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Precommercial release thinning of potential *Acacia koa* crop trees increases stem and crown growth in dense, 8-year-old stands in Hawaii

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ABSTRACT

An 8-year-old dense monotypic stand of naturally regenerated koa (*Acacia koa* A. Gray) on the Island of Hawaii was selected to determine the effects of precommercial release thinning, phosphorous (P) fertilization and herbaceous weed control on growth of potential crop trees over approximately 30 months. Thinning consisted of cutting down all stems within a 4.5-m radius of the crop tree. Phosphorus was added at a rate of 300 kg ha^{-1} over two years. Herbaceous weeds were sprayed once with imazapyr, a broad-spectrum herbicide. Thinning alone or in combination with P fertilization significantly increased stem diameter increment and allometric estimates of the growth of leaf area and aboveground biomass. There was no significant increase in stem diameter, leaf area or biomass in the absence of thinning. Within the thinned treatment, P fertilization resulted in significant increases in tree height over time. Herbaceous weed control had no effect on tree growth. The atmospherically resistant vegetation index (ARVI), which was derived from spectral analyses of high-resolution satellite imagery (GeoEye1), was significantly higher for thinned than unthinned trees 25 months after study initiation, suggesting greater light absorbance and a possible explanation for overall greater growth of thinned trees. When considered with results from previous studies, these findings indicated that crop tree selection and precommercial release thinning in dense, even-aged koa stands should be done early in stand development to prevent loss of crown vigor and growth potential. Additional interventions like P fertilization or herbaceous weed control may not be necessary until trees are older or site conditions suggest important soil resource limitations.

1. Introduction

The endemic Hawaiian koa tree (*Acacia koa* A. Gray) is the most valuable native timber species from Hawaii's forests. Traditionally, koa was used for construction of voyaging canoes and surfboards. Today the wood is used for cabinetwork and fine furniture; koa products account for three-quarters of Hawaii-grown wood products (Friday et al., 2006). Koa forests are critically important for watershed function and protection, habitat for threatened and endangered species, particularly forest birds (Pejchar et al., 2005), and native forest diversity (Baker et al., 2009). Koa is a fast-growing, shade intolerant, nitrogen-fixing tree that grows from near sea level to 2000 m elevation in mesic sites across a range of soil types on several of the main Hawaiian Islands. Mature trees can grow to over 25 m in height with stem diameter at breast height (DBH) greater than 1.5 m (Friday, 2011). The hard-coated seed can remain viable in the soil for many years, even after deforestation (Baker et al., 2009).

Conversion of forests to cattle pastures reduced koa forest coverage throughout the 19th and 20th centuries (Cuddihy and Stone, 1990), but declining profitability of grazing, increasing koa wood prices, and increased emphasis on conservation of biodiversity and native ecosystems have resulted in increased interest in reforestation (Baker et al., 2009). Today, harvests are almost exclusively from old-growth forests, but private landowners have expressed interest in commercial reforestation with koa if silvicultural guidelines can be developed (Pejchar and Press, 2006). Natural regeneration of koa may be accomplished by soil scarification in degraded forests or open pastures where there is a remnant seed bank, and these monotypic, even-aged stands can reach initial densities of over 20,000 seedlings ha^{-1} (Scowcroft et al., 2007). Where seed banks are lacking, koa seedlings are planted at densities of approx. 1000 trees ha^{-1} (Friday, 2011). Both methods of stand establish-

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ment lead to early canopy closure and intense intraspecific competition. Self-thinning does occur, but stands often remain overstocked, which can result in a significant loss of crown vigor, reduced live crown depth, and branch dieback within the crown (Scowcroft and Yeh, 2013). This can greatly reduce average tree growth in stands as young as 10 years of age (Scowcroft and Stein, 1986).

Koa trees, being legumes, typically have poor apical dominance and branchy or even multiple-stemmed form. Open-grown trees or plantations planted at wide spacing may produce few potential crop trees with single, straight boles long enough to be commercially valuable (Scowcroft et al., 2010). Intra-specific competition among individuals in dense, naturally regenerated stands results in enough trees per hectare with good form to produce a reasonable crop if these trees are released from competition. Baker et al. (2009) summarized a number of silvicultural studies that provide useful guidelines for management, but they acknowledged that much work needs to be done to improve understanding and consequently management recommendations. Recommendations for established stands generally include thinning to a target density to achieve desired stocking levels (Baker and Scowcroft, 2005). Stocking is based on crown space requirement of trees at different stem diameters (DBH), calculated as the growing space index (GSI), which is equal to the ratio of average crown diameter:stem DBH. While no one approach to thinning is generally accepted for koa, several studies of hardwood trees have used crop tree selection, which is a thinning method that targets future crop trees for release by removing at least competing canopy dominant or co-dominant trees if not all woody tree stems within a fixed radius of the crop tree main stem or crown (Perkey et al., 1993; Smith et al., 1997; Ward, 2013).

Selection of crop trees prior to thinning usually takes into account canopy dominance, crown vigor, stem diameter, stem form and length of clear bole. Koa displays poor apical dominance; thus both natural and planted stands often have a low frequency of commercially valuable trees. Crop tree selection, thus, may offer advantages in reducing overall thinning effort while ensuring desirable trees have sufficient space and resources to reach their growth potential. Although the criteria for acceptable crop trees may vary (e.g. Scowcroft and Stein, 1986), it requires trees to grow to a certain size for differentiation of these characteristics to become manifest and measurable. Waiting for trees to meet the acceptable criteria, however, may result in significant loss of crown vigor and tree growth due to high stem density. This can reduce their growth potential, even in response to silvicultural interventions (e.g. Scowcroft et al., 2007). Thus, deciding when to first conduct thinning operations depends on a balance between tree size and stand density in order to distinguish superior tree stems without compromising growth potential.

While intraspecific competition can be relieved by thinning, additional interventions have been deployed to maximize crop tree and overall stand growth response. Thinning typically re-allocates growth to selected trees but decreases stand growth, overall. Fertilization and control of understory weedy species may be able to increase overall stand productivity (Smith et al., 1997). For koa, several studies have demonstrated significant increases in DBH increment in response to thinning at different stand ages, from approximately 10 to 30 years of age (Baker et al., 2008; Pearson and Vitousek, 2001; Scowcroft and Stein, 1986). In Baker et al. (2008), DBH growth increased with increasing thinning intensity, down to a residual stand density of 200 trees ha^{-1} for a stand with crop trees that averaged 13–18 cm DBH. There was no additional response to control of understory grasses. Similarly, in Scowcroft and Stein (1986) addition of a multi-element fertilizer (N-P-K and $MgSO_4$) had no signficant effect on basal area growth in either thinned or unthinned plots. However, in Scowcroft et al. (2007), crop tree thinning alone did not change DBH increment for trees that averaged 20–25 cm DBH. Only thinning combined with herbicide grass control and phosphorus (P) fertilization (at a rate of 750 kg ha^{-1} of P added incrementally over two years) produced a significant response. The variable soils and climates over which koa naturally exists and pre-existing stand conditions likely influence crop tree response to these combinations of interventions, but there are no generalized guidelines at present other than stocking rates.

Measuring forest structure to select crop trees and soil or other conditions to determine the need for thinning and other interventions requires a tradeoff between sampling intensity and spatial coverage, which can be costly and admittedly imprecise. A complementary approach that has the potential to provide valuable information on crown vigor and thus relative response to silvicultural intervention is analysis of high resolution imagery. The analysis of spectral bands from fine pixel resolution satellites (2–4 m multispectral, 0.5–1 m panchromatic), such as Quickbird, IKONOS and GeoEye1, has provided reliable tools to analyze canopy conditions and to extract biophysical information of forest stands and individual trees across entire regions quickly and reliably (Clark et al., 2004; Martinez Morales et al., 2008; Morales et al., 2012). Low forest canopy reflectance in the red region (~650 nm wavelenth) is associated with chlorophyll absorption, and strong reflectance in the near infrared region (NIR, 750–1500 nm wavelengths) is related to internal leaf structure (Asner, 1998; Roberts et al., 1997). Therefore, these two bands have been commonly used to calculate vegetation indices (VIs) for biomass assessment (Baugh and Groeneveld, 2006), detection of phenological changes (Huete et al., 2002) and detailed identification of forest tree species (Soudani et al., 2006).

Similar analysis using VIs has been applied to accurately classify productivity of koa forests in Hawaii. Morales et al. (2012) compared several VIs calculated from IKONOS data to differentiate koa stands across an 850-m elevation gradient in Hawaii. Stands with higher VI values had greater average tree height and foliar nutrient concentration. A similar approach may allow for assessment of koa growth responses to silvicultural treatments, both as a selection criterion and as an evaluation of growth response after treatment application.

In this study, an 8-year-old koa stand growing on the Island of Hawai‘i was chosen to apply a combination of silvicultural treatments that included precommercial release thinning, phosphorus fertilization, and herbaceous weed control via herbicide application. Based on previous research, phosphorus was chosen as the most likely limiting nutrient, and nitrogen was assumed to be non-limiting (Pearson and Vitousek, 2001; Scowcroft et al., 2007). To our knowledge, this was younger than any stand previously chosen for experimental thinning and other silvicultural interventions. Standard responses of forest growth and productivity from ground-based measurements were combined with analysis of a high-resolution satellite image in order to relate ground-based to canopy spectral measurements. The objectives of the study were: (1) to measure a broad range of individual-tree responses to thinning and other interventions in order to understand both drivers of tree growth response and ways in which crop trees respond to changing resource availability; and (2) to test whether canopy spectral information is related to growth responses or other tree characteristics. We hypothesized that the combination of thinning, P fertilization and herbaceous weed control would result in the greatest growth responses through alleviation of light, nutrient, and water limitations. We also hypothesized that the crowns of released trees would have distinct reflectance characteristics and VIs that positively correlate with indicators of productivity, such as larger crown area, leaf area, and depth of live crown.