Silva Fennica 1986, vol. 20 n:o 2: 149–156

Weibull function in the estimation of the basal area dbh-distribution

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SELOSTE: WEIBULL-FUNKTIO POHJAPINTA-ALAN LÄPIMITTAJAKAUMAN ESTIMOINNISSA

Kilkki, P. & Päivinen, R. 1986. Weibull function in the estimation of the basal area dbh-distribution. Seloste: Weibull-funktio pohjapinta-alan läpimittajakauman estimoinnissa. Silva Fennica 20(2): 149–156.

The paper demonstrates the possibility of using data from small relascope sample plots in the derivation of the regression models which predict the Weibull function parameters for the dbh-distribution. The Weibull parameters describing the basal area dbh-distribution were estimated for relascope sample plots from the Finnish National Forest Inventory. In the first stage of the estimation nonlinear regression analysis was employed to derive initial parameter estimates for the second stage, in which the maximun likelihood method was used. The parameter estimates were employed as dependent variables for the derivation of the regression models; the independent variables comprised of the compartment-wise stand variables generally estimated in ocular inventories.

Tutkimuksessa tarkastellaan pienten relaskooppikoealojen käyttöä Weibull-funktioon perustuvan pohjapinta-alan läpimittajakauman parametrien ennustemallien laadinnassa. Aineistona käytettiin valtakunnan metsien inventointikoealoja. Ensimmäisessä vaiheessa parametrit estimoitiin epälineaarisella regressioanalyysillä; nämä estimaatit olivat alkuarvoina toisessa vaiheessa tehdylle maximun likelihood estimoinnille. Weibull-funktion parametrien estimaatit olivat selitettävinä muuttujina regressiomalleissa, joiden selittävinä muuttujina olivat kuvioittaisessa arvioinnissa yleisesti mitattavat metsikkötunnukset.

Key words: Diameter distribution, beta function, *Pinus sylvestris,* nonlinear regression, maximum likelihood, initial parameter estimates, relascope sample plot
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Approved on 3. 9. 1986

1. Introduction

A matrix, in which each vector consists of the frequency and all relevant variables of the tree, is the most detailed description of the growing stock of the forest stand or compartment. The trees may then be employed for calculating growing stock parameters and making growth simulations. If the stand matrix is available only individual tree models are needed for the estimation of the stem volume, volumes of the timber assortments, future growth and structure of the growing stock, etc. (Kilkki 1985).

In most forest inventories by compartments, it is not practicable to obtain the tree matrix for each compartment via elaborate tree tally and sample tree measurements, rather the matrix has to be derived from the forest stand variables obtained via ocular estimation or rough measurements. In Finland, for example, the main parameters estimated in the field inventories by compartments are: the basal area, basal area median diameter and the respective height. The parameters are estimated either for the total growing stock or separately for each tree species or tree storey. These parameters are employed in the derivation of the mathematical models which determine the tree distribution; thereafter a sample from this distribution may be employed as an estimate of the tree matrix.

The basic tree distribution is usually the dbh-distribution (see e.g. Linnilä 1985). In Finland, the beta function has been used in the description of the dbh-distribution (Päivinen 1980). In order to give more weight to the large and more valueable trees Päivinen employed the basal area dbh-distribution instead of the stem frequency dbh-distribution.

The data used by Päivinen (ibid.) to derive the regression models for the prediction of the beta function parameters did not represent the actual Finnish forests. He also employed the observed minimum and maximum diameters on the sample plot as the minimum and maximum diameters of the beta distribution. Although the sample plots were relatively large these diameter limits proved to be too narrow for the whole stands.

The National Forest Inventory sample plots satisfy the most rigorous representativeness requirements in Finnish conditions, but they are handicapped by their small size (relascope factor 2, i.e., each tree represents 2 m^2/ha), which results in an average of 8 trees per sample plot. The estimation of the beta function parameters for these sample plots might be problematic; consequently the Weibull function was chosen.

The Weibull function has been widely used to describe the diameter distribution of the trees (see e.g. Bailey and Dell 1973; Clutter et al. 1983; Cao and Burkhart 1984; Green et al. 1984). For the Weibull distribution, the probability density function is

$$f(x) = 0 \quad (x<a)$$

$$= \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} \exp\left(-\left(\frac{x-a}{b}\right)^{c}\right) \quad (a \le x < \infty) \qquad (1)$$

where

a,b,c = parameters

and the cumulative distribution function

$$f(x) = 0 \quad (x<a)$$

$$= 1 - \exp\left(-\left(\frac{x-a}{b}\right)^{c}\right) \quad (a \le x < \infty) \qquad (2)$$

Parameters b and c must always be positive, and for the diameter distribution, parameter a, the miminum diameter, must be nonnegative. If the median diameter is known, one of the Weibull parameters can be estimated from the two other parameters and from the median diameter.

An approach similar to that of Päivinen (ibid.) but using the Weibull function has been presented by Rennolls et al. (1985). First, they have estimated the Weibull parameters for a number of sample plots. Secondly, they have related the Weibull parameters to the mean diameter and to the minimum diameter at breast height with regression analysis.

The aim of this paper is to demonstrate the applicability of the relascope sample plot data of the Finnish National Forest Inventory in the derivation of the regression models, which determine the basal area dbh-distribution parameters of the Weibull function. The explanatory variables of the regression models are the stand parameters generally estimated in the ocular inventories by compartments.

2. Material

The National Forest Inventory in Southern Finland is based on systematic cluster sampling. The inventory cycle varies from 7 to 8 years and the total number of relascope sample plots measured on forest land in each inventory cycle is roughly 50 000. For all sample plot stands a number of site and growing stock variables such as site type, soil quality, drainage situation, age, basal area, dominant tree species, basal area median diameter, and the respective height are measured or estimated. The tree species, dbh, canopy layer, and the tree class (saw timber – pulpwood) are determined for all trees on the sample plot. On every fifth sample plot, "sample tree plot", the sample tree variables i.e., the height, diameter at the height of 6 meters, age, diameter increment, and the height increment for conifers are measured for all trees.

The test material was selected from the sample tree plots of the seventh inventory in the Forestry Board District of Northern Karelia (years 1979–80). Only Scots pines belonging to the dominant and codominant crown layers were included in the study. This restriction is based on the fact that in ocular estimation the lower crown layers are described as another tree storey. A further requirement was a minimum of five acceptable trees per sample plot. The material consisted of 188 sample plots.

3. Estimation of the Weibull parameters

To obtain appropriate initial values for the maximum likelihood estimation (Krug et al. 1982), the Weibull cumulative basal area distribution function (2) was first fitted to each sample plot using nonlinear regression analysis. The trees were ranked in an increasing order by their diameters. In the regression analysis, one observation consisted of a measured breast height diameter (cm) as a predictor and the average of the cumulative frequency of this diameter and of the previous diameter as the predicted variable. Values a = 0, b = 20, and c = 10 were used as the initial values in the nonlinear regression analysis. The first phase gave the initial estimates for the Weibull parameters and the residual standard error of the cumulative Weibull function, which was used later in weighting the observations.

The final Weibull parameters were estimated using the maximum likelihood method. The parameters a, b, and c were obtained by equating the partial derivatives of the logarithm of the likelihood function with respect to these parameters to zero (Harter and Moore 1965). The maximum-likelihood equations are

$$(1-c) \sum_{i=1}^{n} (x_i-a)^{-1} + cb^{-c} \sum_{i=1}^{n} (x_i-a)^{c-1} = 0 \qquad (3)$$

$$-\frac{cn}{b} + c \sum_{i=1}^{n} (x_i-a)^{c}/b^{c+1} = 0 \qquad (4)$$

$$n\left(\frac{1}{c} - \ln(b)\right) + \sum_{i=1}^{n} \ln(x_i-a) - \sum_{i=1}^{n} \left(\frac{x_i-a}{b}\right)^{c} \ln\left(\frac{x_i-a}{b}\right) = 0 \qquad (5)$$

where

n = number of observations

In order to avoid nonsensical values of the parameter a, heuristic boundaries were set. The maximum value for parameter a is

$$a_{max} = 0.3^{(1/n)} d_{min} \qquad (6)$$

where

d_{min} = minimum diameter of the sample trees on a sample plot, cm

and its minimum value is

$$a_{min} = 0.5 a_{max}, \qquad (7)$$

In each iteration round parameter b could be estimated from formula (Bailey and Dell 1973)

$$b = \left(\frac{1}{n}\sum_{i=1}^{n}(x_i - a)^c\right)^{1/c} \quad (8)$$

Consequently, the numerical iteration was done only with respect to parameters a and c.

The solution was found using the ZSCNT-subroutine of the IMSL-library (IMSL . . . 1984). In order to guarantee the convergence of the algorithm a minimum value 1.1 and maximum value 15.0 were set to parameter c during the estimation. The minimum value of parameter c guarantees that the maximum frequency always occurs between the minimum and maximum diameters. In seven cases parameter c assumed the minimum value and in one case the maximum value. The other estimates fell within these limits. After parameters a, b, and c had been estimated, the basal area median diameter (variable d_{gM}) was solved from (2) by writing the cumulative frequency function to be equal 0.5.

The minima, maxima, means, and standard deviations of the stand variables and the Weibull parameters of the test material are given in Table 1.

Table 1. Mimima, maxima, means, and standard deviations of the stand variables and Weibull parameters

	min	max	mean	sd
d_{min}	15.000	312.00	126.19	67.794
d_{max}	65.000	570.00	276.94	90.492
DD	960.00	1160.0	1051.0	47.629
HA	80.000	220.00	142.61	34.735
Site	0.0000	4.0000	1.8457	0.9380
T	–	205.00	77.660	35.871
G	–	47.000	21.027	7.8634
N	5.0000	18.000	8.2021	3.2262
d_{gM}	3.8306	40.645	19.340	7.3527
a	0.7999	23.760	9.9093	5.4339
b	3.4203	24.416	11.207	4.6917
c	1.1000	15.000	2.4309	1.5065
sf	0.0227	0.1945	0.0804	0.0318

List of variables

d_{min} = minimum diameter of the sample trees on a sample plot, cm
d_{max} = maximum diameter of the sample trees on a sample plot, cm
DD = effective temperature sum (> 5°C), degree days
HA = height above the sea level, m
Site = forest taxation class (site class)
T = age, years
G = basal area, m^2/ha
N = number of sample trees (= basal area of the dominant pines, 2 m^2/ha)
d_{gM} = basal area median diameter of the sample trees, cm
a, b, c = Weibull parameters
sf = residual standard error of the cumulative Weibull function

4. Regression models

It is assumed that in the applications phase the basal area median diameter (d_{gM}) is measured from the stand. Consequently, one of the three Weibull parameters can be derived from the other two. Parameters a and c were chosen as the parameters to be predicted by the regression models. In order to homogenize the variance logarithms were used. The observations were weighted by the inverse of the residual variance of the cumulative distribution estimate. Two models were derived for parameter c: when model (10) is used it is assumed that the minimum diameter (parameter a) is predicted by model (9), and when model (11) is used it is assumed that the minimum diameter is measured from the forest stand. Stepwise regression analysis yielded the following regression models and their standard errors.

ln(a) =	0.8418	(t= 11.54)	(9)
	0.6883E−01 d_{gM}	(t= 19.21)	
	(s_e = 0.374)		

ln(c) =	0.3793	(t= 4.77)	(10)
	−0.2850E−02 T	(t= 3.45)	
	−0.1298E−01 G	(t= 4.09)	
	0.4526E−01 d_{gM}	(t= 10.79)	
	(s_e = 0.349)		

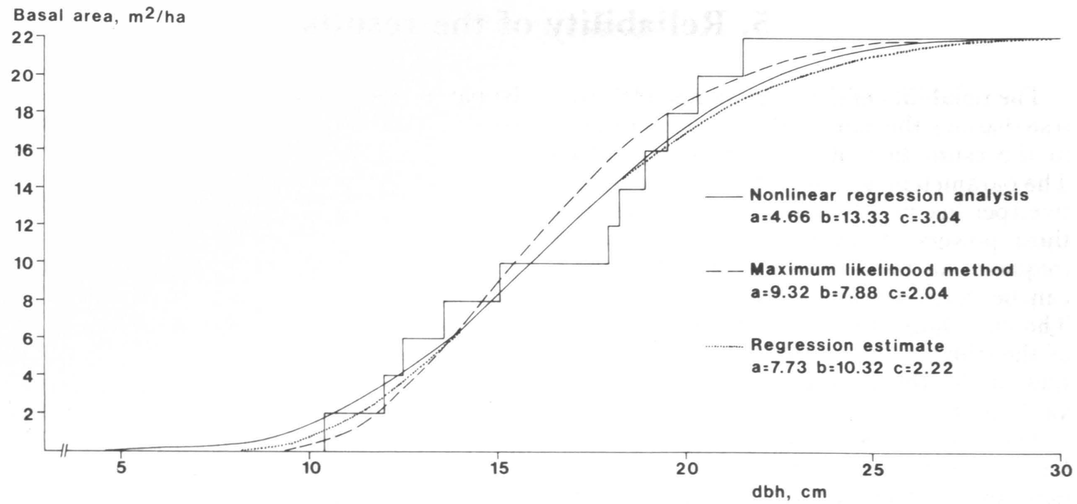

Figure 1. The measured basal area cumulative distribution of one relascope plot with 11 trees and three estimated Weibull distributions.

ln(c) =	0.2998	(t= 3.89)	(11)
	−0.2580E−02 T	(t= 3.30)	
	−0.1224E−01 G	(t= 4.08)	
	−0.3332E−01 a	(t= 4.82)	
	0.6511E−01 d_{gM}	(t= 11.39)	
	(s_e = 0.336)		

Parameter b can be derived from formula

$$b = \frac{(d_{gM} - a)}{(-\ln(0.5))^{1/c}} \quad (12)$$

As an example, the measured basal area cumulative distribution of one relascope plot with 11 trees and three estimated Weibull distributions: (1) via nonlinear regression analysis, (2) via maximum likelihood method, (3) via regression models (9) and (10), are given in Fig. 1. In the third method the basal area median diameter (d_{gM}) was needed. It was derived from the diameter distribution estimated by the nonlinear regression analysis. The values of the predicting variables were: d_{gM} = 16.5 cm, T = 45 years, G = 20^2/ha (obs! G refers to the whole stand).

Methods (1) and (3) gave fairly similar distribution estimates. This is largely due to the employment of exactly the same basal area median diameter in method (3) as in method (1). If the basal area median diameter estimate (= 15.9 cm) corresponding to the parameters of method (2) had been employed the diameter distribution from method (3) would have been quite similar to that from method (2).

5. Reliability of the results

The reliability of the regression models was tested using the same data which were used in the estimation of the regression models. The parameters to be tested were the cumulative (per hectare) frequencies of the first and third powers of the dbh's; the cumulative frequency of the second power of the dbh's can be derived exactly from the basal area. The cumulative frequency of the first power of the dbh's refers to the stem number and that of the third power to the volume and value of the growing stock.

The parameters a and c together with the basal area median diameter and basal area determine the cumulative Weibull distribution function. The basal area median diameter of the trees on each sample plot was estimated from the Weibull distribution derived from nonlinear regression analysis. The diameter distribution was approximated by dividing it into 5 mm classes. The upper limit for the diameter distribution was set to be 50 cm. The upper tail of the distribution was added to the frequency of the last diameter. In all cases the sum frequency of this upper tail was practically zero.

The basal areas were changed into stem numbers (per hectare) with the circle area formula

$$n_i = \frac{4 A_i}{\pi d_i^2} \qquad (13)$$

where

n_i = stem number in class i

A_i = basal area of class i

d_i = diameter in the middle of class i

The parameter estimates and their root-mean-square errors were calculated under the following three assumptions:

A) both parameters a and c obtain their original values, i.e., the values derived by the maximum likelihood method.

B) parameter a obtains its original value and parameter c is estimated by the regression model (11), and

C) both a and c are estimated by the regression models (9) and (10).

The corrections for the logarithmic transformation (see Meyer 1941) were made when parameters a and c were derived by the regression models.

The mean errors and the root-mean-square errors of the estimates of the cumulative frequencies of the first and third powers of the dbh's when compared to the true values of the sample plots are:

	Σ d	Σ d^3
	%	
Estimate A		
mean error	−1.5	−0.5
root-mean-square error	5.2	1.5
Estimate B		
mean error	−2.5	−1.9
root-mean-square error	10.0	4.7
Estimate C		
mean error	−4.0	−1.8
root-mean-square error	14.3	4.5

There is a slight negative bias for both the cumulative frequencies of the first and third powers of the dbh in each method. This result indicates the estimated distributions are too narrow. The knowledge of the minimum diameter (parameter a) does not help in the estimation of the cumulative frequency of the third power of the dbh. The results might have been a little better if the basal area median diameter had been based on the maximum likelihood Weibull parameters instead of the parameters derived from the nonlinear regression analysis.

6. Discussion

The aim of this paper was to study the applicability of the tree data from the small sample plots of the Finnish National Forest Inventory in the estimation of the dbh-distribution using Weibull function. There seems to be no major obstacles for large scale application of the method. Further research is still needed to establish the optimal rules for the determination of the minimum diameter (parameter a). The present heuristic rules for its limits might be improved.

The comparison of the Weibull and beta functions would call for a new study. In this study the importance of the upper diameter limit should be studied. Then also the possibility of using the negatives of the diameters in the Weibull function could be tested.

The greater importance of the large trees may suggest that instead of the basal area (= the second power of the diameter) the third or even higher powers of the diameter might be used in the estimation of the diameter distribution. The use of the negatives of the diameters in the estimation of the Weibull function might have the same effect; then the parameter a would indicate the maximum diameter.

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Seloste

WEIBULL-FUNKTIO POHJAPINTA-ALAN LÄPIMITTAJAKAUMAN ESTIMOINNISSA

Tutkimuksen tavoitteena oli tarkastella pienten koealojen käyttöä läpimittajakaumaa kuvaavien mallien laadinnassa. Aineistona olivat valtakunnan metsien seitsemännessä inventoinnissa Pohjois-Karjalan piirimetsälautakunnassa mitatut koepuumännyt. Mukaan hyväksyttiin ne relaskooppikoealat, joilla pää- ja lisävaltapuumäntyjä oli vähintään 5 kappaletta.

Puuston pohjapinta-alan läpimittajakaumaa kuvaamaan käytettiin Weibull-funktiota, jonka parametrit estimoitiin koealoittain kaksivaiheisesti. Ensimmäisessä vaiheessa Weibull-kertymäjakauman parametrit estimoitiin epälineaarisella regressioanalyysillä. Nämä parametrien arvot olivat lähtötietoina toisessa vaiheessa maximum-likelihood-menetelmällä estimoitaville Weibull-parametreille. Toisesta vaiheesta saatuja parametrien arvoja käytettiin selitettävinä muuttujina regressiomalleissa; selittävinä muuttujina olivat silmävaraisessa kuvioittaisessa arvioinnissa arvioitavat metsikkötunnukset.

Tulosten luotettavuutta testattiin vertaamalla estimoiduista runkolukusarjoista saatuja puuston läpimittojen ensimmäisten potenssien (= runkolukujen) ja kolmansien potenssien summaa mitatuista puista saatuihin arvoihin. Tulokset olivat lieviä aliarvioita molemmissa tapauksissa. Tämä osoittaa, että estimoidut jakaumat olivat hieman liian suppeita.

On ilmeistä, että valtakunnan metsien inventoinnissa kertyvää suurta ja edustavaa, mutta pieniä koealoja käsittävää aineistoa voidaan käyttää silmävaraisessa kuvioittaisessa arvioinnissa tarvittavien runkolukusarjojen estimointiin. Menetelmän kehittäminen vaatii kuitenkin vielä paljon työtä, jotta kaikenlaisille metsiköille ja kaikille tärkeimmille puulajeille löydettäisiin sopivimmat teoreettiset jakaumamallit ja niiden parametrien estimointimenetelmät.

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