Koa Stand Development and Grazing Impacts

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Introduction

People have a lot of questions about koa. "How long does it take for a full-statured stand to grow?" "How long do I have to wait before I get trees of commercial size?" "To maximize the profitability of a plantation, how long do I have to wait, and how many trees of what sizes will I get?" "If I want to thin, how many trees should I remove, and how long until the stand is again fully stocked?" "Can we graze cattle under and amongst koa trees, and what will this do to the koa stand?" Questions like these are quantitative, meaning that instead of "yes" or "no" answers, they ask "how much" or "how long," and the answers to them have to be based on measurements. Questions like these are also long-term, and would take longer than most professional careers (and certainly longer than funded research projects) to answer by "trying and seeing." Finally, the answers to these questions are affected tremendously by all the soil, weather, insect, disease, economic, and management factors and fluctuations that affect tree growth, vigor, and value.

Our research tackles these questions. Everything presented here is the result of measurements on koa trees in field environments, mainly upland areas of the island of Hawai'i. To make reasonable predictions about long-term events, we have analyzed records from permanent inventory plots, some of which are nearly 50 years old, and we brought together these patterns of koa recruitment, growth, and death into a quantitative prediction tool (a computer model) and added to this results of short-term, intensive studies of cattle impacts, light absorption by koa canopies, and grass growth. Finally, we have taken into account some of the ways that koa stands grow differently on sites ranging from "good" to "poor," the seemingly random fluctuations in sapling density and risks of tree death, and some reasonable estimates of timber quality and of effects of financial interest rates on economic outcomes of management choices.

It is my hope that this summary of our research will give land owners, managers, and advisors the information they need to sort out some of the choices confronting them. Naturally, we don't guarantee anybody that if they follow one of our graphs, they can become wealthy in a certain number of years, or that biodiversity of native flora and fauna will be perpetuated. For one thing, we don't claim to predict what catastrophes the future might hold. Also, the details, mathematical derivations, and assumptions of this work would take too much space (and have too much jargon) for this presentation, although they have been spelled out in a thesis (Grace 1995) and are soon to be reported in technical journals. What I hope to do here is to give enough detail and substance that people can put the results to work for them, and to provide just enough background that they understand how these came to be our best quantitative estimates of koa growth and effects of management.

Field studies

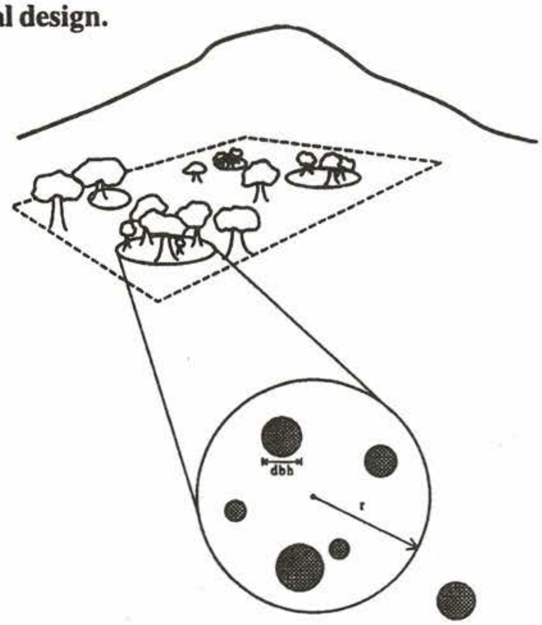
Three kinds of field studies have gone into this synthesis: long-term growth monitoring, grazing, and pasture shading (Table 1). Long-term monitoring plots were established by Hawai'i DLNR Division of Forestry and Wildlife foresters 5 to 12 years after clearing. Each tree was measured and its position recorded in 0.04 ha circular plots. Each plot was remeasured approximately every 5 years, until most recently in 1994. These results were analyzed to learn about and quantify the controls of growth, dominance, and death of koa trees. At each measurement, each tree had its growth rate calculated as the change in stem diameter since the last measurement. The rate of growth of each tree was compared with the relative ranking of the tree among the others in the stand. For each tree alive at a measurement, the probability of its dying before the next measurement was analyzed as a function of its current growth rate and relative dominance in the stand. Three plots (12, 23, and 24) were analyzed and used to estimate the coefficients of the computer model; plot 41 data was reserved as an independent test of the model.

A key concept in understanding the dynamics of koa forest development is stand basal area (Fig. 1). Stand basal area is the cross-sectional area of tree stems per

Table 1. Koa field studies.

Site location, Plots	Start date	Elev. (m)	Annual Rainfall (mm)
1. Long-term growth plots			
Waiakea Forest Reserve,			
Plot 12	1949	1250	3800
Plot 23	1963	1500	2500
Plot 24	1963	550	5000
Hilo Forest Reserve			
Plot 41	1974	1450	3800
2. Grazing study			
Pu'u Wa'a Wa'a Wildlife Refuge, Hualalai			
31 plots	1992	1400	1200
3. Shading and pasture			
Keauhou Ranch			
16 plots	1993	1500	1500

Figure 1. Stand basal area illustrated as the cross-sectional area of tree stems within a circular plot of radius r. Several other conceivable plots are illustrated to show that assessment of a tract of land requires a sampling strategy incorporating proper statistical design.

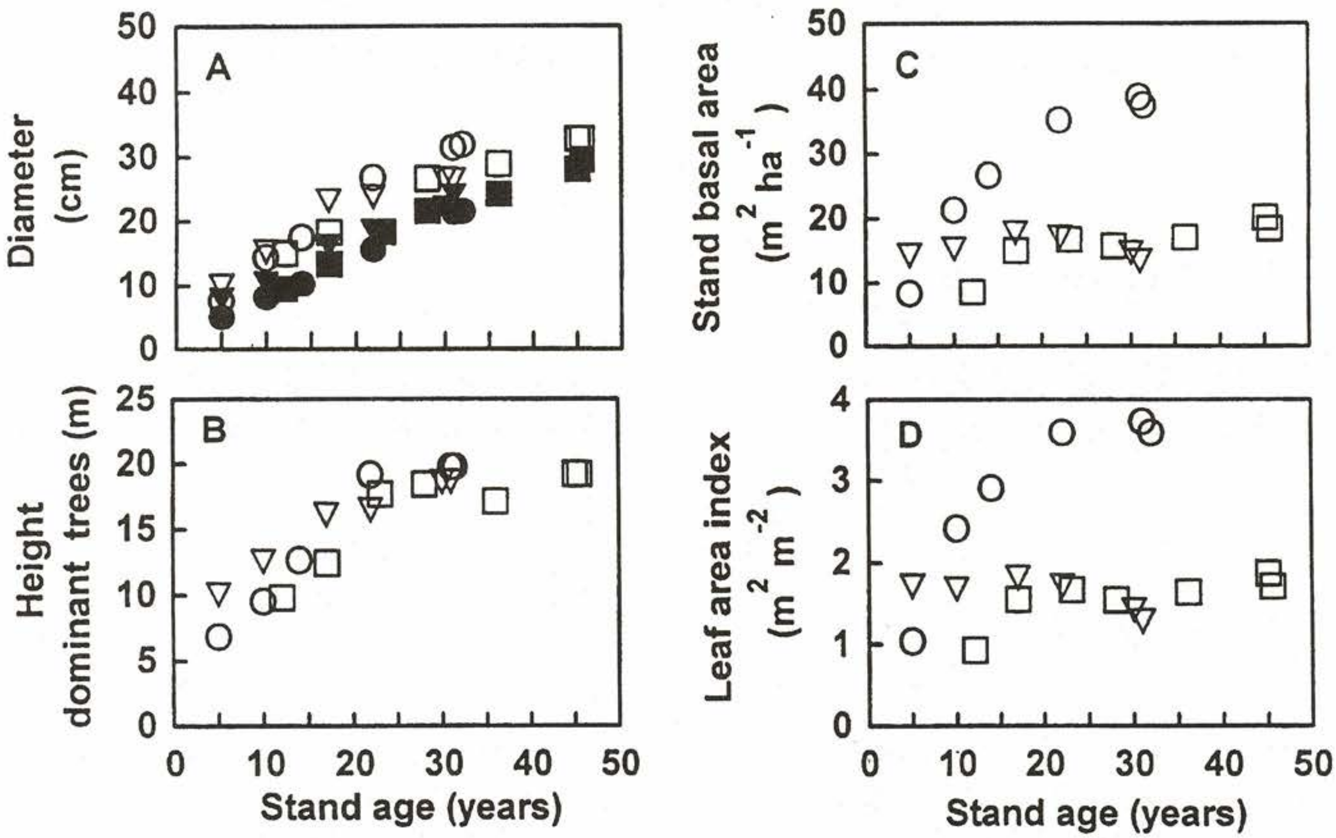


unit of land area. This index combines the effects of number and sizes of trees into one number that reflects the relative occupation of the site by forest. The biological basis for its use is the rough proportionality between sapwood, which conducts water through the stem, and the area of leaves exposed to the sun and drying air. Stand basal area can be measured by measuring tree trunk diameter at 1.4 m height (DBH) of each tree in a plot. These diameters are squared, added up, and multiplied by p/4, then divided by the land area. Typical ranges of basal area for fully developed koa stands would be 20 m^2 / ha for a "poor" site to 40 m^2 / ha for a "good" site. What soil, plant, and climate factors result in high or low maximum basal area for koa is only partly known: on Kaua'i we showed that it was related to rainfall and relative water stress (Harrington et al. 1995), and the question is being studied now on a variety of soil types in the Honaunau Forest by Adrián Ares.

The grazing study consisted of two experiments performed from 1992 to 1994 at the Pu'u Wa'a Wa'a Wildlife Refuge in Hualalai, Island of Hawai'i. One was a replicated trial using large paddocks, where high and low intensities of cattle grazing were compared with an ungrazed control treatment. Tree growth, survival, degree of defoliation, and indices of water status were measured. The initial tree population density and size class distributions from these plots were also taken to give a statistical picture of the variability of koa regeneration in former pasture land. The second experiment treated replicate single-tree plots with every combination of four possible grazing impacts: defoliation, soil trampling, grass removal, and manure deposition. This information, compared with the results of the large grazing trial, allowed us to establish which of these factors was most important in causing the observed effects on koa.

The pasture shading experiment was performed in 1993 and 1994 at the koa reforestation area of Keauhou Ranch. Sixteen 0.03 ha plots were established in areas of varying canopy density of koa. Light absorption by the koa canopy was measured with a group of sensors and a datalogger and averaged for a two week period. Permanent quadrats centered on each light sensor were harvested by clipping, to measure grass biomass, species composition, and forage quality. Rates of grass production (regrowth) were measured by clipping again at 0.5, 1, and 2 months.

Figure 2. Results of long-term monitoring of koa growth plots 12 (□), 23 (○), and 24 (▽), showing (A) average diameter of all trees (filled symbols) and of dominant trees (open symbols), (B) average height of dominant trees, (C) stand basal area, and (D) leaf area index (leaf area per unit ground area).



Results of field studies

The three growth plots had fairly similar trends of average stem diameter and dominant tree height over time but differed considerably in stand basal area (Fig. 2). Plot 23 in particular had nearly twice the basal area (Fig. 2C), and correspondingly greater wood volume, compared to the other plots. This result means that "site index" (height of dominant trees at a reference age), as used in some temperate forest management, would not be a useful indication of site potential for koa forest management. Instead, we propose that the maximum stand basal area that stands approach over time (Fig. 2) is more nearly related to a site's ability to support koa forest. In using this index at another site, the question arises, "How do we know whether a stand is at its maximum or not?" The only sure way is to measure it over time, but the present-day stand basal area could be used if, based on the experience and judgement of the land manager, the stand has not been disturbed for 10 or more years or if it seems to be as fully stocked as any nearby stands ever get under similar soil and climate conditions.

The approach of stands to a maximum basal area suggests that either tree growth slows down as the maximum capacity to support koa forest is reached, or that some trees die as fast as the remaining ones grow (or some combination of these two effects). The answer is found by analyzing the diameter growth rates of dominant trees: they slow down to nearly one third of their initial growth rates as the stand as a whole approaches its maximum basal area (Fig. 3). Why the dominant trees slow down as the stand as a whole reaches its maximum is a complicated question that is under study in several related projects. The answer may have to do with the size and proportions of leaves versus respiratory tissue in individual trees, or with depletion of resources (e.g., water or nutrients) by all the trees in the stand. Never-

Figure 3. Average growth of dominants in each plot and growth interval, versus stand basal area relative to the maximum basal area.

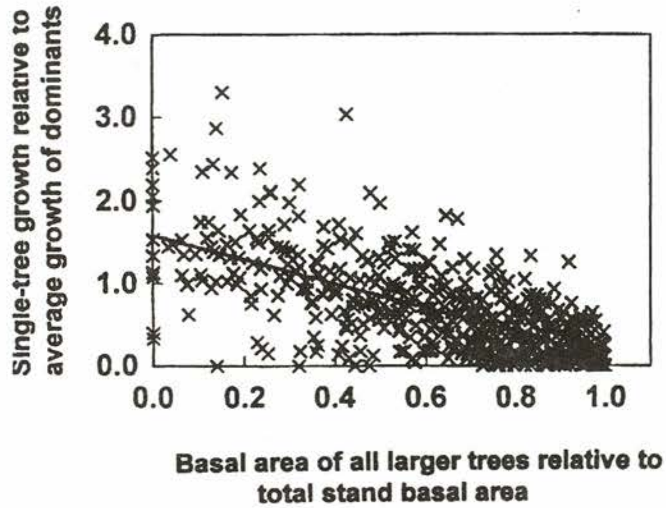
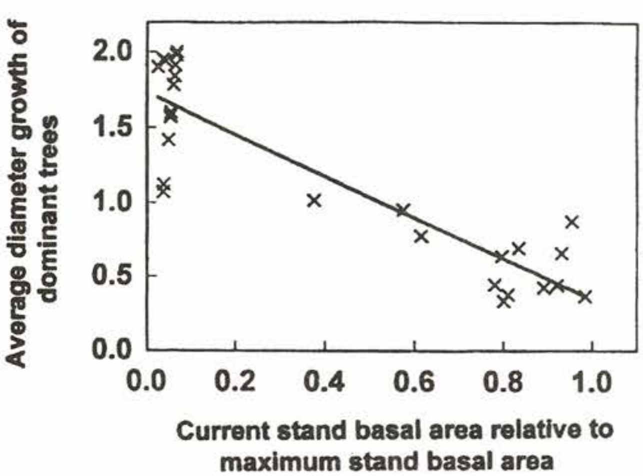


Figure 4. Growth of individual trees relative to the growth of dominants, versus an index to suppression within the stand (fraction of stand basal area in trees larger than the subject tree).



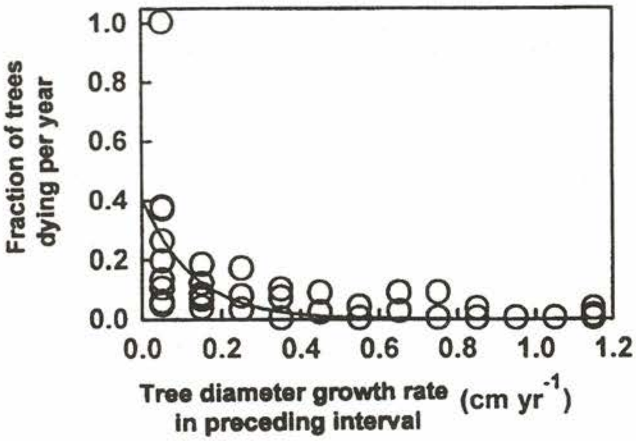
theless, the finding that dominant trees slow down is important in projecting how fast stands grow and develop. Whether the subdominant trees are suppressed by the dominants is the next question we took up.

One of the new findings of our work is the clear demonstration of a competitive hierarchy within koa stands. Because growth rates vary tree by tree, year by year, and also with site quality and stand age, it is difficult to see this pattern in the raw data. However, when diameter growth of each tree is expressed relative to the dominant trees in the plot, and suppression is expressed as the basal area of all the larger trees in the plot, relative to the total stand basal area, a strong trend can be discerned (Fig. 4). The more severely suppressed it is, the slower a tree grows compared to the dominants of the stand. Although there is a lot of scatter around the relationship, it should be noted that these data are for individual trees from all three plots across all the measurement intervals.

It is often assumed in predictions of temperate forest dynamics that trees growing below some threshold rate have a greater chance of dying. The idea is that trees with barely enough energy to keep growing are less likely to survive the insults of drought, disease, insects, and storms. We did not want to assume that the same relationship applied to koa forest without good evidence. For each plot, in each measurement interval, we grouped trees together according to their growth rates, and then calculated what fraction of each group did not survive until the next measurement. The results were striking—trees growing in the range of 0 to 0.1 cm / yr had on average three times the risk of dying as trees growing from 0.2 to 0.3 cm / yr (Fig. 5). It is somewhat hard to see in the scale shown, but even vigorous trees also had some chance of mortality, and the smooth fit to the data never quite reaches zero chance of dying. Although these stands did not suffer catastrophic disease, insect outbreaks, or direct hurricane impact, it should be noted that this sample includes more than 100 plot-years of data, during conditions when nearly 80 percent of the trees initally present had died before the last measurement. Taken together with the previous results, we can then predict that there is a strong tendency for smaller trees in a stand to be suppressed, and that these are more likely to die. This finding has important implications for management practices such as thinning or grazing.

In our second group of studies, on the effects of cattle grazing, we found that there was a strong relationship between the removal of leaf area by browsing and the reduction in tree growth (Fig. 6). For trees greater than 3 cm DBH, there was almost no mortality. In our second experiment, we attempted to understand what factors produced this result. We obtained clear proof that trampling the soil decreased tree growth rates (Fig. 7).

Figure 5. Probability of mortality versus diameter growth class.



In both experiments, koa shoot water status (xylem pressure potential) was decreased, suggesting that root damage interfered with water uptake. Interestingly, clipping the kikuyu grass from around the trees increased growth, showing competition from below the tree crowns (Fig. 7). We found a slight indication that this competition was for water, but further studies need to be done to really prove it. Manure had no significant effect on tree growth, because the nutrient content, averaged over the land area, was insignificant as a source of fertilizer. The approximate sizes of the negative trampling effect and the positive effect of release from competition with grass were about the same (Fig. 7), suggesting that the effects of grazing could be predicted well enough from simply the degree of defoliation from browsing. Interestingly, when the growth rate decrease from browsing was entered into the mortality function from the growth plots (Fig. 5), the calculated chances of a tree dying were very close to the observed mortality in the grazing trial. This check on the consistency of results from different studies suggests it is reasonable to integrate them for the purposes of long-term prediction of management outcomes.

In the third group of studies, we found that the koa canopies decreased kikuyu grass production in proportion to the density of shade cast. Interestingly, there seemed to be a competitive shift in the grass community from kikuyu to pu'u lehua grass as the shade increased. In kikuyu grass, there was a tendency for higher protein content under shade in both the standing and regrowth forage. The effects of these shifts in species

Figure 6. The relationship between stem diameter growth during the 12 months after grazing treaments versus the fraction of leaf are remaining after the treatment in light (◇) and heavy (▽) grazing treatments. "Heavy" grazing was putting enough cows into the experimental paddock to deplete all available forage in 3 days, while "light" was the same stocking for only 1 day.

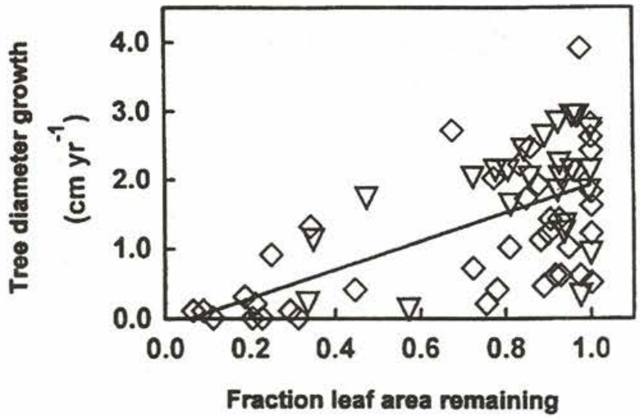


Figure 7. Mean diameter (A) and diameter growth rate (B) of trees trampled (circles) versus untrampled (squares) with grass clipped (open) versus unclipped (closed).

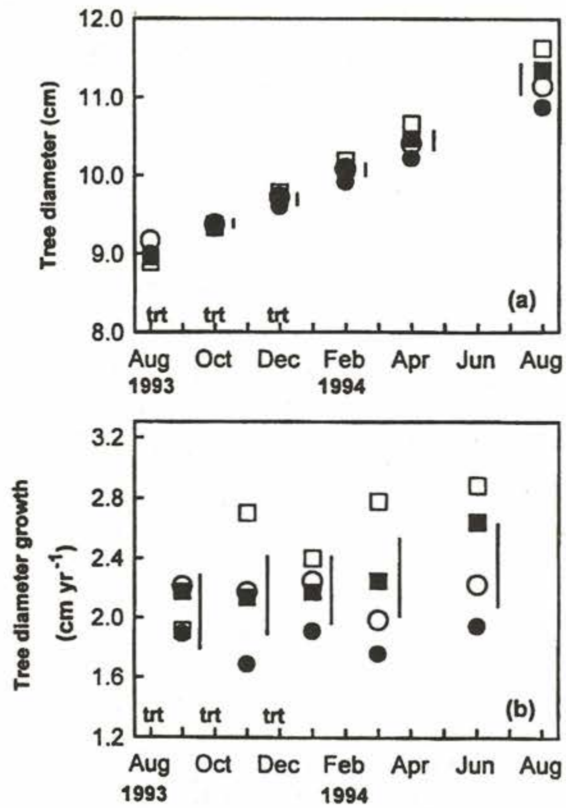
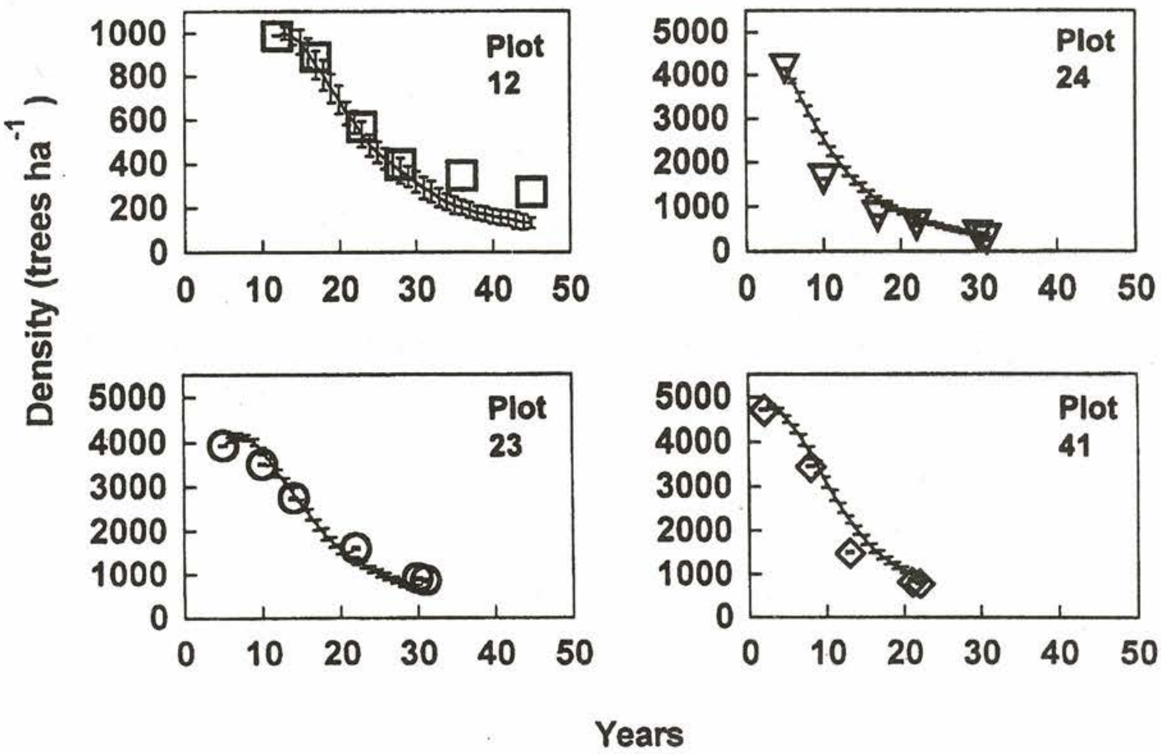


Figure 8. Measured (symbols) versus simulated (mean plus or minus 1 standard deviation) koa tree density over time, beginning with the initial conditions of the long-term growth plots.



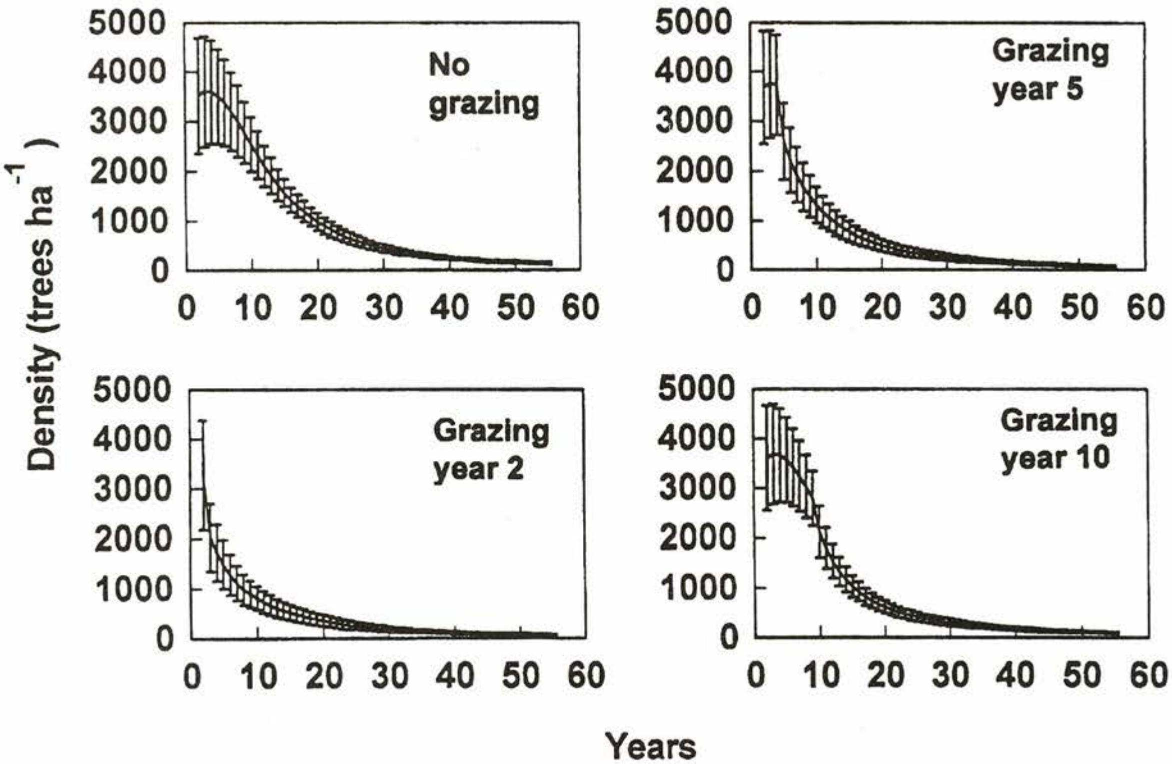
and forage quality were relatively small compared to the decrease in pasture productivity. We conclude that the basic decrease in grass growth under shade is the primary effect on pasture to be considered in a silvopastoral system of grazing under koa trees.

Predictions from synthesis of field studies

The goal of our synthesis is to pull all of these different studies together and come up with some answers to the questions posed by land managers. Naturally, the assumption has to be made that what was observed, perhaps in one place in certain years, applies to other places. But if we are unwilling to make this assumption, everything that has been learned about koa remains piecemeal, and thus unable to provide even provisional answers. I also want to reemphasize that in creating a computer model of koa growth and management, we did not take a model of some other forest and "tweak" it to resemble koa, nor did we invent functions with no basis in reality. Our first objective was to link these studies together by seeing their effects on the population processes (recruitment, growth, death) of koa. The results of the field studies, as summarized above, were statistically fitted by equations, and these equations were linked together to predict the outcomes of management choices.

In addition to synthesis, another objective of our approach is to deal directly with variability. It is obvious from the results that trees, groups of trees, sites, management impacts, and years fluctuate considerably despite our attempts to discern "average" trends. Nowhere is variability more important than in initial stand establishment in old pasture and in mortality of trees. Furthermore, some decisions may be based more on consideration of risk ("What are my chances of going bust?") rather than average or typical returns. For these reasons, we used the number-crunching power of the computer to simulate a collection of plots, which might be viewed as a sample of plots from a larger landscape, and drew random numbers (distributed according to measured averages, probabilities, and variances) to determine the number of saplings starting a plot and, annually, whether each tree dies. An interesting result of

Figure 9. Simulated effects of cattle grazing on reforested old pasture based on cattle being intoduced in various years since stand establishment.



this approach is that the computer predictions are not exact, but cover a range similar to the range observed in field studies.

In addition to variability, the clear effect of tree size on damage by cattle and the development of suppression and its effects on growth and mortality required that we adopt a size-structured approach. In simpler words, the assumption that a koa population acts like collection of "average" individuals is simply no good. This approach is again dependent on the processing powers of the computer, but it has the advantage of bringing together the size-dependent and seemingly random features of forest growth.

Initial conditions specified at the beginning of each scenario are equations describing the relative proportions of leaf area and woody biomass as a function of tree size, the maximum basal area for the simulated site and the land area of the simulated plot, and the parameters for the equations describing koa recruitment, growth, death, shading, and pasture growth. There are two ways of creating initial populations. The first is to read in a list of measured tree diameters. This approach was useful in the testing of the model versus field data from growth plots. The second approach is to draw a random number of saplings (with a random average size) based on the plots set up in young koa forest growing on old pasture. This approach was useful for simulating various potential management strategies for silvopastoral systems.

In each simulated "plot" we keep track of the size of each individual tree, and each year we estimate its growth rate based on site, stand basal area, position in the size hierarchy, and leaf area removal by grazing (if any); chances of mortality are calculated from growth rate. If the draw of a computer-based random number falls within the range of mortality, then that tree "dies" and is removed from the list of living trees. Then the next tree is considered, until the plot is finished and a new year begins. An estimate of merchantable wood volume of the stand is made from measurements of the size of the clear bole in field-grown koa trees, then reduced 50% to roughly account for defects in the wood.

Each run of the same initial conditions was repeated 50 times to give a reasonable picture of the outcomes of the specified conditions.

Beginning with the initial measurements of the growth plots, the model predicted well the changes in tree density due to mortality over time (Fig. 8). Plot 41, which was not used in the calibration of the model, also was well predicted by the model. The large drop in number of living trees means that deliberate thinning to increase the value of the koa stand is a good idea. Because so many of the trees are ultimately doomed to die, in particular the suppressed ones, forest managers may want to choose healthy or promising trees to be among the few that survive. For example, given roughly 50 percent natural mortality between years 10 and 20, a fairly radical 50 percent thin at age 10 would seem justifiable. At present, we cannot predict some of the characteristics that most affect the economic value of a stand (e.g., wood color and figure), so the decision of how much and what to thin out must also be made based on the experience and judgement of the manager.

Another interesting feature of the model results is the relatively small spread among the replicate runs (Fig. 8). The competitive hierarchy was already established early in the life of the stands, and despite all of the random-number drawing in the program, the predictions converged on a relatively tight trajectory around the averages. By comparison, the simulation of reforestation of old pasture showed much wider variability as a result of the patchiness of koa sprouting and early growth (Fig. 9). This variability was then "funnelled down" into a much tighter pattern, again as the result of competition and its effects on growth rate and mortality in stands. Although simulation of grazing beginning at years 2, 5, or 10 had fairly large effects on the number of trees (Fig. 9), there was relatively less effect on simulated merchantable volume (Fig. 10). This surprising result is caused by the fact that the largest trees have the bulk of the merchantable volume and are dominant in the stand, and suffer the least damage from cattle browsing. Even the most radical treatment of bringing in the cattle at year 2 only reduced volume by one-third or so at age 50. The appearance of trees of merchantable volume around year 15 was highly variable, due to the decision that any stem less than 30 cm was "not" merchantable. As the accumulation rate of merchantable volume tapers off around 40 years, the discount rate would become greater than the relative rate of increase in volume or value; for this reason one might conclude that 35 to 40 years is the time required until peak profitability of a koa timber harvest. Obviously many other factors are weighed in the decision whether or not to harvest all or parts of a stand.

Conclusions

To answer some of the questions posed at the beginning, although trees of commercial size (30 cm) begin to be obtained around 15 years, it would be inadvisable to harvest them at that point, because they are just starting to accumulate value. Our estimates, which include the effects of discount rates and many other detailed factors, suggest that the time until maximum profitability of a koa rotation would be about 35 to 40 years. After that time, the stand continues to accumulate in value, but at a slower relative rate than the discount rate. A basic problem facing a land manager is determining the ultimate potential of a given site to support koa.

A central concept emerging from this work is that stand basal area is able to capture much of the variation in stand dynamics we see among sites and over time at a given site. Fortunately, it is something that consulting foresters and land managers can measure rapidly without computers or other fancy gear. Henceforth, it should be part of every forest description and management plan, along with a description of what sampling or cruising strategy was used to determine it. Furthermore, if the results summarize here hold up elsewhere in Hawai'i, the traditional concept of site index (height of dominants at a reference age) does not seem useful for koa.

The question of how many trees of what size survive until some point in the future, and the related question of how much to thin a stand, are both based on how important population processes are to koa forests. For one thing, most koa trees die by natural processes before the stand reaches what could be considered its economic point of harvest at 40 to 50 years. Growth rates and chances of dying are inextricably linked together with the whole stands' approach to the maximum capacity of the site and with each tree's relative ranking within the stand. We are only beginning to understand what controls the site capacity for koa, but that doesn't mean we shouldn't be managing forests now. A manager seeking to increase the economic value of a stand may wish to preempt the 50% mortality seen naturally from 10 to 20 years, and perhaps again from 20 to 30 years, in favor of removing the 50% of least promising individuals from the stand. By the same token, the large variability in young regenerating stands may not be a "problem" in the sense that stand densities eventually even out due to self-thinning of the higher-density areas. Finally, although our data spans many years and many conditions, it is fair to admit that none of the growth plots were directly devastated by hurricane or pests, and we cannot yet estimate the risks of factors like these.

About the question of whether cattle can be grazed under koa, and what effects will that have, our results confirm the observations that cattle damage trees, and yet in the long run, the loss of volume may be relatively small compared to other benefits of grazing, such as grass and weed control, cash flow, and (possibly) taxes. A silvopastoral agroforestry system of koa and cattle appears promising on these grounds. A caveat on this conclusion is that our grazing experiments were not chronic and the cattle were very carefully managed, having adequate forage and water at all times. It may be that continued root damage could open the way for diseases and foster decline of koa stands.

A final conclusion to this work is to reiterate the need for synthesis and for performing studies that can be linked into synthetic schemes. Individual experiments, field observations, and unreplicated demonstrations may all have their appeal today, but unless they fit into a larger context their conclusions will forever remain piecemeal. We have a long way to go in pulling together what is already known about koa, but these results suggest a promising future for koa forestry and agroforestry.

Acknowledgements

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Questions

Q: How many animals for grazing?

A: This was a short-term, intensive grazing management. We had five animals in each experimental paddock, which was a small area, but they were only in there for one day. We had a more intensive treatment where they were in there for three days. This was based on their ability to completely browse down all the green fodder on the ground. So this was not like letting your cows go and coming back in two months and saying "Okay, how many head were there on your acreage?" This was very intensive grazing management, but the three-day grazing treatment did remove all the green fodder.