

STOCKING GUIDELINES FOR THE ENDEMIC HAWAIIAN HARDWOOD, *ACACIA KOA*

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BAKER, P. J. & SCOWCROFT, P. G. 2005. Stocking guidelines for the endemic Hawaiian hardwood, *Acacia koa*. Stocking relationships are an important tool for foresters because they provide a means for evaluating how effectively the trees in a stand use available growing space. While stocking guidelines are not available for many tropical tree species, readily obtained measurements of stem and crown diameters can be used to develop preliminary stocking guidelines for most tree species. We demonstrate this approach for the endemic Hawaiian hardwood, *Acacia koa*, a species of major ecological and economic value in Hawaii. Using data from repeated censuses of multiple sites, we evaluated the influence of site quality and stand age on stocking guidelines for *A. koa*. Our results demonstrated that *A. koa* required less canopy space for a given dbh on moist windward sites than on drier leeward sites. In addition, we showed that on the windward sites *A. koa* required relatively less crown space with increasing tree size, whereas on the leeward site the opposite pattern was found. Size-density data from permanent inventory plots at the leeward study site showed excellent correspondence with the stocking guideline derived from the stem-crown diameter allometry. These stocking guidelines can be used to guide the establishment of new *A. koa* stands or to develop thinning regimes where information from spacing and thinning trials is not available and until better information is available.

Key words: Growing space index – Hawaii – spacing – silviculture – thinning

BAKER, P. J. & SCOWCROFT, P. G. 2005. Garis panduan penstockan *Acacia koa*, kayu keras endemik di Hawaii. Hubungan penstockan merupakan alat penting bagi para rimbawan kerana ia membolehkan mereka menilai kecekapan pokok dalam dirian menggunakan ruang tumbesaran. Banyak spesies tropika masih tidak mempunyai garis panduan penstockan. Namun ukuran sedia ada bagi diameter batang dan diameter silara boleh diguna untuk membangunkan garis panduan penstockan awal bagi kebanyakan spesies pokok. Kami menunjukkan pendekatan ini untuk sejenis kayu keras endemik di Hawaii iaitu *Acacia koa*, yang merupakan spesies bernilai tinggi dari segi ekologi dan ekonomi di negara ini. Kami menggunakan data daripada banci berulang di beberapa tapak untuk menilai pengaruh kualiti tapak serta usia dirian terhadap garis panduan penstockan bagi *A. koa*. Keputusan kami menunjukkan bahawa bagi diameter aras dada (dbh) yang tertentu, *A. koa* di tapak hadap angin yang lembap memerlukan kurang ruang sudur berbanding pokok di tapak lindung angin yang lebih kering. Kami juga menunjukkan bahawa di tapak hadap angin, *A. koa* memerlukan kurang ruang silara apabila saiz pokok meningkat. Bagaimanapun, di tapak lindung angin pemerhatian sebaliknya dicerap. Data saiz-ketumpatan daripada plot inventori tetap di tapak lindung angin mempamerkan kesepadanan yang sangat baik dengan garis panduan penstockan yang diperoleh daripada alometri diameter batang-silara.

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Garis panduan penstockan ini dapat diguna dalam penubuhan dirian *A. koa* yang baru. Ia juga berguna untuk membangunkan regim penjarangan apabila tidak terdapat maklumat daripada kajian jarak serta penjarangan dan juga sehingga maklumat yang lebih baik diperoleh.

Introduction

Forest managers try to control the stocking level of a stand in order to make the most effective use of available growing space for individual trees. Typically, the objective is to maintain relatively high levels of stand growth while minimizing the amount of tree mortality within the stand. Quantitative models of the relationship between stand density and mean tree size provide foresters with an objective method for evaluating stocking levels and guiding decisions to alter these levels at different periods of stand development. Such stocking guidelines can be used to determine initial spacing of trees, as well as to develop sound precommercial and commercial thinning regimes. Stocking guidelines are typically developed from long-term spacing and thinning trials, from inventories of undisturbed, fully stocked, even-aged stands, or from growth and yield models. In tropical forestry, where these types of data rarely exist, alternative methods are required to develop stocking guidelines. One approach, proposed by European foresters in the early 20th century and described in detail by Dawkins (1963), employs the allometric relationship between stem and crown diameters to predict basal area and stand density for a given mean tree diameter. In recent years the crown diameter approach has been used to develop density relationships for several tropical tree species of economic importance, including *Alstonia macrophylla*, *Michelia champaca*, *Paraserianthes falcataria*, *Swietenia macrophylla* (Samarasinghe *et al.* 1995), *Hibiscus elatus* (Ashton *et al.* 1989), and *Tectona grandis* (Larson & Zaman 1985).

The primary objective of this study was to develop preliminary stocking guidelines for *Acacia koa* (koa), a native Hawaiian hardwood. *Acacia koa* is ecologically and economically important in Hawaii. It is one of two endemic tree species that dominate the native montane forests of Hawaii and it is also one of the most valuable timber species in the world. Despite its importance, little silvicultural information is available to guide foresters and other land managers who grow *A. koa*. In this paper, we evaluate data on crown width and stem diameter for *A. koa* from three studies established on the island of Hawaii during the past 16 years. The studies were established in areas of the island that differed in site quality. Thus, we were able to evaluate the effect of site quality on stocking relationships for *A. koa*. In addition, repeated measurements of crown and stem diameters at one study site (Hakalau) over a 10-year period enabled us to evaluate whether stand age influenced crown/stem relationships and the inferred stocking relationships. Finally, we used permanent inventory data from another of the study sites (Honomalino) to evaluate the accuracy of the stocking guidelines derived from the allometric relationship between crown and stem diameter.

Materials and methods

Data on crown and stem diameter were obtained from three study sites (Hakalau, Honomalino and Keauhou) on the island of Hawaii (19° 30' N, 155° 20' W; Figure 1). On oceanic islands of volcanic origin, several factors influence the productivity of a given site, including the age, nature, and depth of the rooting medium (which influences nutrient availability), the position of the site relative to the prevailing winds (which influences rainfall and light regimes), and the elevation of the site (which influence temperature and rainfall regimes). The present study combines data collected over a period of 16 years from three separate research projects. As such the dataset does not represent the full gradient of potential site qualities on Hawaii. It does, however, include sites that differ markedly in rainfall regimes, namely, the relatively dry, leeward site (Honomalino) and the moister, windward sites (Hakalau and Keauhou), as well as sites that differ in substrate age, composition, and depth, namely, a relatively young shallow ash-over-a'a soil (Keauhou) and a much older deep ash soil (Hakalau). Table 1 compares the factors influencing the productivity of each study site. Two of the *A. koa* stands (Honomalino and Keauhou) were naturally regenerated second-growth stands of almost pure even-aged *A. koa* that developed following logging; the Hakalau stand was a plantation of pure *A. koa* planted at 1.5 m spacing.

Selected *A. koa* trees from each study site were measured for stem diameter and crown width. Tree selection differed between sites. At Hakalau, all *A. koa* in the study plantation were measured, with the exception of the outer row of trees. At

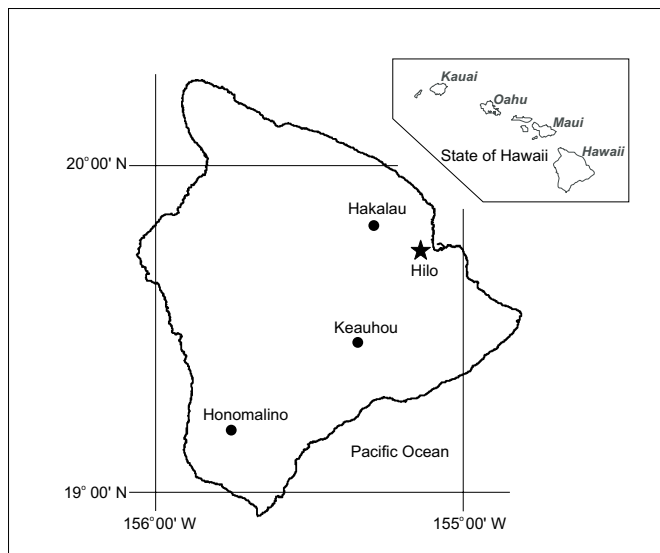


Figure 1 Map of the study sites on the island of Hawaii

Table 1 Description of study sites from the island of Hawaii

	Hakalau	Honomalino	Keauhou
Mountain	Mauna Kea	Mauna Loa	Mauna Loa
Aspect	East	West	South-east
Location	Windward	Leeward	Windward
Substrate age (year)	> 10 000	1000–3000	1000–3000
Substrate type	Deep volcanic ash	A'a lava	Shallow ash-over-a'a
Elevation (m)	1980	1450	1680
Rainfall (mm year ⁻¹)	2000	800	1800
Stand age (year)	16	27	26
Year measured	1990, 1992, 1997, 2000	2002	1992, 2002
Number of trees	563–877	25	80–85

Honomalino and Keauhou, *A. koa* were randomly selected along systematically established transects. Stem diameter was measured at breast height (dbh 1.4 m) to the nearest 0.1 cm. Mean crown width (CW) was estimated by averaging the lengths of longest axis of the horizontal projection of the crown and the axis perpendicular to the longest axis. The number of trees and range of sizes measured varied among sites and measurement periods. Repeat measurements were made at the Hakalau site (1990, 1992, 1997, 2000) and at the Keauhou site (1992, 2002).

Quantitative relationships between CW and dbh were developed using regression analysis. For each dataset (site $\times$ year), we modelled the data with linear, quadratic, and power functions. We compared the models for each dataset using a corrected Akaike Information Criterion (cAIC), which allowed comparison of models of differing functional forms (Anderson *et al.* 2000). In general, the model with the lowest cAIC score was chosen as the best model. However, we also considered differences in model mean square error, significance of model coefficients, and model performance at the extremes of the data range in making the final selection. All regressions were computed using SAS (version 8.1).

Regression equations were then used to calculate a growing space index (GSI) for a range of stem diameters at each site, where GSI is the ratio of estimated crown diameter and stem dbh. Size-density relationships were developed using the approach described by Dawkins (1963), which calculated the number of trees of a given crown size that can coexist within a unit area (e.g. 1 ha). The procedure involved, first, using the regression model for crown and stem diameters to estimate crown diameter for a given stand quadratic mean diameter, then converting crown diameter to projected crown area, assuming a circular crown. Stem density was then obtained by dividing the mean crown area into a unit area (hectares) and multiplying the result by a spacing constant, e.g. 0.9069 for triangular spacing, used in this study, or 0.7854 for square spacing (Dawkins 1963). The resultant size-density relationships were compared across sites and among years within sites.

Graphical stocking guides were developed for each study area using a modification of the procedures described by Gingrich (1967). The Gingrich stocking guide is an effective tool for quickly determining relative stocking levels in a stand and its development only requires knowledge of basal area, stand density, and quadratic mean diameter (i.e. diameter of the tree of mean basal area), which are easily obtained from a field cruise (Ernst & Knapp 1985). In this study, we used the calculated dbh-stand density relationships (described above) in place of field cruise data. We assumed that the dbh-density relationship derived from the stem-crown allometry defined the average maximum level of competition, which is the A-line or upper boundary on the Gingrich stocking guide. Gingrich (1967) showed that open-grown *Quercus* spp. fully exploit the growing space in a stand at 55–60% of the maximum stand density. However, insufficient data exist for *A. koa* stocking levels to justify identifying a specific stocking level as the minimum for a fully stocked stand. As such, we present a general *A. koa* stocking guide with the maximum stocking (100%) and 20% intervals down to 40% stocking to allow foresters to make their determinations based on experience.

Results

Regression models for crown and stem diameter relationships were significant for all sites (Figure 2, Table 2). In most cases, the quadratic and linear models had lower cAIC scores than the power functions. In those instances in which the power functions had the lowest cAIC scores, differences in cAIC scores and model mean square errors among the models were < 0.5%. Based on other considerations relating to model fit we chose the linear or quadratic model. Second-order terms in the quadratic models were significant for the first two measurements taken at the Hakalau site (1990, 1992), but not for any measurements at the other two sites. Thus, for the 1997 and 2000 measurements at Hakalau and all measurements at Honomalino and Keauhou, a simple linear regression model suitably described the relationship between CW and dbh.

The coefficients of the linear regression equations for the Honomalino site differed significantly from those for the Hakalau (1997 and 2000) and Keauhou sites (Table 2). The relationship between crown and stem diameter at Honomalino had a lower y-intercept and a steeper slope than the others (Figure 2). While the slightly negative y-intercept for the Honomalino data is biologically implausible; it has been noted by others in the past (Dawkins 1963). Since the smallest tree in the Honomalino dataset was 3 cm dbh, the most likely explanation was that the crown and stem diameter relationship was non-linear between seedling stage and saplings that were 3 cm dbh. However, for the purposes of creating stocking guidelines for *A. koa* stands, this is of minor consequence.

Dbh-dependent changes in GSI for *A. koa* stands were similar among the two study sites on the windward side of Hawaii (Figure 3). GSI was lower in the smallest size classes for *A. koa* at the Honomalino site, but by the time mean tree dbh reached 10 cm, GSI exceeded values for the other two sites. GSI approached asymptotic values by 20 cm dbh. The Honomalino site had the highest asymptotic GSI (~25) while the other sites had lower asymptotic GSI values of 15–16. The relationships

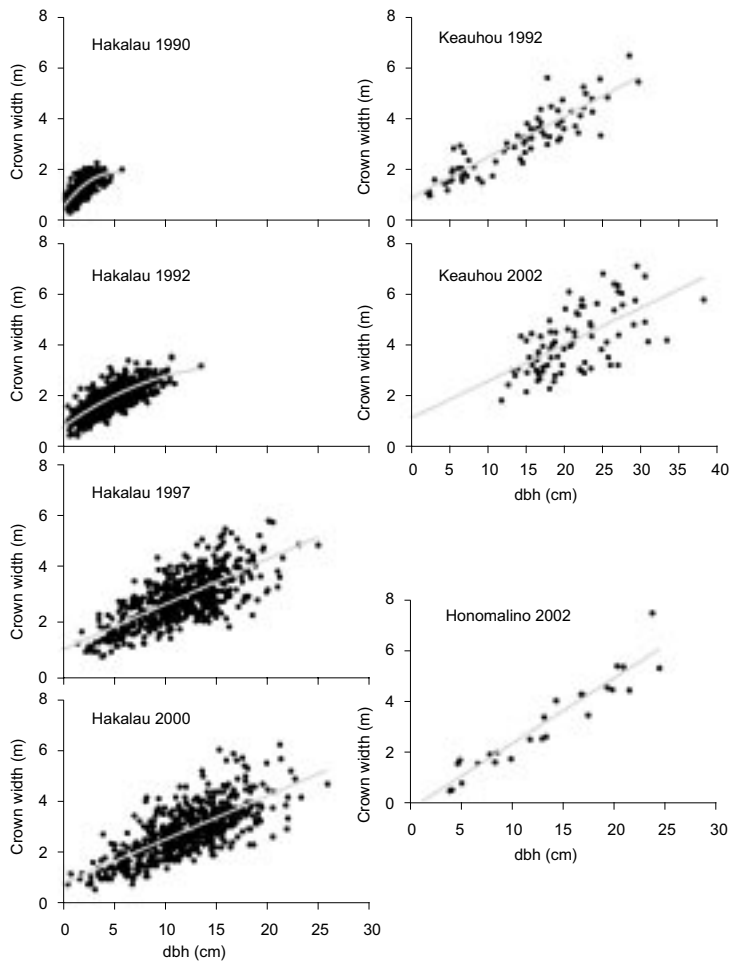


Figure 2 Plots of *Acacia koa* dbh vs. crown width at each measurement period at the three study sites in Hawaii. Grey lines are best-fit regressions for each dataset (see Table 2 for model details).

between dbh and GSI demonstrated that at Honomalino, where the GSI increased asymptotically with increasing dbh, *A. koa* required more crown canopy area as trees mature. In contrast, at Keauhou and Hakalau, where GSI decreased asymptotically with dbh, *A. koa* required relatively less crown canopy area as trees mature.

Predicted stand density for trees 20–50 cm dbh was 75–120% greater at the windward sites than at the leeward site based on the data from the most recent measurement dates (Figure 4). For example, a stand with a mean dbh of 50 cm at the Hakalau and Keauhou sites would be expected to have a maximum density of 145 and 162 trees ha⁻¹ respectively, whereas the Honomalino site would be expected to have only 79 trees ha⁻¹ (Figure 4 inset). However, this required extrapolating the

Table 2 Summary of regression statistics and equations predicting crown width (CW) from diameter at breast height (dbh; both in units of meters) for *Acacia koa*. All datasets were fitted to a linear [CW = $a + b(\text{dbh})$] or quadratic model [CW = $a + b(\text{dbh}) + c(\text{dbh}^2)$]. Standard errors of the estimated parameters are in parentheses. For the linear regression models, regression coefficients were compared among sites and years; coefficients with different letters were significantly different ($p < 0.05$)

Study site	Year	Regression coefficients			df	R ²	P > F
		<i>a</i>	<i>b</i>	<i>c</i>			
Hakalau	1990	0.51(0.027)	50.2 (3.12)	-486.87 (79.40)	884	0.55	< 0.001
	1992	0.80 (0.062)	27.56 (2.43)	-83.31 (22.14)	574	0.60	< 0.001
	1997	1.04 ^a (0.084)	16.89 ^a (0.69)	–	562	0.51	< 0.001
	2000	0.70 ^a (0.081)	16.44 ^a (0.63)	–	572	0.53	< 0.001
Honomalino	2002	-0.23 ^b (0.237)	24.59 ^b (1.61)	–	24	0.90	< 0.001
Keauhou	1992	0.78 ^a (0.124)	15.34 ^a (0.81)	–	83	0.82	< 0.001
	2002	1.10 ^a (0.418)	13.80 ^a (1.90)	–	77	0.39	< 0.001

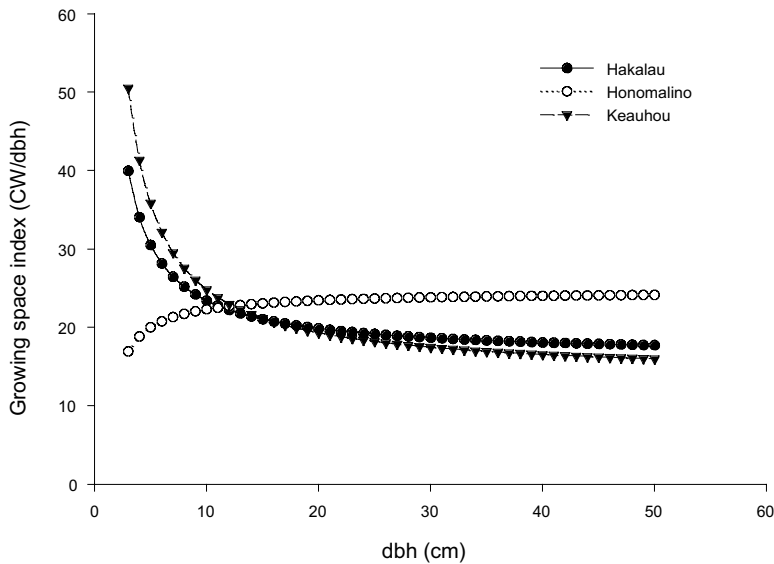


Figure 3 The growing space index (GSI) as a function of dbh for *Acacia koa* at three sites on the island of Hawaii. GSI is the ratio of crown width (CW) to mean stem diameter (dbh), both measured in meters, although in the figure dbh is scaled to cm for consistency with the other figures.

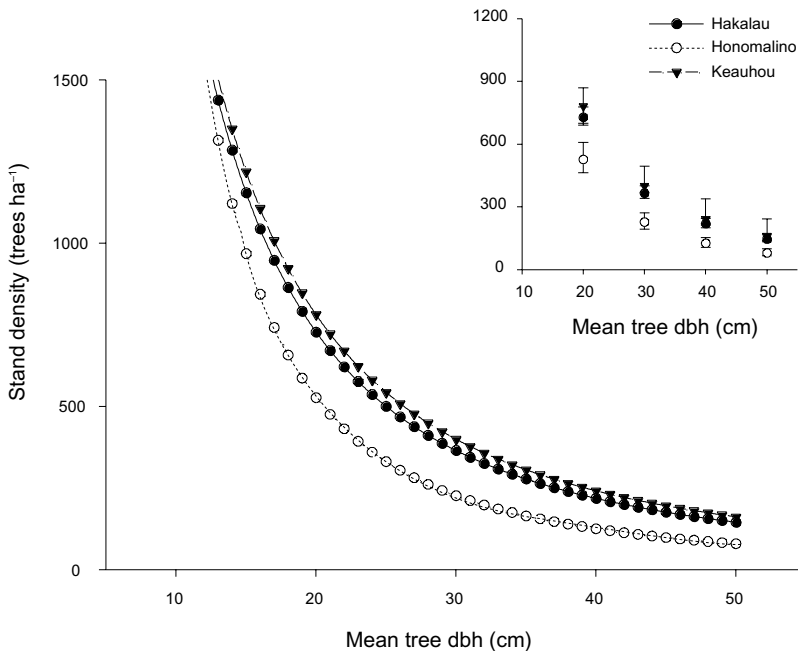


Figure 4 Size-density relationships for *Acacia koa* at three sites on the island of Hawaii based on crown-stem diameter regressions obtained from the most recent measurement at each site. The inset graph shows 95% confidence intervals for stand density estimates for mean tree dbh values of 20, 30, 40 and 50 cm.

data beyond the range of bole diameters that we used in our regression analyses. As such the analyses should be considered with the caveat that the relationship between crown diameter and stem diameter may change for larger trees than we sampled. However, other studies suggested that this only occurred where the crown-stem diameter relationship was non-linear (e.g. sigmoidal, quadratic). For *A. koa* there was no indication that the nature of the crown-stem diameter relationships changed in form over the extrapolated range of data (35–50 cm dbh). However, it would not be possible to extrapolate the quadratic models for the 1990 and 1992 data from Hakalau beyond the data range on which they were based.

Data were available for comparison of crown-stem diameter relationships at different times within the same site at the two windward sites. At the Keauhou site, measurements made in 1992 and 2002 showed no significant differences between the crown-stem diameter models (Table 2). At Hakalau, where four measurements were made between 1990 and 2000, the models differed significantly between years. The first two measurements (1990 and 1992) were best fit by a truncated quadratic model, implying that the stem-crown diameter relationship was becoming

asymptotic. The significance of the quadratic term was greatest in 1990, but with each subsequent measurement, the values decreased, becoming non-significant (i.e. not significantly different from zero) by the 1997 measurement. Differences in the regression models between years could potentially alter the derived stocking guidelines for a site. At Hakalau, despite differences in the coefficients and form of the best-fit regression models, the crown-stem diameter models for the first three measurements closely overlapped. The largest difference was between the regression models from the 1997 and 2000 measurements. While both models had similar slopes, the y-intercept of the 2000 model was lower (although not significantly) than that of the 1997 model, implying that diameter growth had continued while crown expansion had slowed or stopped. When converted to size-density relationships, the crown-stem diameter model for the 1997 data predicted higher tree densities for a given mean tree diameter (Figure 5).

To assess the utility of our approach for developing stocking guidelines, we compared the size-density relationships derived from the crown-stem diameter relationships with actual inventory data taken from a network of permanent plots at the Honomalino study site. The plots, each approximately 0.04 ha in area, were established in 1999 on a systematic grid across the 2000 ha Honomalino property.

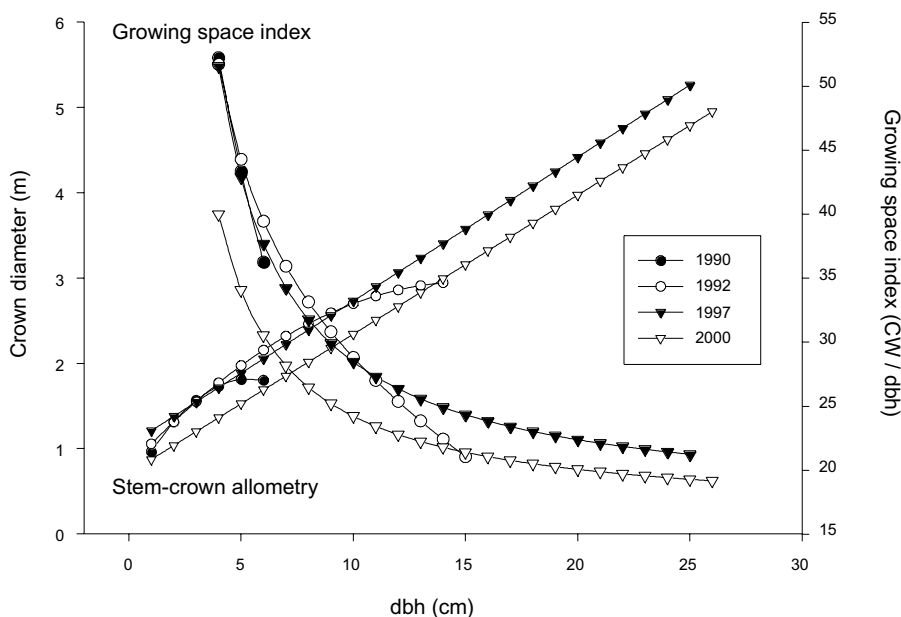


Figure 5 Crown-stem diameter relationships and growing space index (GSI values) for *Acacia koa* from different measurement periods at Hakalau Forest National Wildlife Refuge, windward Hawaii

Of the 135 inventory plots at Honomalino, 51 included one or more *A. koa*. We did not attempt to quantitatively assess the relationship between the predicted maximum stocking levels and the actual stem densities in the inventory plots because the relative abundance of *A. koa* varied among the inventory plots. Instead, we graphically assessed the dbh-density data for the inventory plots against our stocking guideline for Honomalino. We observed excellent correspondence between predicted relationship and empirical data (Figure 6). The inventory plots with the highest stocking levels approached, but never exceeded, the maximum attainable stand density derived from the allometric relationship between crown and stem diameters.

The *A. koa* stocking guide for the Honomalino site (Figure 7a) showed that the range of basal area for fully stocked stands was relatively narrow, approximately $7 \text{ m}^2 \text{ ha}^{-1}$, and that there was little variation in stand basal area across a wide range of mean tree diameters. In contrast, the stocking guide for the wetter windward sites (Figure 7b) indicated a wider range of basal areas for fully stocked stands ($\sim 7\text{--}11 \text{ m}^2 \text{ ha}^{-1}$) and a pronounced increase in stand basal area with increasing mean tree diameter. In both sites the range of stand densities of fully stocked stands was negatively correlated with mean tree diameter; that is, stands with small trees can be fully stocked across a wider range of densities than stands with large trees.

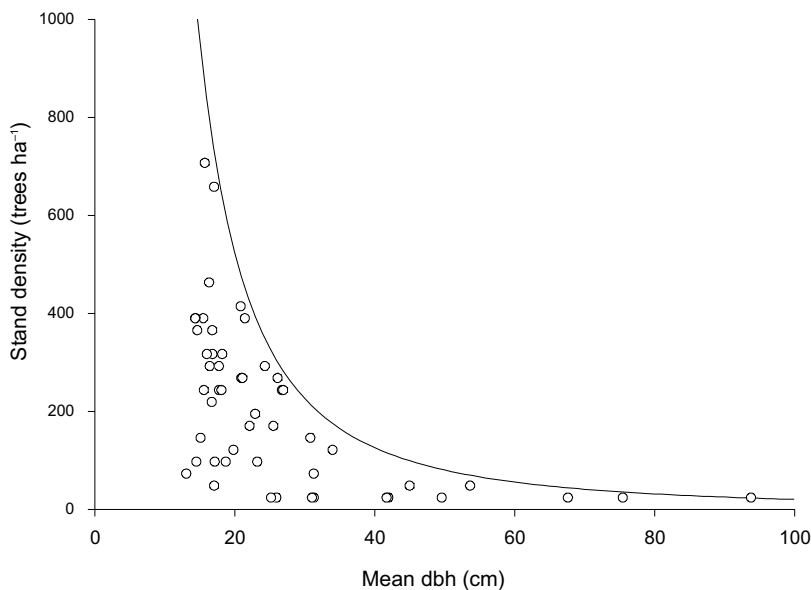


Figure 6 Comparison of maximum density level derived from crown-stem allometry of *Acacia koa* with size-density data from 51 permanent inventory plots in mixed species stands from the Honomalino study site

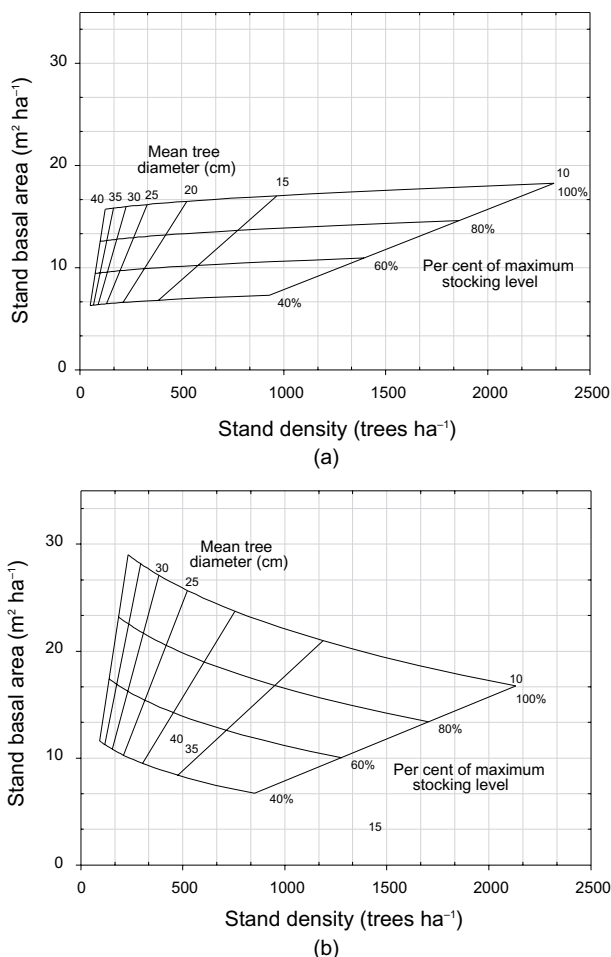


Figure 7 Stocking guide for *Acacia koa* on (a) leeward and (b) windward Hawaii. The upper line of each graph represents the level of average maximum competition (i.e. 100% stocking) based on the size-density relationship derived from the crown-stem diameter regressions. Lower lines are 20% increments of the maximum stocking level.

In addition, the *A. koa* stocking guides showed that as mean tree diameter increased, windward areas could support considerably more basal area per unit area than the leeward area.

Discussion

Growing space index (GSI) provides a relative measure of how efficiently a tree uses growing space, which in this study is defined as the projected crown area of a tree. Trees with low GSI values have smaller crowns for a given dbh than trees of the same diameter with higher GSI values. For most species, GSI changes with

increasing tree size, reflecting underlying changes in allocation patterns and tree architecture with growth. Better understanding of these patterns and the factors that influence them can enable forester managers to grow specific forest products more efficiently by maximizing the use of available growing space. GSI values of *A. koa* in this study are consistent with the range of GSI values published in other studies using similar methodologies (e.g. Dawkins 1963, Ashton *et al.* 1989, Samarasinghe *et al.* 1995; asymptotic GSI values of 13–25). However, GSI trends for *A. koa* differed not only over the range of stem diameters sampled within stands but also between study sites and, in some cases, between measurement periods within a study site.

Changes in GSI across the range of tree size reflected shifts in resource allocation and tree architecture associated with tree growth (Figure 3). For crown-stem diameter data, best fit by linear regression models, the magnitude and direction of this change is controlled by the intercept term of the model. When the intercept is zero (Dawkins' Type 1 model), GSI is constant for all stem diameters. When the intercept is positive (Dawkins' Type 2 model), GSI decreases with increasing tree size. When the intercept is negative (Dawkins' Type 3 model), GSI increases with increasing tree size. In this study, the Hakalau and Keauhou sites conformed to the Type 2 model and the Honomalino site conformed to the Type 3 model, although the intercept term for the Honomalino data was not significantly different from zero, indicating that the change in GSI with increasing tree size should be relatively minor.

GSI values may also differ among sites, possibly due to site-mediated differences in resource-use and biomass allocation. In general, as trees increase in size, GSI values become asymptotic. Inter-site comparisons of these asymptotic values can provide a relative indication of site quality, with good sites having lower asymptotic GSI values than poor sites. For *A. koa* the asymptotic value of GSI was highest at the leeward site at Honomalino (Figure 3). The two windward sites, Hakalau and Keauhou, had nearly identical asymptotic GSI values, both of which were significantly less than at Honomalino. The higher asymptotic GSI values at Honomalino indicated that *A. koa* required a larger crown area for a given stem diameter or, for a given crown size, individuals at Honomalino had smaller stem diameters than at Hakalau and Keauhou.

The observed differences in asymptotic GSI values between the leeward and windward sites may be a consequence of differential allocation of photosynthate to above- versus belowground biomass. As on most tropical oceanic islands, the local climate of Hawaii is strongly influenced by the rain shadow effect, which substantially lowers the annual precipitation levels on the leeward side of the island. Previous studies have demonstrated that the productive capacity of *A. koa* is strongly influenced by water availability (Harrington *et al.* 1995, Ares & Fownes 1999). We suspect that on the drier leeward site, which is also characterized by a porous substrate with small rooting volume, *A. koa* allocates a greater proportion of photosynthate to root biomass to maximize water and nutrient uptake than on wetter sites on the windward side of the island. These different allocation patterns

should become increasingly apparent as tree size and demand on belowground resources increases, resulting in changes in GSI with increasing dbh that are consistent with our observations (Figure 3).

The effects of stand age on the crown-stem diameter relationship within a site were mixed. Repeated measurements at the Keauhou site showed only minor, non-significant differences in the regression models (Table 2) and the GSI curves calculated from them (Figure 5). At the Hakalau site, the first three measurements closely overlapped, despite differences in the functional form of the regression models. However, these models differed somewhat from the 2000 data. Although the regression coefficients for the 1997 and 2000 linear models were not significantly different, the model for the 2000 measurement was shifted to the right of the other models. This suggested that while dbh growth continued between 1997 and 2000, crown expansion of *A. koa* stopped or slowed. The difference between the 1997 and 2000 regression models also affected the predicted size-density relationships: the 1997 model predicted slightly higher tree densities for a given mean stand diameter than the 2000 model (Figure 5).

Previous studies in temperate and tropical forests have shown that in many cases stocking relationships are insensitive to site conditions. For example, Dawkins (1963) concluded that the ratio of crown to stem diameter was constant for a given species across a range of sites and tree ages. The author presented data for *Triplochiton*, *Maesopsis*, and *Aucomea* collected from various sites in Central and West Africa to demonstrate this pattern. Similarly, Krajicek *et al.* (1961) and Gingrich (1967) suggested that the amount of space used by a tree of a given size was independent of site quality for upland oak-hardwood forests in the eastern United States, although they sampled across a relatively narrow range of site quality. In contrast, other studies have shown that site quality influences the allometric relationship between stem diameter and crown diameter and, therefore, the size-density relationships. For example, Rajkhowa (1970) found that for *Tectona grandis* in India the linear model for the stem diameter/crown diameter allometry had a positive intercept on high quality sites and a negative intercept on poor quality sites. Larson and Zaman (1985) conducted their study of *T. grandis* on poor sites where the stem-crown allometry had a negative intercept as well. Our results also suggested that site quality may influence the relationship between crown and stem diameters of *A. koa*. However, in our study inter-site differences were associated with major differences in climatic regime and may be more equivalent to regional differences in continental situations.

The stocking guidelines developed in this study are of immediate practical importance. Most secondary stands of *A. koa* in Hawaii are overstocked at the time of establishment. Scarification of the soil by bulldozer or fire can lead to massive recruitment of *A. koa* seedlings (10 000–100 000+ seedlings ha⁻¹) and the development of severely overstocked stands. Such dense stands are characterized by high mortality and poor growth and require costly pre-commercial thinning. The stocking relationships can be used by foresters to determine a target stand density for a future mean stand dbh. Other criteria, such as available economic and labour resources and the impact on associated fauna and flora, can then be

incorporated to determine the timing, frequency, and intensity of thinnings required to meet target stand densities. Silvicultural prescriptions must account for the dbh-dependent nature of GSI values for *A. koa* because the amount of canopy space an individual needs changes over time and varies among sites. For instance, on the windward side of Hawaii *A. koa* used canopy space more efficiently as dbh increased (Figure 3), implying that thinning should be heavier (or more frequent) during the early stages of development. In contrast, *A. koa* on the leeward side of Hawaii showed the opposite pattern, suggesting that thinnings should be heavier later in stand development as trees became less efficient in their use of canopy space.

Major differences in site quality occur across small spatial scales in Hawaii as a consequence of steep topography and a mosaic of substrate (lava flow) ages (Aplet *et al.* 1998). While the stocking relationships developed for *A. koa* from the crown-stem diameter allometries provided a good fit for the permanent inventory plot data for the Honomalino site (Figure 4), they should be considered provisional guidelines to be used with good silvicultural judgement. As more silvicultural data become available and foresters and conservationists gain greater experience in managing *A. koa*, these stocking guidelines should be evaluated and updated to ensure that land managers have the best available information for restoring and managing Hawaii's native forests.

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