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# Stimulating Growth of Stagnated *Acacia koa* by Thinning and Fertilizing

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Building *Acacia koa,* Hawaii's most marketable native tree, into a viable resource is economically and ecologically desirable. But little is known about natural stand development and management of this scarce resource. Therefore, the effect of thinning, fertilizing, or both on short-term growth and survival was studied in a stagnated 12-year-old koa stand on Haleakala, Maui. Mean relative basal area growth rates (RGR) for the period 1975-77 ranged from 6.7 percent per year for control trees to 10.0 percent per year for thinned-fertilized trees. Both thinned and thinned-fertilized trees grew significantly faster than control trees. An unplanned, complete defoliation of all trees occurred in the study area in January 1977. RGR's after defoliation were significantly smaller than rates before defoliation for all treatments. Differences among treatments after defoliation were not significant. Survival in 1978 ranged from 51 to 73 percent and was not significantly different among treatments.

*Retrieval Terms: Acacia koa,* koa, defoliation, *Scotorythra paludicola,* thinning, fertilization, tree survival, Maui, Hawaii

Koa *(Acacia koa)* is Hawaii's most valuable native tree as both a commercial timber species and a dominant component of koa-ohia forest ecosystems. Yet the dramatic loss of koa-ohia forests, reported as early as 1913,[1] failed to stimulate development of reforestation guidelines. As a result, the koa resource further dwindled until timber operators now find few commercial quality trees available. Equally alarming is the decline in associated flora and fauna populations.[2] Timber and environmental interests, though divided over the fate of remnant koa-ohia forests, are united in their desire to reestablish koa on some parts of its historic range.

Developing stands of koa saplings is easily promoted by scarifying soil that contains viable seeds, though trees in such stands are often patchily distributed. On sites where seeds no longer exist, stands can be successfully promoted by planting nursery-grown seedlings. Hastening the development of these stands to target objectives is more difficult because little is known about stand and species requirements and their responses to management.

We had the opportunity to study the effect of precommercial thinning and fertilizing on growth of a young stagnated stand of koa. We hypothesized that thinning plus fertilizing would significantly increase growth above levels reached by leaving the stand untreated. The effect of treatments on understory vegetation was not studied.

The Borge Ridge koa stand on Maui, Hawaii, was divided into four blocks. Four treatments—control, fertilized, thinned, and thinned plus fertilized—were imposed in designated portions of each block. Diameter-at-breast-height and merchantability class were determined for sample plot trees in 1975, 1977, and 1978. Relative basal area growth rates from 1975 to 1977 indicated that thinning or thinning plus fertilizing significantly increased growth of koa relative to controls. An unplanned defoliation in 1977 greatly depressed growth in all treatments from 1977 to 1978. Tree survival was not significantly different among treatments in 1978. We conclude that precommercial thinning is an effective management practice, but its efficacy will be determined partly by timing, method of application, and microsite variability. Fertilization in conjunction with thinning may further enhance growth of some stands, but this effect was not seen in the Borge Ridge stand.

## STUDY AREA

The koa stand, known as Borge Ridge, is located on the northeast flank of Haleakala, on Maui, between 1050 to 1160 m elevation, at the upper end of the Makawao Forest Reserve *(fig. 1)*. Median annual rainfall is about 2500 mm, falling mostly from November through April.[3] Fog frequently covers the site in afternoons. The soil is a medial, isomesic, Entic Dystrandept of the Olinda soil series *(table 1)*. Agronomically, the reddish-brown loam is low to very low in phosphorus (trace), potassium (45 kg/ha), calcium (<560 kg/ha), and magnesium (<280 kg/ha). Acidity of surface horizons is typical of ash-derived koa-ohia forest soil and ranges from pH 4.0 to 4.5.

The forest overstory is even-aged koa, the result of site preparation following a 1962 fire and subsequent natural regeneration. The initial stocking density was over 41,000 seedlings per ha,[4] well within the range of values observed by others.[5] Data from a growth plot established by the Hawaii Division of Forestry and Wildlife (DOFAW) in 1968 showed that density had decreased to 6200 trees per ha. In 1973, when the study reported here was being planned, density had further decreased to 2100 trees per ha on the DOFAW growth plot. Decreases in density of the magnitude observed are normal in natural koa stands.[5]

In 1971, a preliminary examination of the stand showed that natural thinning processes were still actively reducing stand density, but the onset of stagnation was also indicated. The diameter class distribution by subjective vigor class and canopy position *(fig. 2)* showed that dying trees comprised about 40 percent of the stand. They tended to be of small diameter with canopies below the codominants. Vigorous trees, mostly codominants, made up only one-fourth of the stand. Few trees expressed dominance *(fig. 2)*. Of 181 trees in the preliminary sample of ten random 0.004 ha plots, only four were dominants. Of these four dominants, three were weakened or dying.

By 1973, it was clear that the height growth of koa had stagnated.[6] Data from the DOFAW growth plot showed that trees increased in height an average of 7.4 m from 1963 to 1968 compared to 1.3 m from 1968 to 1973. Furthermore, data from the DOFAW plot showed that mean annual diameter growth had decreased from 16 mm (s.d. = 4) from 1963 to 1968 compared to 6 mm (s.d. = 3) from 1968 to 1973.[7]

Blackberry *(Rubus penetrans)* formed dense thickets in canopy openings created by debris piles that remained after site preparation in 1962. Elsewhere, blackberry was sparse, held in check by low light beneath the koa overstory and unfavorable site conditions.

## METHODS

In 1973, a reconnaissance survey was made to assess stand density and basal area. Forty variable-radius plots were systematically located and sampled using a wedge prism with a basal area factor of 20. Tallied trees were rated as desirable, acceptable, or cull.

Following the reconnaissance survey, a study was developed using a randomized complete block design to determine the effect of fertilizing, thinning, and thinning plus fertilizing on diameter growth of koa. Four blocks were established on the narrow 245 by 730 m ridge. Four treatments were imposed on the koa stand: thinned to a maximum density of 1300 trees per ha, fertilized with N-P-K (10-30-10) at a rate of 460 kg/ha plus $MgSO_4$ at a rate of 170 kg/ha applied by aircraft, both thinned and fertilized, and not thinned or fertilized.

From October 1974 to March 1975, the stand was thinned by the Hawaii Division of Forestry and Wildlife. Our target was to reduce stand density by about 50 percent. Leave-trees, those selected to remain based on their form and potential as crop trees or nurse trees, had to be at least 2 m from their nearest neighbor. Three merchantability classes were used to aid in selecting leave-trees:

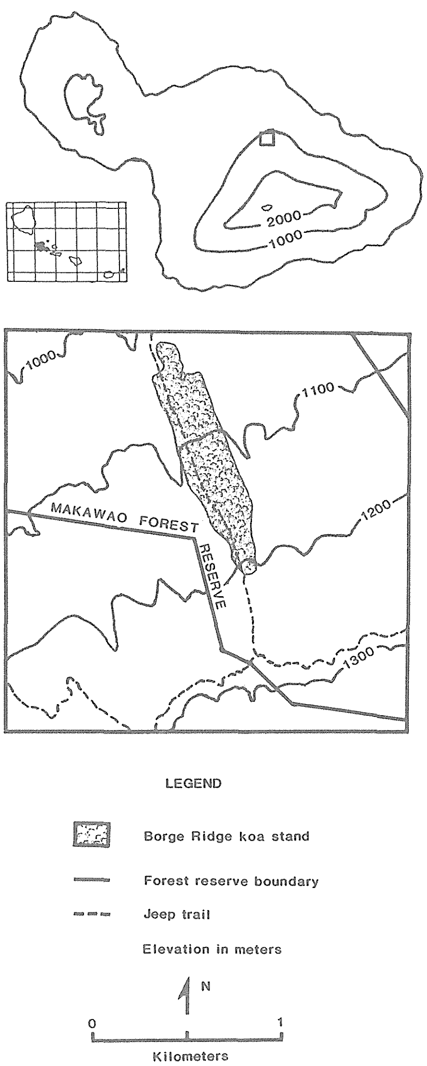


**Figure 1**—The Borge Ridge koa stand occupies a narrow elongated flat between two deep valleys on the north flank of Haleakala, Maui, between elevations 1050 and 1160 m.

Table 1—*Physical characteristics and pH of the soil profile within the koa stand on Borge Ridge, Maui*

| Horizon (cm) | Color[1] | Texture | Structure | Consistence | Roots | pH |
|---|---|---|---|---|---|---|
| A11 (0-8) | 5YR3/4 Dark-reddish | Loam | Weak, very fine granular | Friable, slightly sticky | Abundant | 4.1 |
| B21 (8-36) | 2.5YR3/6 Dark red | Silty clay loam | Moderate fine and very fine subangular blocky | Friable, sticky, plastic, weakly smeary | Common | 4.6 |
| B22 (36-48) | 2.5YR4/8 Red | Do. | Do. | Do. | Do. | 4.5 |
| IIC1 (48-69) | 5YR4/6 Yellowish red | Do. | Do. | Do. | Few | 5.7 |
| IIC2 (69-94) | 5YR4/4 Reddish brown | Do. | Do. | Do. | Do. | 5.5 |
| IIR (94 +) | Slightly weathered basalt | | | | | |

[1]Color code from Munsell Soil Color Charts, Munsell Color Company, Inc., Baltimore, Maryland, 1975 edition.

- Desirable trees: Growing stock shows no visible defects, good vigor as judged by bark and crown characteristics, an existing or potential sawlog length of 9.8 m, less than 10 cm sweep or crook in the butt 4.9 m, and a clear panel at least 2.4 m long in the poorest of the best three faces in the butt log.
- Acceptable trees: Growing stock fails to meet the specifications for desirable or cull trees, but has an existing or potential butt sawlog length of at least 3.7 m.
- Cull trees: Growing stock has at least one of the following characteristics: lodged or arched main stem, stem lean of more than 8 degrees, fork in the main stem below 3.7 m, and overtopped or of low vigor.

Desirable trees were rare and cull trees were most abundant. Consequently, many cull trees were retained to meet the target level of stand density. In those areas consisting entirely of cull trees, stand density was reduced to target levels by cutting out the worst trees.

Fertilizer was applied by a fixed-wing crop duster to half the designated plots on May 8, 1975. The remaining plots were fertilized on May 20. The amount of fertilizer reaching the forest floor was estimated by catching it in 12 plastic pots (27 cm top diameter) per sample plot.

We used three randomly located circular sample plots per treatment per block, each 0.02 ha in size. All trees with a diameter at breast height (1.4 m) greater than 1.3 cm were sampled within each plot. D.b.h. was determined to the nearest 0.25 cm. The distance and azimuth of each tree from plot center was determined to facilitate relocation. The merchantability class of each tree was also recorded.

Data were collected from January to April 1975. Trees were scheduled for remeasurement in 1978, but a complete defoliation in early 1977 prompted us to remeasure some trees a year ahead of schedule. Manpower and time constraints kept us from remeasuring every sample tree in 1977. So we remeasured instead six randomly selected trees per plot. We did not count dead trees on sample plots.

We again remeasured sample trees in summer 1978, as scheduled. However, blackberry grew luxuriantly in the interim, making relocation of many plots impossible in 1978 and complicating data analysis.

## DATA ANALYSIS

Diameter data for each tree were converted to basal areas which were used to calculate the mean relative growth rate for the periods 1975-77 and 1977-78 based on the formula[8]

$$RGR = (A_{t_2}/A_{t_1})^{1/(t_2-t_1)} - 1$$

where $A_{t_1}$ and $A_{t_2}$ are stem basal areas at time $t_1$ and $t_2$, respectively. RGR can be interpreted as the rate of interest on the capital; that is, the rate of basal area growth on the initial basal area.

Average relative growth rate $(\overline{RGR_{ijk}})$ for a plot was determined by the formula

$$\overline{RGR_{ijk}} = \left( \sum_{l=1}^{n_{ijk}} RGR_{ijkl} \right) / n_{ijk}$$

where $RGR_{ijkl}$ is the relative growth rate for the lth tree in the kth plot of the jth block and ith treatment, and $n_{ijk}$ is the number of trees in each plot.

Data were analyzed using the SAS general linear models procedure (GLM) and the following model:

$$RGR_{ijkl} = \mu_i + B_j + (\mu B)_{ij} + p_{k(ij)} + e_{ijkl}$$

where

$\mu_i$ = fixed effect for treatment i
$B_j$ = random effect for block j; $B_j \sim N(O, \sigma_B^2)$
$(\mu B)_{ij}$ = random interaction of treatment i and block j; $(\mu B)_{ij} \sim N(O, \sigma_{TB}^2)$
$P_{k(ij)}$ = random effects of plot k within treatment i and block j; $p_{k(ij)} \sim N(O, \sigma_{P(TB)}^2)$
$e_{ijkl}$ = residual error; $e_{ijkl} \sim N(O, \sigma^2)$

All plots were represented by the 1975-77 data. Differences among treatment means and among block means were tested using Bonferroni multiple comparison procedures. Each comparison was done at a significance level that achieved an overall type I error rate of at most 5 percent.

Only 27 of the original 48 sample plots were relocated in 1978. The 1977-78 data

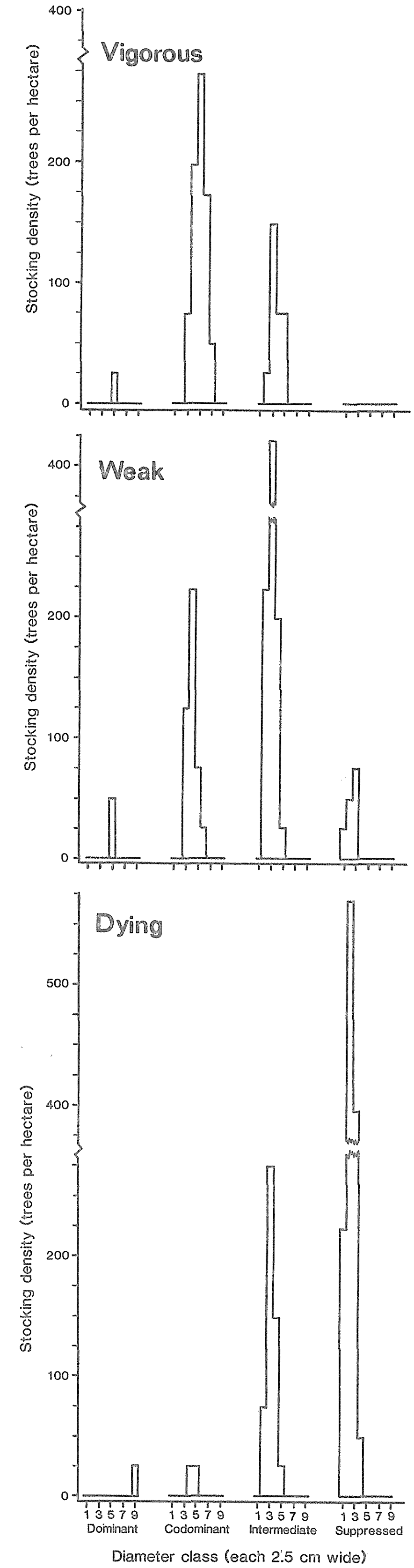


**Figure 2**—Preliminary examination of the koa stand in 1971 showed that, despite heavy natural thinning, over 75 percent of the trees were weak or dying and that few trees expressed dominance. Most vigorous trees were codominants.

were therefore unbalanced and none of the usual mean squares had the right expectation for the denominators. Approximate F-tests were therefore constructed to examine the significance of treatment and block effects and treatment-block and plot-treatment-block interaction effects. Using data from the SAS output, the variance components $\sigma^2$, $\sigma^2_B$, $\sigma^2_{P(TB)}$, and $\sigma^2_{TB}$ were estimated and the degrees of freedom associated with the estimates were calculated. Differences in mean relative basal area growth rates (per tree) among treatments for 1977-78 were tested using Bonferroni multiple comparison procedures. Each of the six possible pairwise comparisons was tested at the 0.083 percent significance level to achieve an overall type I error rate of at most 5 percent.

A similar approach was used to compare basal area per plot, number of trees per plot, and percent survival per plot among treatments in 1978. Pairwise comparisons were done at a significance level that achieved an overall type I error rate of at most 5 percent.

Differences between mean relative growth rates for 1975-77 were compared with rates for 1977-78 using paired comparisons and the Bonferroni 't' statistic.[10]

Differences in initial diameter of trees that survived and those that did not were tested within treatments using a two-sample t test with the Bonferroni 't' statistic.

Differences in mean basal area and mean stocking density among treatments and blocks, measured in 1975, were also examined using the GLM procedure. There were no missing cells and analysis followed standard procedure. Multiple comparisons were done using the Bonferroni procedure with significance levels that achieved an overall type I error rate of 5 percent.

Treatment effects on catch of fertilizer on sample plots was examined using two-way analysis of variance (ANOVA) procedures.

## RESULTS AND DISCUSSION

### Pretreatment Stand Conditions

In 1973, stand density averaged 2640 trees/ha and basal area averaged 26.4 m²/ha. About 25 percent of the trees were classed as acceptable and none were classed as desirable. Acceptable trees accounted for about one-third of the total basal area, which was distributed among trees ranging in diameter class from 7.6 to 22.9 cm *(fig. 3)*. Many cull trees were small in diameter.

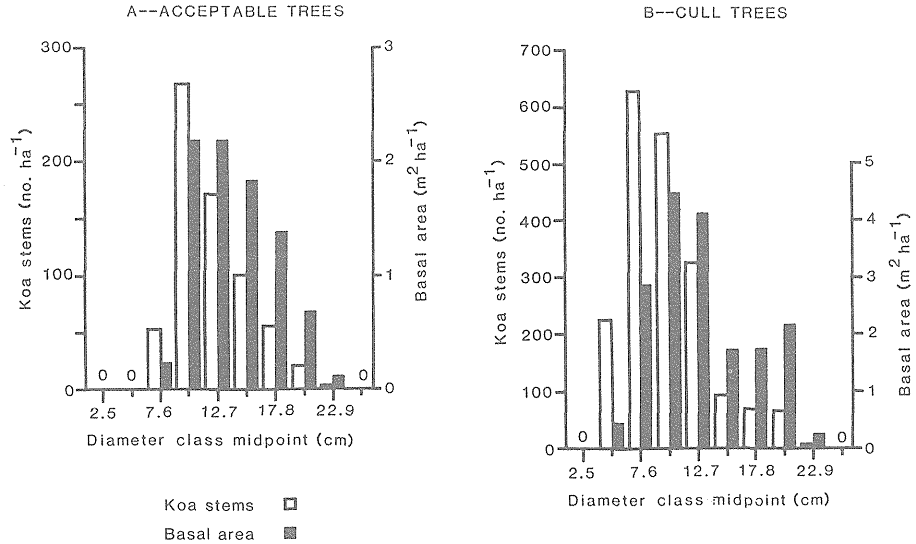


**Figure 3**—Data from a reconnaissance survey in 1973 showed that no specimens met the criteria for desirable crop trees. Only one-fourth of the trees qualified as acceptable. About one-third of the stand basal area comprised acceptable trees.

### Postthinning Stand Density in 1975

The mean basal area and total number of trees in each of four treatments after thinning in 1975 are shown *(table 2)*. Difference in stand density was not biologically or statistically significant either between control and fertilized treatments or among thinned treatments. The two thinning treatments were significantly different from the two unthinned treatments. Basal area in 1975 for unthinned treatments averaged 25.1 m²/ha ($S_{\bar{x}}$ = 1.0) compared to 15.8 m²/ha ($S_{\bar{x}}$ = 0.8) for thinned treatments. Trees averaged 1460/ha ($S_{\bar{x}}$ = 91) on unthinned treatments in 1975 and 750/ha ($S_{\bar{x}}$ = 45) on thinned treatments.

Trees classed as acceptable occurred on 36 of the 60 sample plots. The density of acceptable trees was about 90 trees/ha on unthinned plots *(table 3)*, much less than indicated by the 1973 reconnaissance survey (cf. *fig. 3*).

### Postthinning Stand Density in 1978

Basal area per hectare was almost unchanged between 1975 and 1978 levels for all treatments *(table 2)*. Comparisons between years should be made cautious-

Table 2—*Mean basal area and mean tree number among treatments in 1975 and 1978*[1,2]

| Treatment | 1975 Basal area | 1975 Total trees | 1978 Basal area | 1978 Total trees |
|---|---|---|---|---|
| | *m²/ha* | *no./ha* | *m²/ha* | *no./ha* |
| Control | 26.1a | 1375a | 27.7a | 854a |
| | (1.7) | (113) | (3.0) | (122) |
| Fertilized | 24.2a | 1550a | 24.1ab | 792a |
| | (1.2) | (144) | (2.8) | (118) |
| Thinned | 16.5b | 780b | 16.6ab | 443b |
| | (1.6) | (68) | (2.4) | (48) |
| Thinned and fertilized | 15.2b | 720b | 14.8b | 523b |
| | (1.2) | (82) | (2.5) | (53) |

[1]Within columns values followed by the same letter do not differ significantly at the 5 percent level.

[2]Values in parentheses are standard errors of the means.

Table 3—*Initial stocking, initial stand density, and survival of acceptable koa trees by treatment*[1]

| Treatment | Stocked plots | Stand density | | Survival |
|---|---|---|---|---|
| | | Basal area | Total trees | |
| | *pct* | *m²/ha* | *no./ha* | *pct* |
| Control | 58 | 2.0 (0.7) | 78 (25) | 50 |
| Fertilized | 92 | 2.4 (0.5) | 107 (22) | 71 |
| Thinned | 58 | 2.0 (0.5) | 70 (20) | 55 |
| Thinned and fertilized | 42 | 0.9 (0.4) | 41 (16) | 60 |

[1]Values in parentheses are standard errors of the means.

ly, though, because only 29 of the original 48 plots were used to compute means in 1978. Larger variance estimates due to missing data probably account for the changes in significance among treatment means, though the absolute values of the means, were unchanged (i.e., fertilized and thinned treatments) (cf. *fig. 4*). Though tree density decreased in all treatments due to mortality, both unthinned treatments still had significantly more trees per hectare than the two thinned treatments.

### Fertilization

Aerial application of fertilizer was uneven. Catch at the forest floor ranged from 40 to 1650 kg/ha and averaged 500 kg/ha ($S_{\bar{x}}$ = 80) for all plots receiving fertilizer. The average catch was not significantly different from the target application rate. Significantly less fertilizer ($P<0.05$) reached the forest floor in fertilized plots than in thinned-fertilized plots—400 kg/ha ($S_{\bar{x}}$ = 80) versus 590 kg/ha ($S_{\bar{x}}$ = 135). The difference was probably due to fertilizer caught in the denser canopy of unthinned plots. The data failed to indicate greater growth on more heavily fertilized plots within a given treatment. Although more fertilizer was caught at the forest floor in thinned-fertilized plots than in fertilized plots, growth was not significantly different ($P<0.05$) between them. No doubt any fertilizer caught on aerial plant surfaces was washed to the forest floor by the first sizable rainfall.

### Relative Growth Rates

*The DOFAW growth plot*—A single 0.04 ha DOFAW growth plot was randomly established in 1968 in an area that became a control portion of the present study.[7] Remeasurements in 1973 and 1978 provided data for estimating relative growth rates during the first 15 years. To estimate the relative growth rate before 1968, we made two assumptions which directly affected calculations of relative growth rates. Based on the fact that sample trees averaged 7.4 m tall at age 5 years, we assumed that every sample tree was tall enough at the end of the first year to have a measureable d.b.h. Our second assumption was that the d.b.h. of every sample tree was 0.1 cm. The RGR's were 228.0, 12.4 and 4.8 percent/tree/year for 1964-68, 1968-73, and 1973-78, respectively.

The RGR for the DOFAW plot during 1973-78 was lower than the mean RGR calculated for our control plots during 1975-77 and higher than the mean RGR during 1977-78 (cf. *fig. 5*). This ranking is what we would predict.

*The study site before defoliation (1975-77)*—During 1975-77, RGR's expressed on a per tree basis ranged from 5.6 percent/year for a thinned-fertilized plot to 14.2 percent/year for a thinned plot. On the average, growth rates were least for control trees *(fig. 5)*. Mean RGR for thinned-fertilized trees was slightly larger than for thinned trees—10.0 versus 9.7 percent/year *(fig. 5)*, both of which were significantly greater than the rate for controls ($P<0.05$). Fertilizing alone did not significantly increase rate of growth.

We expected greatest growth in thinned-fertilized plots. Miller[11] sug-


**Figure 4**—Stocking densities for unthinned portions of the stand (A) were high, with over 1300 trees per hectare. Thinning reduced stocking density to about 750 trees per hectare (B).

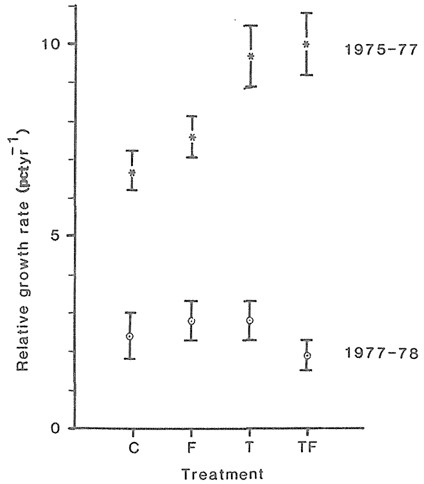


**Figure 5**—Before defoliation (1975-77), both thinning and thinning-fertilizing significantly increased the mean relative growth rate (RGR) of koa trees relative to controls. After defoliation (1977-78), differences among treatments were not significant. Defoliation significantly depressed RGR's for all treatments. Vertical bars are standard errors of the means.

gested that once a forest canopy closes, it is unlikely that fertilization increases growth because demands on soil nutrient pools may be so low that supplies are rarely inadequate. But if the closed canopy forest is thinned and then fertilized, a growth response would be likely due to increased demand on soil nutrient pools. Finding that thinning alone was as effective as thinning-fertilizing indicates that the soil was able to adequately supply the needs of the thinned trees.

We believe that growth on thinned and thinned-fertilized plots would have been even greater except for the rapid growth of blackberry *(Rubus penetrans)* following thinning. Blackberry was already present when the study was established. It was so dense in open areas that crews laying out block boundaries spent many days cutting through it. In areas with a dense koa overstory, blackberry was sparse. After treatment, blackberry spread rapidly and grew to heights greater than 3 m in all thinned areas. Unfortunately, we did not quantify treatment response of blackberry. Nevertheless, we suspect that increased competition between koa and blackberry on thinned and thinned-fertilized areas reduced tree growth rates below their potential.

While conducting the 1973 reconnaissance survey, we saw differences in stand structure and understory species composition that lead us to believe that site conditions were not uniform throughout the stand. We successfully used blocking to account for site variability, although we did not quantify the variability. Our analysis revealed that trees in block 2 grew significantly faster than trees in the other three blocks regardless of treatment. Thus, the tests of treatment effects were more precise than would have been possible without blocking. The blocking effect also indicates that site conditions can be so variable over short distances that responses to thinning or thinning-fertilizing are affected.

We examined trees classed as acceptable to determine if their mean RGR's were greater than stand averages *(table 4)*. Statistical tests were not possible because of small sample sizes. Mean RGR for surviving acceptable trees in the two unthinned treatments averaged 6.3 percent/year ($S_{\bar{x}}$ = 3.1) and in thinned treatments averaged 8.3 percent/year ($S_{\bar{x}}$ = 2.0) for 1975-77. These growth rates were not greatly different from the mean growth rates for all trees (cf. *fig. 5*).

*The study site after defoliation (1977-78)*—Not foreseen was a complete defoliation of koa trees by the koa looper *(Scotorythra paludicola)* over 1840 ha of forest, including the Borge Ridge study area *(fig. 6)*.[8] The defoliation occurred in January 1977, about 2 years after thinning and fertilizing treatments were imposed.

Table 4—*Mean relative basal area growth rates of surviving acceptable koa trees by treatment for the periods 1975-77 and 1977-78*[1]

| Treatment | Total trees | Mean relative growth rate 1975-78 | 1977-78 |
|---|---|---|---|
| | | ——*pct/tree/yr*—— | |
| Control | 1 | 4.9 (n.a.) | 6.0 (n.a.) |
| Fertilized | 2 | 7.1 (1.7-12.3) | 5.0 (0.0-9.9) |
| Thinned | 6 | 8.9 (1.7-15.0) | 2.9 (0.0-13.4) |
| Thinned and fertilized | 2 | 6.5 (1.8-11.2) | 2.9 (0.0-5.7) |

[1]Values in parentheses are ranges associated with the means.

The short-term effect of the defoliation was a significant reduction in the relative growth rates of koa in all treatments *(fig. 5)*. Differences among treatments and among blocks were not significant (P>0.05).

Growth of acceptable trees was depressed the year after defoliation. Trees in the two unthinned treatments grew an average of 5.3 percent ($S_{\bar{x}}$ = 2.9). In the two thinned treatments, trees grew an average of 2.9 percent ($S_{\bar{x}}$ = 1.7). We saw no evidence that acceptable trees grew faster or slower than their neighbors.

In temperate forests, thinning plus fertilizing has been shown to increase resistance of some forest trees to defoliation and attack by other insects.[12] We observed no such protection in the Borge Ridge stand. All trees were defoliated regardless of treatment.

## Survival of Koa

We expected greater survival in thinned and thinned-fertilized plots than in either control or fertilized plots, due partly to the elimination of high-risk trees and partly to reduced competition among leave trees. Instead, mean survival of koa trees was not significantly different among treatments for the 1975-78 period *(table 5)*.

The lack of significant differences among treatments is probably due to the combined effects of severe defoliation, stimulated competition with blackberry which was further intensified following defoliation, and incomplete sampling in 1978 which affected the magnitude of means and associated variances.

Initial tree diameter appeared to be a factor in survival for all treatments. Survivors generally had larger initial diameters than those that died.

Few acceptable trees were found initially on our sample plots and mortality, which averaged 35 percent for all treatments, reduced that number further *(table 3)*. Consequently, we had too few acceptable trees to statistically test whether they had higher rates of survival within and among treatments than all sample trees as a group. Survival percentages for acceptable trees *(table 3)* are not markedly different from comparable values for treatments as a whole *(table 5)*.

**Figure 6**—The 1977 defoliation by the koa looper *(Scotorythra paludicola)* was total in the Borge Ridge koa stand. The temporary increase in light and available soil nutrients and water stimulated growth of blackberry which in turn may have contributed to depressed growth of koa after defoliation.

## Management Implications

Our results indicate that tree growth in a crowded koa sapling stand was significantly increased by precommercial thinning. We suspect that similar responses are obtainable at other sites where sapling or pole stands exist. The magnitude of the responses at other sites will be determined by many factors, including but not limited to physical and chemical soil characteristics, amount and distribution of rainfall, temperature, composition and abundance of understory vegetation, as well as age, vigor, and genetic potential of the koa trees.

The intensity of thinning will also have a marked effect on subsequent tree growth. In this study, stand density was reduced 50 percent by thinning. We did not examine the effect of more or less severe thinning, but we suspect that the response would have been different in both cases.

Managers cannot only vary the intensity of thinning, they can choose alternative thinning methods. In this study, the stand was uniformly thinned without regard to the presence of a potential crop tree. Because the precommercial thinning was labor intensive, thus costly, the economic return may not justify the high investment. An alternative approach would be to fell or poison only those trees competing with potential crop trees. No thinning would occur where there are no potential crop trees. This method would be less costly than uniform stand thinning, and cost is an important consideration in planning a precommercial thinning.

Timing of precommercial thinnings is important.[13] The Borge Ridge koa stand may have deteriorated to a point where the canopy of most trees was too sparse for rapid response to release from competition even though the stand was only 12 years old. Analysis of DOFAW koa growth plots on the island of Hawaii has led to a recommendation that precommercial thinning be done around age 8 to 10 years.[14]

Variability within and between stands is also an important consideration in thinning koa. In this study, we found significant within stand differences in rate of growth; i.e., a significant block effect. Thus, thinning to a prescribed density may not elicit the desired growth response even within a discrete stand.

In this study, we found that fertilization of thinned stands also stimulated growth of koa relative to untreated trees. The relative rate of growth of thinned-fertilized trees was slightly greater than growth of thinned trees, but the difference was not significant. We conclude that fertilization did not contribute significantly to growth response and the additional cost was not warranted. This does not imply that fertilization should never be done.

We suspect that fertilization did not further stimulate growth of thinned trees because of increased blackberry competition. Wherever aggressive noxious alien plants occur, such as blackberry, banana poka *(Passiflora mollissima)*, and clidemia *(Clidemia hirta)*, increased root competition for water and nutrients should be expected following thinning. Fertilization will probably intensify the competition. In situations where aggressive competitors are absent, fertilization should cause an additional increase in rate of growth beyond that attained by thinning alone.

Broadcasting fertilizer over the entire stand, as in designated areas of this study, may not be the most desirable

Table 5—*Survival among treatments[1] and comparison of initial mean diameter of survivor and dead koa within treatments[2,3]*

| Treatment | Survival | Mean diameter breast height: Survivor | Dead |
|---|---|---|---|
| | *pct* | *cm* | *cm* |
| Control | 62(9)a | 6.7(0.2)a | 5.3(0.2)b |
| Fertilized | 51(8)a | 6.3(0.2)a | 4.8(0.2)b |
| Thinned | 57(6)a | 6.4(0.2)a | 5.8(0.2)b |
| Fertilized and thinned | 73(7)a | 7.1(0.3)a | 5.2(0.3)b |

[1]Within the column, values followed by the same letter do not differ significantly at the 5 percent level.

[2]Within rows, values followed by the same letter do not differ significantly at the 5 percent level.

[3]Values in parentheses are standard errors of the means.

method of application. The distribution of aerially applied fertilizer was irregular. Fertilizer was wasted on noncrop trees and understory vegetation. An alternative is to apply fertilizer only to potential crop trees by either broadcasting or spot placement around the projected edge of the canopy. This approach could be coupled with the individual crop-tree thinning method suggested earlier. The tradeoff would be hand application of small quantities to small areas versus aerial application of large quantities to extensive areas.

At the outset of this study, managers asked if fertilization alone could be used to increase growth of the stagnated koa stand. There are instances in which stagnation of conifers on poor sites has been overcome by fertilization alone.[15] But our data indicated that this did not happen for koa on Borge Ridge. In general, fertilizers are more likely to enhance tree growth prior to canopy closure, toward the end of the rotation, or following thinning of a closed canopy stand.[16]

Studies underway in Bishop Estate's Keahou koa regeneration area on the island of Hawaii indicate that fertilization can increase seedling growth.[17] Fertilizing individual seedlings imposes a form of spacing control on the stand. Fertilization was not effective in older closed-canopy stands in the same area.

The value of koa wood is high—so high that the merchantability classes defined in this paper are probably outdated. Managers who want to grow and sell koa wood should think in terms of producing bolts and half logs rather than sawlogs and canoelogs. Even trees with heart rot may contain enough colored heartwood to make them marketable. If production of short lengths of highly colored heartwood is the goal instead of production of tall straight-stemmed trees with clear boles, then more drastic thinning accompanied by fertilization to maximize growth of selected trees may be desirable.

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