

Growth and Yield in *Eucalyptus globulus*¹

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Various species of *Eucalyptus* have been of interest in California since their introduction in 1860 (Metcalf, 1924), with *Eucalyptus globulus* (Blue Gum) being the most widely planted. While its wood has limited use as lumber, its rapid growth has caused it to be favored as windbreaks and ornamentals. The recent increase in demand for firewood and a growing market for hardwood fiber has caused renewed interest in planting eucalyptus.

The purpose of this article is to present a model for growth of *Eucalyptus globulus* and to use this model to generate variable site-density yield tables. These yield tables are then used to determine optimum stocking levels and rotation length under various site conditions. This model deals solely with biological growth and does not consider economic implications of stand establishment and management.

The models derived represent unmanaged stands only. Certain management practices increase site quality and some means of assessing this increase must be applied in order for the models to be meaningful under intensive management conditions.

Within this article, the following topics are discussed:

- The source, limitations, and adjustments made to the data used to generate the model.
- A description of the model itself and how it

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Abstract: A study of the major *Eucalyptus globulus* stands throughout California conducted by Woodbridge Metcalf in 1924 provides a complete and accurate data set for generating variable site-density yield models. Two models were developed using linear regression techniques. Model I depicts a linear relationship between age and yield best used for stands between five and fifteen years old. Model II depicts a sigmoidal relationship between age and yield with slightly poorer statistical fit but greater reliability beyond fifteen years of age. Significant independent variables used in Model I are: initial plantation density; site index; and an interaction variable consisting of age x site index. Significant independent variables in Model II are: natural log of initial plantation density; site index; and inverse age. Variable site and density yield tables are developed from Model II for stands under minimal management. Culmination of mean annual increment occurs at age ten under all conditions. Assuming a goal of maximization of mean annual increment of merchantable cordwood, planting densities of 435, 680 and 1210 trees per acre are recommended for low, medium, and high sites respectively.

is used to generate variable site-density yield tables.

- Conclusions drawn from analysis of the yield tables.
- Suggestions for further analysis and research.

THE DATA

The data used in this analysis was gathered by Louis Margolin in 1910 (Margolin, 1910) and by Woodbridge Metcalf in 1924 (Metcalf, 1924) in their studies of the major Blue Gum stands in California. As described in his article, in order to generate site and yield functions, Metcalf used data collected in these two studies, which included a total of 96 stands. This data was adjusted to result in the data set used in the current analysis.

The Metcalf and Margolin Data

Location of Stands

Stands were located in 19 counties throughout California, from Arcata in Humboldt County to Escondido in San Diego County, representing a wide variety of soil and climatic conditions.

Information Collected

Information collected for each stand includes the following:

- Stand age
- Initial plantation density in trees per acre
- Surviving trees per acre

- Average diameter, height, and volume of surviving trees
- Volume per acre in cubic feet and cords
- Soil and water characteristics

Also, in order to develop a measure of site quality, height was measured on the tallest 10 percent of trees in most of the stands.

Methods of Collection

Selection of Plots--In the data collected by Metcalf, "one or more of the rows running through representative portions of the stand" were selected for measurement. The method of row selection was not described and therefore randomness of the sampling procedure is not assumed.

In the Margolin data, sample areas were ¼-acre plots within the interior of each grove. Usually only one such plot was taken per stand and these were selected to show average conditions. This method of plot selection is not random and could result in bias toward higher yield.

Surviving Trees Per Acre--Metcalf states that "each surviving tree" was measured, as well as blank spaces and "scrubby trees." A scrubby tree is not defined and no lower diameter limit is given for surviving trees. In assessing trees per acre at time of measurement, one must assume that none of the "scrubby" trees are survivors of the original plantation.

In the Margolin study, all trees with dbh of 1½ inches or more were measured. As with the Metcalf data, one must assume that trees less than 1½ inches dbh were not counted as survivors of the original plantation.

Average Diameter of Surviving Trees--In the Metcalf data, since "scrubby" trees are assumed not to be survivors, it must also be assumed that the distribution of diameters of surviving trees has some lower diameter limit. Since we do not know what this limit is, it is difficult to assess the amount of variation around the average diameter. Diameters measured by Margolin, however, were recorded by 1-inch diameter class, giving a diameter distribution, or stand table, for each stand sampled.

Height of Surviving Trees--Total heights, including stump and top were measured for as many trees as possible. A height-diameter curve was derived in order to estimate heights on trees not measured.

Calculation of Volume--Volumes were calculated using the following formula:

$$V = BA \times H \times ff \times TPA$$

where: V = Volume in cubic feet per acre
BA = Basal area in square feet of the

average single tree.
(BA = [Average Diameter/24]²)

H = Total height of the average single tree
ff = Form factor relating stem volume to (BA x H). Stem volume is from the top of a one-foot stump to a minimum diameter of two inches at the top.

TPA = Number of surviving trees per acre at time of measurement

Site Classification

In order to develop a height-age relationship as a measure of site quality, Metcalf measured the tallest 10% of the trees sampled and plotted heights of these dominant trees against age. Groves in which overcrowding was thought to have interfered with height growth were not included. In all, Metcalf included 45 of the Metcalf groves and 26 of the Margolin groves in his site classification.

An average age-height curve was drawn through the data and harmonized curves were drawn to intersect with maximum and minimum values. The area between the maximum and minimum curves was then divided into three zones, labeled Site I, II, and III. Figure 1 represents the Metcalf site classification curves.

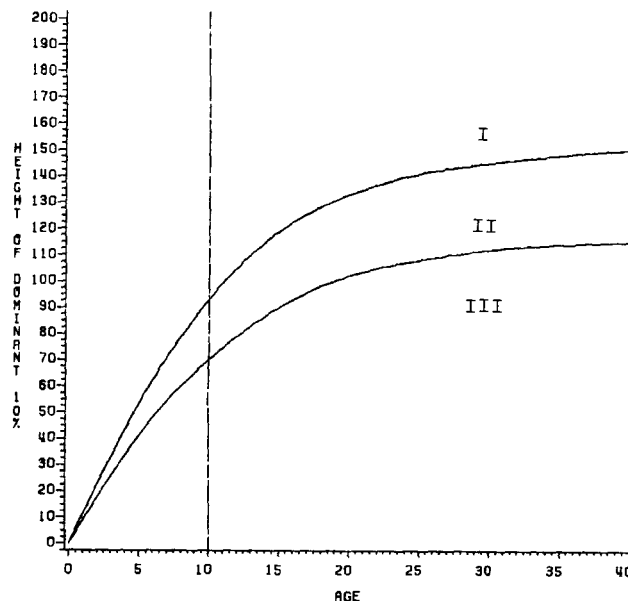


Figure 1 -- Metcalf Site Classifications

The Current Data Set

Adjustments

The following adjustments were made in the above data to result in the data set used in the analysis.

Elimination of Observations--Only those stands for which the height of dominant trees was recorded are included, thus eliminating 20 of the stands. An additional stand was eliminated because it had been thinned.

Addition of Observations--Eight of the Metcalf stands were measured twice at different points in time. Metcalf used only the first measurement in his estimation of site. The current data set includes the eight remeasurements, with the assumption that site remains constant over time. A total of 78 stands are included in the current data set.

Volume Estimation--The method used by Margolin to estimate volume was not specified other than by reference to volume tables. In order to merge the two data sets, volumes for Margolin stands were recalculated using the formula noted above.

Developing a Site Index Measurement

Metcalf's site quality measure resulted in site ratings of I, II, or III. In order to be consistent with other yield studies for Eucalyptus globulus, a site index was developed from Metcalf's age-height curves in figure 1, using a base age of 10. The following table represents the relation between Metcalf's site class and the site index derived from it.

Table 1 -- Site Class-Site Index Relationship

Site Class	Site Index (Height of Dominants at 10 Years)
I	Greater than 93
II	65 to 93
III	Less than 65

Site indices for the stands in the data set ranged from a low of 41 to a high of 118.

The method used was to locate age and height of dominants for a given stand on figure 1 and then to follow a harmonized curve through that point to its intersection with the base age 10 reference line. For instance, a dominant height of 126 feet at age 25 would equate to a site index of 82. In this way, figure 1 can be used to determine site index for any stand where age and height of dominants are known.

Range of Ages

The ages of stands in the current data set ranged from 2 to 40 years. Only 12 (15.4 percent) of the stands were in excess of 15 years of age. Models derived from this data show best fit in younger age classes and caution must be used in estimating volume in age classes between 15 and

40. Models should not be used for extrapolation beyond age 40. This limitation is not significant for commercially-grown stands since harvest is likely to occur prior to age 15.

ANALYSIS

Analytical Systems Used

Linear regression analysis was performed using the Statistical Analysis System -- General Linear Model (SAS-GLM) program package.

Yield Models

The analysis yields two production models with statistically significant fit. The first gives a linear plot of predicted yield against age. The second gives a plot of predicted yield against age which more closely approximates a sigmoidal biological production function which one might anticipate. Figure 2 depicts these models for a given site and initial plantation density. Both models can be used, given certain constraints, as explained below.

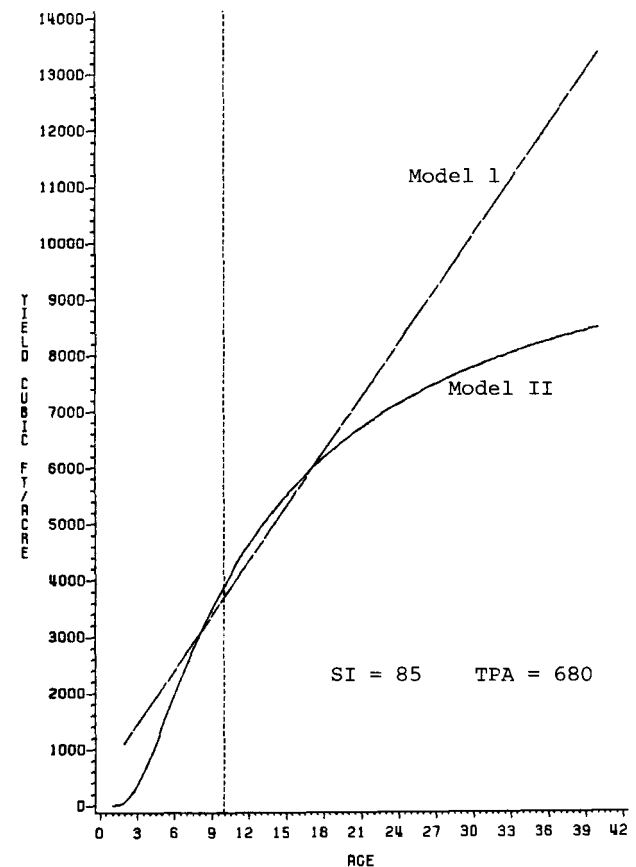


Figure 2 -- Model I and Model II Yields

Model I

Model Form--Model I takes the form of:

$$Y = -3177.17 + 1.70(TPA1) + 29.47(SI) + 3.77(AGSI)$$

where: Y = Yield in cubic feet per acre
 TPA1 = Initial plantation density in trees per acre
 SI = Site index in feet at age 10
 AGSI = Age x site index

Analysis of Variance--Table 2 presents the analysis of variance for Model I.

Table 2-- ANOVA - Model I

Source of Variation	DF	Sum of Squares	T	F	R ²	C.V
Intercept			-4.28			
TPA1	1	3.19 x 10 ⁷	3.07			
SI	1	30.15 x 10 ⁷	2.95			
AGSI	1	53.34 x 10 ⁷	18.95			
Residuals	74	11.04 x 10 ⁷				
Total	77	97.72 x 10 ⁷		193.7	.887	34.6

Note the high correlation coefficient (R²) of .887 and the coefficient of variation (C.V) of 34.6.

Discussion -- Because site index appeared to have a greater effect on yield with increasing age, an interaction variable consisting of Age x Site was anticipated. As indicated by its high T value relative to other variables, AGSI is the most significant independent variable. This is logically sound since, with a given initial plantation density, site quality will have a strong effect on rate of growth while total volume will vary most directly with age.

While this model gives a good prediction of volume within the range of most of the data, it does not give an intuitive depiction of growth, as shown by figure 2. The linear relationship between age and yield results from the fact that 80 percent of the data falls between the ages of 5 and 15, the linear range of the anticipated sigmoidal function. This data so weights the model in this form that statistical significance is high even though the model is linear.

Model II

Model Form--Model II takes the form of:

$$\ln Y = 4.86449 + .02547(SI) + .34896 (\ln TPA2) - 10.41628(I/A)$$

where: lnY = The natural log of yield in cubic feet per acre
 SI = Site index in feet at age 10
 lnTPAI = The natural log of initial stocking density in trees per acre
 I/A = Inverse age

Analysis of Variance--Table 3 presents the analysis of variance for Model II.

Table 3--ANOVA - Model II

Source of Variation	DF	Sum of Squares	T	F	R ²	C.V.
Intercept			5.80			
SI	1	27.11	8.52			
lnTPA1	1	1.34	2.75			
1/A	1	42.38	-15.81			
Residuals	74	12.54				
Total	77	83.37		139.3	.850	5.3

Note that while the statistics for Model I are slightly better than those for Model II, the differences are relatively minor. The lower C.V. for Model II is a result of the dependent variable being a logarithm. Exponentiating results in a coefficient of variation similar to that of model I.

Discussion--Schumacher (1939) and Clutter (1963) suggested methods of generating linear models to express nonlinear production functions by transforming dependent and independent variables into natural logarithms. Model II is essentially the Clutter model using lnTPA1 rather than Clutter's ln of Basal Area.

As shown in figure 2, when lnY is transformed back to cubic foot yield and plotted against age, the result is close to the expected sigmoidal curve. Since the Clutter-based model gives nearly as good a fit as Model I with greater confidence when using the model for stands older than 15 years, this model was used to generate subsequent yield tables.

Variable Site-Density Yield Tables

In generating yield tables under varying site and initial stocking conditions, one will wish to know average diameter of the stand as a measure of merchantability, as well as total yield. A diameter of two inches is generally considered to be the lower merchantable limit for cordwood and the diameter distributions shown in the Margolin data indicate that for an ASD of six inches, virtually all trees in the stand will be in excess of two inches dbh. The expression for average diameter of the stand is:

$$AD = \sqrt{\frac{BA}{TPA2 \times .00545}}$$

where: AD = Average diameter of the stand in inches
 BA = Basal area per acre in square feet
 TPA2 = Surviving trees per acre

In order to predict AD, then, it is necessary to construct models for basal area and surviving trees.

Basal Area Model

Because basal area is also a measure of production, it is logical that BA could be predicted by the same independent variables as cubic foot yield. The following model results:

$$\ln BA = 2.07854 + 0.496(SI) + .33354(\ln TPA1) - 6.55518(I/A)$$

where: lnBA = Natural log of basal area per acre
 SI = Site index in feet at age 10
 TPA1 = Initial stocking in trees per acre
 I/A = Inverse age

The correlation coefficient for this model is .79. Affective coefficient of variation is about 40.0.

Surviving Trees Per Acre

The only significant predictor of surviving trees per acre is initial stocking density, which gives the following model:

$$TPA2 = 183.69 + .56 TPA1$$

where: TPA2 = Surviving trees per acre
 TPA1 = Initial stocking in trees per acre

While R² for this model is only .54, it is acceptable since it is used only to calculate a rough estimate of the average diameter of the stand.

Final Yield Tables

The final yield tables were generated by combining the three models derived above and iterating through variations in site index, initial

stocking, and age. Tables 4a-c are representative tables for SI = 60, 85, and 105 and initial stocking of 680 trees per acre.

Variable Site Yield Functions

By plotting yield against age for a given stocking level under varying site conditions, one may see graphically how yield varies with site. Figure 3 represents yield with initial plantation density of 680 under three site conditions.

DISCUSSION

Refer to table 4 and figure 3 for the following discussion.

Explanation and Interpretation of Yield Tables

Surviving Trees Per Acre (TPA2)

Note that TPA2 varies only with TPA1 and that mortality occurs immediately. This indicates that survival is linked with establishment and that once established, the stand remains stable over time.

When initial stocking is 300 trees per acre, TPA2 exceeds TPA1. This may be loosely explained by sprouting on under-utilized sites, though this explanation is somewhat weak. As noted earlier, the mortality issue is clouded by problems in interpreting the data as well as by ingrowth from sprouts and volunteers. TPA2 is a rough estimate of survival.

Table 4a--Yield Table (SI = 60, TPA1 = 680)

SITE INDEX = 60			TREES/ACRE: Initial = 680; Surviving = 519					
Age (years)	Average Diameter (inches)	Basal ea (Ft ² /Ac)	Yield		Mean Annual Incr.		Current Annual Incr.	
			Ft ³ /Ac	Cds/Ac	Ft ³ /Ac/Yr	Cds/Ac/Yr	Ft ³ /Ac/Yr	Cds/Ac/Yr
2	1.5	6.5	31.8	.4	15.9	.2		
4	3.4	33.5	430.3	4.8	107.6	1.2	199.3	2.2
6	4.5	57.9	1025.1	11.4	170.9	1.9	297.4	3.3
8	5.2	76.1	1582.2	17.6	197.8	2.2	278.5	3.1
10	5.6	89.7	2052.9	22.8	205.3	2.3	235.3	2.6
12	5.9	100.0	2442.1	27.1	203.5	2.3	194.6	2.2
14	6.2	108.1	2764.5	30.7	197.5	2.2	161.2	1.8
16	6.4	114.6	3033.9	33.7	189.6	2.1	134.7	1.5
18	6.5	120.0	3261.5	36.2	181.2	2.0	113.8	1.3
20	6.6	124.4	3455.8	38.4	172.8	1.9	97.2	1.1
25	6.9	132.9	3835.2	42.6	153.4	1.7	75.9	.8
30	7.0	138.8	4111.0	45.7	137.0	1.5	55.2	.6
35	7.1	143.2	4320.1	48.0	123.4	1.4	41.8	.5
40	7.2	146.6	4483.8	49.8	112.1	1.2	32.7	.4

Table 4b--Yield Table (SI = 85, TPA1 = 680)

SITE INDEX = 85			TREES/ACRE: Initial = 680; Surviving = 519					
Age (years)	Average Diameter (inches)	Basal Area Ft ² /AC	Yield		Mean Annual Incr.		Current Annual Incr.	
			Ft ³ /Ac	Cds/Ac	Ft ³ /Ac/Yr	Cds/Ac/Yr	Ft ³ /Ac/Yr	Cds/Ac/Yr
2	1.8	9.5	60.2	.7	30.1	.3		
4	4.1	48.8	813.5	9.0	203.4	2.3	376.6	4.2
6	5.5	84.2	1937.9	21.5	323.0	3.6	562.2	6.2
8	6.3	110.6	2990.9	33.2	373.9	4.2	526.5	5.9
10	6.8	130.3	3880.6	43.1	388.1	4.3	444.8	4.9
12	7.2	145.4	4616.3	51.3	384.7	4.3	367.9	4.1
14	7.5	157.2	5225.8	58.1	373.3	4.1	304.7	3.4
16	7.7	166.6	5735.1	63.7	358.4	4.0	254.7	2.8
18	7.8	174.4	6165.3	68.5	342.5	3.8	215.1	2.4
20	8.0	180.9	6532.6	72.6	326.6	3.6	183.7	2.0
25	8.3	193.1	7249.8	80.6	290.0	3.2	143.4	1.6
30	8.4	201.7	7771.1	86.3	259.0	2.9	104.2	1.2
35	8.6	208.1	8166.3	90.7	233.3	2.6	79.0	.9
40	8.7	213.1	8475.8	94.2	211.9	2.4	62.0	.7

Table 4c--Yield Table (SI = 105, TPA2 = 680)

SITE INDEX = 105			TREES/ACRE: Initial = 680; Surviving = 519					
Age (years)	Average Diameter (inches)	Basal Yea (Ft/AC)	Yield		Mean Annual Incr.		Current Annual Incr.	
			Ft ³ /Ac	Cds/Ac	Ft ³ /Ac/Yr	Cds/Ac/Yr	Ft ³ /Ac/Yr	Cds/Ac/Yr
2	2.1	12.8	100.1	1.1	50.1	.6		
4	4.8	65.8	1353.9	15.0	338.5	3.8	626.9	7.0
6	6.3	113.5	3225.1	35.8	537.5	6.0	935.6	10.4
8	7.3	149.2	4977.8	55.3	622.2	6.9	876.3	9.7
10	7.9	175.8	6458.5	71.8	645.8	7.2	740.3	8.2
12	8.3	196.1	7682.9	85.4	640.2	7.1	612.2	6.8
14	8.7	212.0	8697.2	96.6	621.2	6.9	507.1	5.6
16	8.9	224.8	9544.9	106.1	596.6	6.6	423.8	4.7
18	9.1	235.2	10260.9	114.0	570.1	6.3	358.0	4.0
20	9.3	243.9	10872.2	120.8	543.6	6.0	305.6	3.4
25	9.6	260.5	12065.8	134.1	482.6	5.4	238.6	2.7
30	9.8	272.1	12933.4	143.7	431.1	4.8	173.6	1.9
35	10.0	280.7	13591.1	151.0	388.3	4.3	131.6	1.5
40	10.1	287.4	14106.2	156.7	352.7	3.9	103.0	1.1

Average Diameter of the Stand (AD)

This variable behaves as one might expect, increasing with age and site index, but decreasing as initial plantation density increases.

Yield (YFT3)

Gives volume at various ages.

Cords

Gives volume in cords where:

$$\text{CORDS} = \text{YFT3}/90$$

Mean Annual Increment (MAIFT3 and MAICD)

Gives mean annual increment in cubic feet and cords per acre per year, where:

$$\text{MAI} = \text{Yield}/\text{Age}$$

Note that for all variations of site and initial stocking, MAI culminates at age 10. Thus, for maximum biomass production, given the two-inch merchantability standard for volume determination, harvest will occur at about age 10.

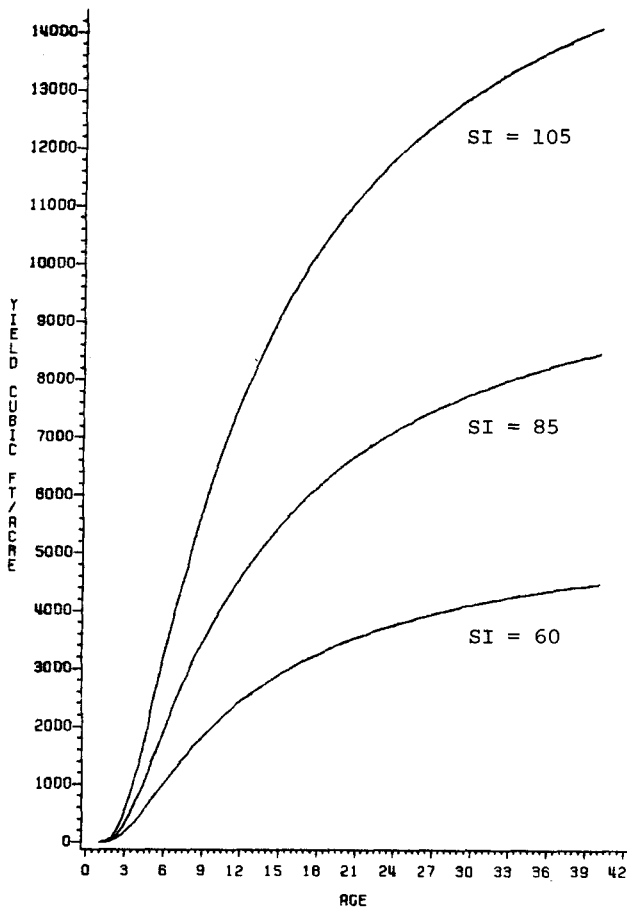


Figure 3--Yield-Age Relationships Varying Site Index (TPA1 = 680)

Current Annual Increment (CAIFT3 and CAICD)

Gives current year's growth in cubic feet and cords. Note that CAI culminates at age 6, somewhat before MAI, as one would anticipate. Note also that at culmination of MAI, MAI approximately equals CAI, again as one would expect.

Recommended Planting Densities

Assuming a goal of maximum merchantable cordwood, the yield tables generated from the models in this analysis can be used to determine optimal spacing for any given site. Optimal spacing will be that which yields highest. MAI at age 10 with minimum ASD of 6 inches. Table 5 represents recommended planting density to achieve this goal for a range of site indices.

NEEDS FOR FURTHER RESEARCH

Site Quality - Soil Correlation

The above analysis assumes that a 10-year site index for Eucalyptus globulus is known at time of planting. If Blue Gum has not been grown before

Table 5 -- Recommended Planting Densities for Maximum Merchantable Cordwood

Site Index	Recommended Planting Density
55	300 TPA
60	435
65	435
75	680
85	680
95	1210
105	1210
115	1210

on the site, and if there are no stands growing on similar sites available for comparison, this assumption may not be met. E. globulus appears to grow best on well-drained, sandy-loamy soils with a 10- to 12-foot water table. This relationship between edaphic-climatic-geomorphological conditions and site index requires further research so a site index may be estimated prior to planting.

For the present time, individuals who wish to use these models and yield tables to assess growth and yield can use some general observations of the soil-site quality relationship provided by Metcalf. This information is shown in table 6.

Table 6 -- Relationship Between Site Index and Soil-Site Characteristics

Approximate Site Index	Soil-Site Characteristics
Greater than 93	<ul style="list-style-type: none"> . Soils - loamy-sandy loam - deep bottomland . Agricultural quality -- high . Water table -- near surface during most of the year . Slope - flat
65-93	<ul style="list-style-type: none"> . Soils - sandy-sandy loam . Agricultural quality -- fair to good under irrigation . Water table -- low; irrigation required . Slope -- medium to flat
Less than 65	<ul style="list-style-type: none"> . Soils - sandy, adobe . Agricultural quality - low . Water table - low; irrigation infeasible . Slope - steep . Windy

Older Stands

As noted earlier, the data analyzed was heavily weighted to stands 5 to 15 years old, making extrapolation of the model to older stands somewhat risky. Similar data should be gathered for stands 15-60 years old to see if a better fit can be obtained.

Economic Analysis

This analysis assumes that maximum biomass production is the only management goal. Costs of site preparation, irrigation, fertilization and harvest are not considered; nor are projected stumpage prices or (demand for fuelwood or chips. Further analysis should combine biological growth potential with economic factors to give a return on investment analysis for Eucalyptus globulus plantations.

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