$) affect mean height and GLD responses (Figure 3). The positive effects of fertilization during the nursery phase were still apparent, compared to non-fertilized seedlings. No significant differences were found, however, among fertilized seedlings within all container types for both height and GLD responses (Figure 3). These results were similar to those at the time of planting: stocktypes from the larger container (656 cm³) with the addition of fertilizer continued to be significantly greater than all other stocktypes (Figure 3).

Ten years after planting (May 2016), many of the observed differences in height and GLD responses to treatments had diminished. Height responses showed few significant differences among

treatments (Figure 3). The main exceptions included the 164 cm³ control, which had significantly smaller height than all other treatments, as well as the 164 cm³ 7.2 kg m⁻³ and 656 cm³ control stocktypes that had significantly smaller total heights compared to some of the other stocktypes (Figure 3). GLD responses also showed few significant differences among treatments (Figure 3). Similar to height, the smallest mean GLD was observed in the 164 cm³ control stocktype, which was 40% of the next smallest GLD (Figure 3) and significantly smaller than all other treatments. The 656 cm³ container with fertilization at the highest two rates (7.2 and 9.6 kg m⁻³) produced stocktypes with the largest GLDs, but they were significantly different from only a few of the other stocktypes (Figure 3). Diameter at breast height (DBH) followed a similar pattern as that observed with GLD: only the 164 cm³ control stocktype had significantly lower mean DBH compared to all other stocktypes (Figure 4).

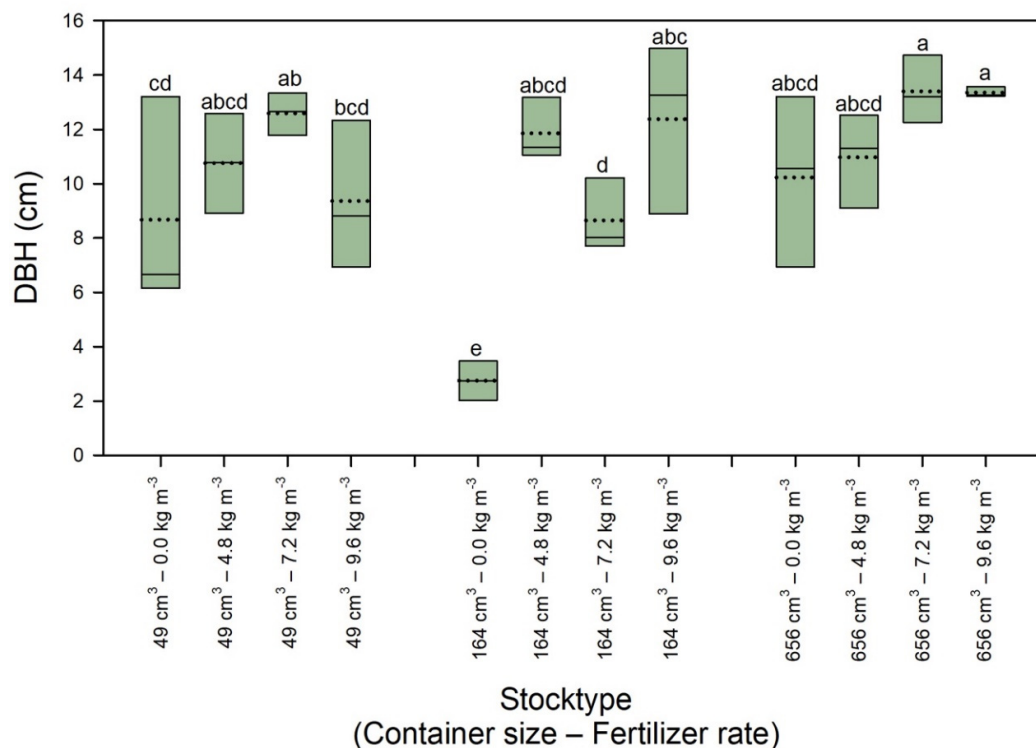


Figure 4. Diameter at breast height (DBH, 1.37 m height) of *Acacia koa* by stocktype treatment 10 years following outplanting. Vertical boxes represent the range of means across the three blocks for each stocktype. Within each box, the solid horizontal line is the median value and the dotted line is the mean. Treatment mean values followed by different letters denote significant differences at $\alpha = 0.05$ using Fisher's LSD.

4. Discussion

As expected, initial (post-nursery cultivation) height and stem diameter of koa seedlings generally increased with container size (Figure 3), similar to past studies with koa [7,59] and other tree species [28,75]. Within each container treatment, the initial size of outplanted seedlings also tended to increase with increasing fertilizer rate (Figure 3), but the most pronounced differences occurred between the control and all fertilizer rates, as also previously shown for koa [58,59]. Using these same nursery fertilizer rates with koa, Dumroese et al. [59] reported that seedling size and N concentration differed between fertilized seedlings and the non-fertilized control, but not among fertilizer rates. They suggested that plants were already experiencing luxury consumption even at the lowest fertilizer rate. In our study, however, the higher fertilizer treatment rates did produce an increase in initial seedling size for the largest two containers (164 and 656 cm³), suggesting that the

relatively larger seedlings in this container type had a greater capacity to allocate higher nutrient availability to growth [59,76].

The ability of outplanted tree seedlings to overcome plant competition effects on degraded tropical sites dominated by invasive species is one of the greatest challenges to successful native species restoration projects [77–79]. While site preparation treatments to alleviate the effects of invasive introduced vegetation have been identified, remaining ecological concerns with some of these treatments (e.g., pesticide use; [15,80]) suggest that producing seedling stocktypes that resist such competition may represent an effective alternative and/or produce an additive effect to site preparation [7,16,17,81]. Our study results effectively demonstrate the potential for nursery treatments to aid in koa establishment on kikuyu grass-infested restoration sites even without mechanical or chemical site preparation. After 16 months in the field, seedling survival was $> 80\%$ for all treatments except for seedlings grown without fertilization in containers of $\leq 164 \text{ cm}^3$ volume. (Figure 1). After 10 years, this pattern persisted (Figure 1). Other field experiments with koa have reported much lower survival rates during establishment, especially without site preparation [56,57].

Culturing seedlings with sufficient nutrient and carbohydrate reserves for the outplanting site is an important prerequisite for survival and growth [82]. For koa and other *Acacia* spp. in particular, outplanted seedlings having these characteristics can readily form a symbiotic relationship with *Bradyrhizobium* spp., N-fixing bacteria that increase N availability [83,84]. During nursery production, a lack of nutrition and *Bradyrhizobium* spp. inoculation leads to low nutrient availability and poor growth [58,59]. Although the paradigm was that fertilization may reduce nodulation and N-fixing capacity of legume symbionts, the aforementioned work with koa suggested that nursery fertilization, nodulation, and N-fixing capacity need not be mutually exclusive. Recent nursery fertilization studies have shown that growth and N status of other leguminous N-fixing tree species can be enhanced through a synergistic effect provided by robust fertilization in concert with inoculation of symbiotic N-fixing bacteria [85,86].

One year after planting, none of the non-fertilized seedlings had transitioned to mature phyllodes from juvenile true leaves, regardless of container size (Figure 1). Koa's bipinnately compound true leaves may be functionally relevant to help ensure early growth at a low carbon cost following regeneration in forest canopy gaps [63,67,69]. Our field site was, however, open pastureland and therefore not light-limited during at least the first year of establishment. Phyllodes, conversely, appear to be important for drought resistance and as an adaptation to high-light environments because of increased stomatal responsiveness to reduced vapor pressure deficit and ability to respond to desiccation and rehydration [64–69]. Thus, seedlings planted into our open, relatively dry site conditions should have benefited in drought resistance with rapid transition from true leaves to phyllodes, and this may help to explain the improved survival of fertilized trees.

While ensuring high seedling survival is paramount in forest restoration generally [87], and for koa specifically [42], increasing the growth rates of outplanted trees will help to more rapidly meet the diverse goals (i.e., habitat creation, carbon sequestration, timber) of native species restoration [7,40,88,89]. Overall, nursery fertilization was more influential on seedling height and groundline diameter response 16 months after planting (August 2007) than container size (Figure 3). However, the largest container (656 cm^3) with addition of fertilizer produced significantly larger trees than all other treatments during this establishment stage (Figure 3). Koa restoration in Hawaii has traditionally relied upon relatively small stocktypes [56,90], similar to those produced in our smallest (49 cm^3) container treatment. Dumroese et al. [59] have since shown that koa nursery seedling size generally increased with increasing container volume, and Pinto et al. [7] found that stocktypes produced with larger (207 cm^3) containers outperformed smaller (111 cm^3) ones in the field, with or without site preparation to control kikuyu grass. These results with koa verify the general finding of improved survival and growth for larger stocktypes in reforestation [28] and forest restoration [17,75,91–93]. This response is mainly attributable to greater seedling size and nutrient/carbohydrate reserves facilitating root growth and physiological coupling to the outplanting site to resist extreme periodic drought [17,33,82,94,95]. In our study, fertilized seedlings in the largest (656 cm^3) container treatment were not only larger at planting, but also 78%–85% of these seedlings had transitioned to

phyllodes within one year, which was significantly greater than any other treatment except the 164 cm³ 9.6 kg m⁻³ container–fertilizer combination (Figure 1). Thus, in our case, the greater initial size along with faster transition to phyllodes for high fertilized (7.2, 9.6 kg m⁻³) koa seedlings in the largest (656 cm³) container treatment likely facilitated establishment on this site, thereby maintaining significantly greater size after 16 months in the field.

With the exception of the maintenance of some significant differences between non-fertilized and fertilized seedlings within a container treatment, early size differences tended to fade at 10 years (Figures 3 and 4). This effect was likely due to inter-tree competition that occurred beginning midway (~year 5) through the experiment. Seedlings were planted on a 2 × 2 m spacing (equivalent of 2500 trees ha⁻¹), no thinning was conducted, and trees were generally > 7 m in height and > 10 cm DBH at 10 years (Figures 3 and 4). Fast growing tropical plantations may already exhibit crown recession at 3–4 years of age with live crown ratios < 40% and/or height:diameter > 100 [96]. In some fast-growing tropical systems, optimal thinning schedules may require three entries prior to age 10 [97]. Past thinning studies in koa have demonstrated that stands may begin to show significant growth reductions after 11 years due to overstocking and loss of crown vigor [98–100], indicating that the first pre-commercial thinning in dense koa stands should occur by 10 years of age, and preferably 2–3 years earlier [100]. Thus, thinning before the end of our trial may have helped to minimize crown recession and maintain some of the initial size differences in this fast-growing species. Late thinning is, however, fairly typical of management in this region [100] and in restoration of many other fast-growing, native tropical tree species [96,97,101].

5. Conclusions

We generally confirmed our initial hypothesis that koa stocktypes produced in relatively large nursery containers would demonstrate greater height and diameter after 16 months in the field. Additionally, seedlings grown in the largest containers exhibited faster transition from juvenile true leaves to mature phyllodes. Survival differences were not detected among container treatments, however. We also partially confirmed our second hypothesis that survival, rate of transition to phyllodes, as well as height and diameter after 16 months in the field would be significantly greater for fertilized vs. non-fertilized trees within a container type. However, no significant survival or height and diameter differences were found among fertilized seedlings within each container type at 16 months after outplanting. Thus, nursery fertilization was overall more influential on seedling establishment success than container size. Our third hypothesis, that at least some of the treatment differences that occurred during the establishment phase would be maintained to the end of the experiment after 10 years, was only partially confirmed, as survival continued to be significantly different for fertilized vs. non-fertilized seedlings. This implies that, in the long-term, on this site container size may be relatively inconsequential, as long as seedlings were adequately fertilized in the nursery. However, the fading of other treatment size differences detected during the establishment period was attributed to inter-tree competition that occurred beginning midway through the experiment, a tangible longer-term benefit of the aforementioned high rate of seedling survival. Future studies examining effects of nursery culture on long-term plantation responses in fast growing tropical forestry systems should incorporate timely thinning operations with sufficient post-thinning sample sizes that allow potential for continued expression of early treatment responses. Based on results of this study and Dumroese et al. [58,59], relatively low applications of N during nursery production are sufficient to maximize koa growth and development in various container sizes. Additionally, although koa is able to fix atmospheric N through rhizobium associations, our data confirm the importance of nursery fertilization to ensure that seedlings have sufficient resources for field establishment, and recent research suggests this is not mutually exclusive of inoculating N-fixing symbionts during the nursery phase. This experiment demonstrates that nursery cultural techniques may play an important role in forest restoration of dry tropical sites invaded by exotic vegetation, particularly in the absence of effective site preparation to reduce vegetative cover.

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