HEIGHT - DIAMETER RELATIONSHIP FOR PLANTATION GROWN EUCALYPTS IN KENYA

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KIMONDO, J.M. 1995. Height - diameter relationship for plantation grown eucalypts in Kenya. The relationship between height and diameter for estimating individual tree volume in *Eucalyptus saligna* was investigated. Data on height and diameter were collected from 365 trees from five forest stations. Eight equations previously used in other studies were fitted to the data using least square technique. The equation, $ht = 1.3 + b_1 dbh + b_2 dbh^2$ was found most appropriate for estimating height based on the percentage of variation expressed by the regression and the standard error.

Key words: *Eucalyptus saligna* - height - diameter - Kenya

KIMONDO, J.M. 1995. Hubungan ketinggian dan diameter bagi pokok-pokok eucalypt yang ditanam di ladang di Kenya. Perhubungan di antara ketinggian dan diameter untuk menganggar isipadu pokok *Eucalyptus saligna* secara berasingan telah dikaji. Data untuk ketinggian dan diameter dikutip daripada 365 pokok daripada lima stesen hutan. Lapan persamaan yang digunakan dalam kajian-kajian sebelum ini telah disesuaikan untuk data berikut menggunakan teknik kuasadua terkecil. Persamaan $ht = 1.3 + b_1 dbh + b_2 dbh^2$ didapati paling sesuai untuk menganggar ketinggian berdasarkan peratus variasi yang ditunjukkan oleh regresi dan ralat piawai.

Introduction

Height estimation in the field is a slow and expensive process and is generally not desirable to measure large number of trees per unit area (Alder 1980). When stand volume is calculated from measurements of diameter for all trees in an area and estimates of height based on a sample of those trees, a common procedure is to relate height to diameter. Thereafter, volume per tree is obtained by entering a standard volume table with the measured tree diameter and the estimated tree height given by the height/diameter function (Curtis 1967, Hilt & Dale 1982, Clutter *et al.* 1983, Buford 1986, Kimondo 1987).

Curtis (1967) suggests that relating height to diameter may introduce erratic and illogical fluctuations into the estimates. He observed that this was mainly because the relationship is based on small samples and usually with measurements by different people. However, these fluctuations can be eliminated by inclusion of age as an independent variable. Alder (1980), on the other hand, suggests that data from stands of different ages and densities should never be pooled together as the resultant function is a poor height predictor for any individual stand.

Clutter *et al.* (1983) and Alder (1980) point out that a single height-diameter relationship should not be developed for different stands unless preliminary tests have shown the stands to be similar. Meyer (1936) suggests that the function should be moderately flexible and possess the following characteristics. Firstly, the slope of the function should always be positive, approaching zero as the diameter becomes larger. Secondly, the function should pass through the origin on the x-y graph.

Even though there exists no strong relationship between height and diameter in some tropical tree species (Alder 1980), this study was undertaken to compare a number of alternative height-diameter and height-diameter-age functions for five forest stations.

Materials and methods

Site description

The data for height-diameter (and age) were collected in Uasin Gishu district in Kenya. The area lies between 0° 30' S and 1° 0' N latitude, 33° 30' and 35° 0' E longitude. It rises from 1200 to 2500 m above sea level. The altitudes of the different forest stations are shown in Table 1.

The total forest land under the forest department management is 61 150 ha and comprises softwood and hardwood plantations as well as natural forests.

Data collection

In each forest station, approximately 10 trees were sampled from each age between 3 and 10 y in temporary sample plots. The sample trees had to be visually straight, with no multiple leaders and showing no signs of supression. The age range and number of trees sampled from each forest are shown in Table 1. In total, 365 trees were sampled for both diameter and height from among felled trees. The heights of the trees were measured with a linear tape and the stump heights added. Their distribution in height - diameter classes is shown in Table 2. The sample trees had an average height of 19.08 m and an average diameter at breast height of 18.5 cm.

Table 1. Geographical distribution of *Eucalyptus saligna* sample trees in five forest stations in Uasin Gishu district of Kenya

Forest station	Area (ha)	Altitude (m)	Annual mean rainfall (mm)	Number of sampled trees	Age range (y)
Kaptagat	27 464	2 400	1 260	60	4 - 9
Turbo	12 951	1 850	1 330	70	2 - 10
Sabor	11 734	2 440	1 260	63	2 - 8
Penon	4 109	2 440	1 260	99	3 - 8
Kapsaret	1 420	1 950	1 100	72	4 - 8

Table 2. Distribution of sample trees from five forest stations in Uasin Gishu, Kenya into height-diameter classes

Diameter (cm)	Height (m)						
	10	15	20	25	30	35	Total
10	16	6	2	0	0	0	24
15	33	68	42	10	1	0	154
20	0	26	45	42	4	0	117
25	0	3	20	25	3	4	55
30	0	0	0	6	5	0	11
35	0	0	2	1	0	0	3
40	0	0	0	1	0	0	1
Total	49	103	111	85	13	4	365

Fitting the equations

Eight equations previously used in other studies were fitted to the data using the least square technique. The linear equations were fitted to the data using the minitab package (Ryan *et al.* 1976) while the non-linear equations were fitted using BMDP statistical package (Dixon 1979).

The equations are:

$\ln(ht) = b_0 + b_1\, dbh^{-1}$ .... (1)
(Clutter *et al.* 1983)

$ht = b_0 + b_1 dbh + b_2 dbh^2$ .... (2)
(Staebler 1954)

$ht = 1.3 + b_1 dbh + b_2 dbh^2$ .... (3)
(Ker & Smith 1955)

$ht = 1.3 + b_0(1 - e^{b_1 dbh})$ .... (4)
(Curtis 1967)

$ht = b_0 + b_1 dbh^2 + b_2\, dbh^{0.5} + b_3 dbh^{-0.5}$ .... (5)
(Curtis 1967)

$\log(ht) = b_0 + b_1 \log(dbh)$ .... (6)
(Curtis 1967)

$ht = b_0 + b_1 \log(dbh)$ .... (7)
(Myers 1966)

$dbh/ht = b_0 + b_1 dbh + b_2 dbh^{-1}$ .... (8)
(Curtis 1967)

where

ht	=	total tree height
dbh	=	diameter at breast height
log	=	logarithm to base 10
ln	=	natural logarithm
e	=	base of natural logarithm
b	=	regression coefficient

Of these equations, (1) has probably been the most frequently used in recent studies of height-diameter relationships (Clutter *et al.* 1983, Burk & Burkhart 1984, Buford 1986). In Buford's study, this equation was found appropriate when applied to an even-aged plantation of loblolly pine at 15 y. Equations (2) and (3) have had considerable use in the northwestern states of USA (Curtis 1967). Equation (4), like (3), is a realistic model which predicts breast height (1.3 m) when diameter at breast height is zero. Equation (5) was initially fitted as a polynomial with several variables using stepwise techniques, while equations (6) and (7) have been used elsewhere (Myers 1966). Equation (8) is of the form,

$$ht = \frac{dbh^2}{b_0+b_1dbh+b_2dbh^2} \quad \text{(Curtis 1967)}$$

and is thus realistic, in that it passes through the origin.

Results and discussion

The results of fitting the eight equations are listed in Tables 3 to 7, for each forest station. Equation (3) was fitted with (ht-1.3) as the dependent variable, but with no constant term. For equations (3) and (4), the coefficient of determination (r^2) was not generated by the computer. In order that all the equations are comparable, the standard errors of those with heights transformed were computed to give figures of height in meters. Among the six equations whose coefficients of determination were generated by the computer, equation (5) was the most appropriate in all cases. However, there is no consistency in the ranking of appropriateness among the remaining five equations. Considering the standard error of all the eight equations, (5) was found to be the best for three forest stations. Where it was not the best, the difference between the most appropriate equation and equation (5) was very small (Tables 3 & 7). Equation (4) had the highest standard error and thus was the least appropriate.

However, the eight equations had different number of parameters. Since both the coefficient of determination and standard error of regression are affected by the number of parameters in the equations, an unbiased criteria method for comparing the equations is necessary. The coefficient value increases while standard error decreases with increasing number of parameters. For each equation, the proportion of variation shown by the individual regression was considered.

Based on this criterion, equation (3), which estimates a height of 1.3 m when diameter at breast height is 0, and equation (4), which is non-linear, are most appropriate for all forest stations. Age, as a predictor variable, when introduced into equation (3) did not improve height prediction. However, since both height and diameter are positively correlated to age (Kimondo 1987), this means that the inclusion of age in height estimation after diameter can cause insignificant change.

Apparently, with the low r^2, the high standard error and proportion of variation shown in the equations fitted, it is necessary that during each inventory work, a height-diameter function be obtained based on the data collected in that particular forest stand. Equation (7) can be fitted easily using a scientific calculator and is thus suitable whenever quick solutions are required, especially in the field. However, Curtis (1967) pointed out that the equation gives negative values for small trees and is therefore not reliable in young plantations.

Equation (1) is asympotic, passes through the origin and the slope is positive throughout the range of diameters of sample trees. Curtis (1967) when discussing a similar equation, indicated that powers other than (-1) may give slightly better prediction in young stands. With the future use of permanent plot data, an elaborate type of function, either equation (3) or (4), should be fitted.

Conclusion

Poor height-diameter relationship of most tropical species (Alder 1980) was observed in the functions fitted. As a result, with the adoption of any one equation, for example equation (3), the quantitative values of the pooled data were not appropriate and the data from each forest station should be fitted separately. Unless an alternative method of estimating height is developed and vigorously tested, probably using height-age relationship based on permanent sample plot data, separate height-diameter functions should be derived at all times whenever yield of this species is being estimated in a specific area.

Table 3. Regression results of eight test equations for Kaptagat Forest

Equation	Intercept	Coefficients			Coeff. of determination (r^2)	Standard error	Variation explained by the equation (%)
	b_0	b_1	b_2	b_3			
1	3.91083	-22.011			52.9	4.110	18
2	-11.740	1.9002	-0.02322		52.5	4.107	23
3		0.8386	-0.00032			4.310	94.7
4		18.437998	-0.09879			5.960	94.7
5	-424.4	-0.06191	68.07	722.5	53.8	4.114	22.9
6	-0.1886	1.07136			52.0	4.151	20.9
7	-38.652	42.760			52.8	4.093	21.6
8	0.9366	0.00570	4.155		51.2	4.206	11.7

Table 4. Regression results of eight test equations for Turbo Forest

Equation	Intercept	Coefficients			Coeff. of determination (r^2)	Standard error	Variation explained by the equation (%)
	b_0	b_1	b_2	b_3			
1	3.77058	-16.5321			83.0	2.619	72.4
2	8.250	1.8560	-0.02424		83.9	2.537	75.2
3		1.06084	-0.006632			2.701	96.7
4		18.14615	-0.09879			6.333	96.6
5	-251.20	-0.06191	45.549	380.96	85.9	2.421	77.7
6	-0.04254	0.98732			79.9	2.865	75.4
7	-29.166	37.098			82.8	2.628	73.9
8	0.5816	0.01475	4.358		82.8	2.639	8.9

Table 5. Regression results of eight test equations for Sabor Forest

Equation	Intercept	Coefficients			Coeff. of determination (r^2)	Standard error	Variation explained by the equation (%)
	b_0	b_1	b_2	b_3			
1	3.52886	-15.1239			86.2	2.245	61.3
2	-3.710	1.1583	-0.008451		90.7	1.817	60.2
3		0.74147	-0.001971			1.861	96.9
4		12.87831	-0.09879			5.972	96.8
5	-192.10	-0.04240	37.077	269.47	92.6	1.656	62.6
6	-0.23436	1.09518			90.5	1.868	65.1
7	-25.241	32.117			87.6	2.103	58.9
8	1.3714	-0.004858	0.594		90.2	1.903	8.2

Table 6. Regression results of eight test equations for Penon Forest

Equation	Intercept	Coefficients			Coeff. of determination (r^2)	Standard error	Variation explained by the equation (%)
	b_0	b_1	b_2	b_3			
1	3.78039	-18.906			69.2	2.760	47.2
2	-9.616	1.8794	-0.026304		68.6	2.774	49.6
3		1.00585	-0.00767			2.830	97.6
4		16.96436	-0.09879			4.930	97.6
5	681.5	0.08248	-90.22	-1308.5	74.0	2.564	60.9
6	0.04440	0.90139			66.1	2.894	57.4
7	-28.055	34.794			69.1	2.749	60.4
8	-1.3479	0.06224	24.814		69.5	2.762	53.0

Table 7. Regression results of eight test equations for Kapsaret Forest

Equation	Intercept b_0	Coefficients b_1	b_2	b_3	Coeff. of determination (r^2)	Standard error	Variation explained by the equation (%)
1	3.77073	-18.265			63.2	2.717	56.5
2	-0.584	1.0385	-0.007076		62.7	2.715	60.1
3		0.98885	-0.006074			2.696	99.0
4		17.831079	-0.09879			4.446	99.0
5	234.5	0.03059	-28.01	-464.3	64.4	2.709	61.8
6	0.1233	0.85275			63.5	2.706	57.4
7	-30.116	36.626			63.2	2.698	60.4
8	0.4565	0.02058	5.993		58.7	3.529	52.9

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