GROWTH MODELS FOR UNTHINNED *ACACIA MANGIUM* PLANTATIONS IN SOUTH KALIMANTAN, INDONESIA

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FORSS, E., GADOW, K. v. & SABOROWSKI, J. 1996. Growth models for unthinned *Acacia mangium* plantations in South Kalimantan, Indonesia. Growth models are presented for unthinned plantations of *Acacia mangium*. The models are based on remeasured data on 24 semipermanent yield study plots (2.3 to 6.8 years of age) in South Kalimantan. In addition, the height data from four small plots from an old provenance trial (0.9 and 2.0 years of age) and from six thinned yield plots (4.0 and 5.0 years of age) were used. The stands had an initial spacing of 2 × 4 m and 3 × 3 m but because of the common multistems the number of stems per hectare varied a lot. Stand growth models for dominant height, survival and basal area and a single tree model for diameter growth were developed. The future development of a stand can be projected from normal inventory data or for different site indices and a limited range of initial spacings without any previously measured data.

Key words: *Acacia mangium* - growth model - reforestation - *Imperata cylindrica*

FORSS, E., GADOW, K.V. & SABOROWSKI, J. 1996. Model-model pertumbuhan untuk ladang-ladang *Acacia mangium* yang tidak dijarangkan di Kalimantan Selatan, Indonesia. Model-model pertumbuhan dikemukakan untuk ladang-ladang *Acacia mangium* yang tidak dijarangkan. Model-model ini adalah berdasarkan kepada data yang diambil semula di 24 plot kajian hasil separa-kekal (umur 2.3 hingga 6.8 tahun) di Kalimantan Selatan. Tambahan pula, data ketinggian daripada empat plot kecil daripada satu percubaan provenans yang lama (berumur 0.9 dan 2.0 tahun) dan daripada enam plot hasil yang tidak dijarangkan (berumur 4.0 dan 5.0 tahun) telah digunakan. Dirian-dirian ini mempunyai penjarakan awal 2 × 4 m dan 3 × 3 m tetapi disebabkan oleh kewujudan multibatang, bilangan batang sehektar amat berbeza. Model-model pertumbuhan dirian bagi ketinggian dominan, kemandirian dan luas pangkal serta satu model pokok tunggal bagi pertumbuhan garis pusat telah diasaskan. Perkembangan sesuatu dirian pada masa hadapan dapat diunjurkan daripada data inventori normal atau untuk petunjuk tapak yang berbeza dan satu julat penjarakan awal yang terhad tanpa sebarang data yang telah diukur.

Introduction

Acacia mangium Willd., originally from Queensland (Australia), Papua New Guinea and East Indonesia, has become a popular plantation species in Malaysia and Indonesia (Halenda 1988, RAPA 1988, Hadi *et al.* 1990b, Groome 1991, Ngah & Ghani 1991, Tsai 1991). The popularity of the species is based on its ability to successfully compete with the vigorous alang-alang grass, *Imperata cylindrica*, (Weinland 1987, Sipayung 1988, Hadi *et al.* 1990b). In Indonesia there are roughly 20 million ha occupied by alang-alang (JOFCA 1990). These areas regenerate naturally very slowly because of the heavy competition by the grass (Soerianegara 1980). The highly productive eucalypts would also do well, but need very intensive weeding and fertilisation (Hadi & Ådjers 1990, Hadi *et al.* 1990b). Reforestation with pines has met with varying success (Golokin & Cassels 1989, Hadi *et al.* 1990b, Lazuardi & Mikkilä 1991). *Acacia mangium* grows well, even in acid and badly eroded soils (RAPA 1988, Tan 1991). It fixes atmospheric nitrogen and produces a rich harvest of litter, which improves the physical and chemical properties of the soil (Halenda 1988, RAPA 1988, Ang & Yusof 1991, Hamsawi & Jugah 1991, Miller & Hepburn 1991).

The wood of *A. mangium* is well suited for pulp and particleboards (Logan 1987, RAPA 1988, RAPA 1990, Chew *et al.* 1991, Fåhrdeus 1991, Groome 1991, Prawirohatmodjo 1991, Razali & Kuo 1991, Salleh & Wong 1991). For the production of sawn timber and plywood the technical quality of the stems is often not adequate because of forking, branchiness, unstraightness (Chan 1986, Weinland 1987, Mead & Speechly 1991, Prawirohatmodjo 1991) and heart rot (Lee *et al.* 1988, RAPA 1990, Mahmud *et al.* 1993).

In South Kalimantan, *A. mangium* has been used for reforestation on a small scale since 1984 (Hadi *et al.* 1990a). The Government of Indonesia is planning to establish 4.4 million ha of timber plantations (HTI) by the end of the Sixth Five-Year-Plan (Pelita VI, 1995-2000), from which 26.9 % will be for industrial purposes. In addition, 5.5 million ha of problematic soils will be afforested, whereby the areas occupied by *I. cylindrica* will have a high priority (Hadi *et al.* 1990b, Lazuardi & Mikkilä 1991).

There is a lot of literature about the volume growth and biomass of *A. mangium* plantations in Indonesia and especially in Sabah in Malaysia (Ruslim 1985, Rizal 1987, Silitonga 1987, Weinland 1987, Halenda 1988, Lim 1988, RAPA 1988, Ahmad Zuhaidi 1993). The mean annual increment (MAI) in these areas varies between 8.7 and 50.9 m^3 ha^{-1} y^{-1} in plantations of different ages.

Acacia mangium has a great economic and ecological potential. For optimising the management of the stands and for the evaluation of the possibilities of building a forest industry which relies on the wood of *A. mangium*, it is necessary to be able to predict its growth performance on different sites, with different initial spacings and silvicultural regimes. Equations for predicting dominant height, site index, diameter and stand volume up to an age of four years have been developed for *A. mangium* in Central America (CATIE 1992). Lim (1991) developed models for maximal diameter and height growth based on data gathered from literature on the growth of *A. mangium* at different parts of southern Asia, and Harbagung (1991) developed polymorphic models for predicting upper height and site index in *A. mangium* based on data from 12 experimental plots of 3-11 years of age in South Sumatra, West Java and East Kalimantan.

In this paper growth models for unthinned plantations of *A. mangium* in South Kalimantan are presented. Stand growth models for dominant height, survival and basal area and a single tree model for diameter growth were developed. The future development of a stand can be projected from normal inventory data or for different site indices and a limited range of initial spacings without any previously measured data.

Materials and methods

The data were collected in the trial plantations of *A. mangium* of the Indonesian-Finnish Reforestation and Natural Forest Management Project (ATA-267) in South Kalimantan, Indonesia. The plantations were situated in Riam Kiwa (3° 30'S and 115° 20'E), in Riam Kanan (3° 50'S and 115° 10E) and in the island of Pulau Laut (3°60'S and 116°20'E) on sites earlier occupied by *I. cylindrica*. The annual rainfall in Riam Kiwa is 2514 mm (Taylor 1991).

For the modelling of the growth of *A. mangium*, 24 unthinned semipermanent yield study plots were available (Table 1). The stands had been established with the commonly practised spacings of 2 × 4 m (1250 planting spots per hectare) and 3 × 3 m (1111 planting spots per hectare) with seed collected in South Sumatra (Subanjeriji). Because of the common multistems, the number of stems per hectare varied a lot. The plot size varied between 10 × 10 and 8 × 10 planting spots. The plots were remeasured 1.0 to 1.7 years after the first measurement. The ages cover almost the expected rotation of less than 10 years. The remeasurement data were collected in November 1992 - February 1993. The data from the first measurement were made available by the project.

Table 1. General description of the data

	A	N	d_g	h_{dom}	G
Min	2.3	935	5.7	7.5	3.8
Max	6.8	2333	18.9	27.5	26.2
Mean	4.7	1451	12.1	17.9	16.6

Note: A = stand age (years); N = stems per hectare; d_g = quadratic mean diameter (cm); h_{dom} = dominant height (m), height of the arithmetic mean stem of the 100 thickest stems per hectare; G = stand basal area (m^2 ha^{-1}); n = 48.

In addition, the height data from four plots (3 × 3 planting spots) in a provenance trial in Riam Kiwa (measured at ages of 0.9 and 2.0 years) and from six thinned yield plots in Riam Kiwa (measured at ages of 4.0 and 5.0 years) were used. The plots had been thinned at the age of 4 years. For modelling of the stand development after thinning the data were not adequate.

From these data, stand growth models were developed for the projection of dominant height, for survival prediction and for the projection of basal area. Also a single tree diameter growth model was developed. The single tree model is integrated with the stand growth models.

Stand level growth models

Dominant height

Dominant height is practically independent of stand density (Kramer 1959, 1988), and can thus be used as an indicator of site productivity. To describe the development of dominant height, the flexible three-parameter Chapman-Richards height/age function was used (Pienaar & Turnbull 1973, Pienaar *et al.* 1990b, Hacker & Bilan 1991, Hui & v. Gadow 1993):

$$h_{dom} = \beta_0 \left(1 - e^{-\beta_1 A}\right)^{\beta_2} \qquad (1)$$

where h_{dom} = dominant height (m),
A = stand age (y),
$\beta_0, \beta_1, \beta_2$ = coefficients.

Because the data were measured in semipermanent plots, the parameters in equation (1) could not be solved as a function of site quality (polymorphic height growth model). Instead, a difference equation form of equation (1) was fitted, which results in an anamorphic model. In an anamorphic model, annual increment culminates at the same age independent of the site. When dominant height h_{dom_1} at age A_1 is known, dominant height h_{dom_2} at age A_2 can be projected (Clutter *et al.* 1983):

$$h_{dom_2} = h_{dom_1} \left[\frac{1 - e^{-\beta_1 A_2}}{1 - e^{-\beta_1 A_1}}\right]^{\beta_2} \qquad (2)$$

The coefficients (and their standard errors) are

$\beta_1 = 0.12975$ (0.0476)
$\beta_2 = 1.31906$ (0.1382)

and the error of prediction in the model is

$$s_{y.x} = 1.44 \text{ m or } 7.8 \text{ \%} \quad (n = 34)$$

With equation (2) a measured dominant height can be projected without former knowledge of the site. It is also possible to determine the site index (SI = dominant height h_{dom_2} at an index age A_2). Site index at an index age of 5 years varied in the data between 14 and 24 m. The implied site index equation is:

$$h_{dom} = 2.68777 \, SI_5 \, (1 - e^{-\beta_1 A})^{\beta_2} \qquad (3)$$

where SI_5 is the site index at an index age of 5 years. Equation (3) was used to generate the site index curves in figure (1). The curves are extrapolated up to the age of 10 years and may predict excessive heights beyond the age of 7 years (cf. Harbagung 1991).

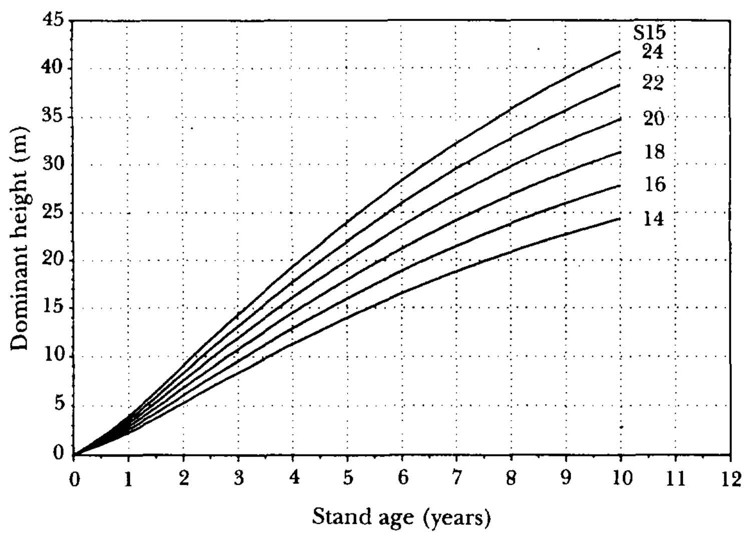

Figure 1. Dominant height growth curves for different site indices (eq. 3)

Survival

In plantations the survival rate due to intraspecific competition depends on the number of survivors, the age and the site quality. With increasing age, the number of trees per hectare decreases. With a given age and initial density, survival is lower on the better sites. With a given age and site index, survival is higher with increasing initial density (Clutter & Jones 1980, v. Gadow 1987, Lee 1993).

The survival function of Pienaar *et al.* (1990a) takes account of such effects:

$$N_2 = \left[N_1^{\beta_0} + \left(\beta_1 + \frac{\beta_2}{SI_5}\right)\left(\left[\frac{A_2}{10}\right]^{\beta_3} - \left[\frac{A_1}{10}\right]^{\beta_3}\right)\right]^{\frac{1}{\beta_0}} \qquad (4)$$

where A_1,A_2 = stand ages (y) at the beginning and end of the period,
N_1,N_2 = stems per hectare at ages A_1 and A_2,
SI_5 = site index.

The coefficients (and their standard errors) are

β_0 = - 0.17075 (1.93865)
β_1 = 0.05222 (0.20851)
β_2 = - 0.59139 (2.68437)
β_3 = 0.98886 (0.73702)

and the error of prediction in the model is

$s_{y.x}$ = 74 N ha^{-1} or 5.3 % (n = 24).

The subtractor 10 was included in order to help the model converge. The standard errors of coefficients are large, which is at least partly due to difficulties in predicting mortality which is not a continuous phenomenon (e.g. v. Gadow 1987). However, the model behaves logically. The result of the fit of equation (4) is presented in Figure 2. In a specific stand, the measured number of stems per hectare can be projected with equation (4), after the site index has been calculated with equation (2). It is also possible to generate survival curves for different site indices and planting survival densities.

Basal area

Unthinned stands of the same age and with the same number of surviving trees per hectare produce more basal area per hectare, the higher the dominant height. Within the bounds of our stand densities at a given dominant height and age, more surviving trees produce more basal area (Grut 1970: 47, Weinland 1987: 97, Pienaar *et al.* 1990b). The model of Pienaar *et al.* (1990b) takes account of such relationships. A simplified form of the model of Pienaar *et al.* (1990b) was found to describe our data well:

$$\ln (G) = \beta_0 + \beta_1 \frac{1}{A} + \beta_2 \ln (h_{dom}) + \beta_3 \ln (N) \qquad (5)$$

where A = stand age (y)
G = basal area (m^2 ha^{-1}),
h_{dom} = dominant height (m),
N = stems per hectare.

The coefficients (and their standard errors) are
β_0 = -4.14724 (0.69346)
β_1 = -2.07358 (0.60905)
β_2 = 0.99584 (0.13499)
β_3 = 0.62386 (0.09684)

and the error of prediction in the model is
$s_{y.x}$ = 2.15 m^2 ha^{-1} or 12.9 % (n = 48).

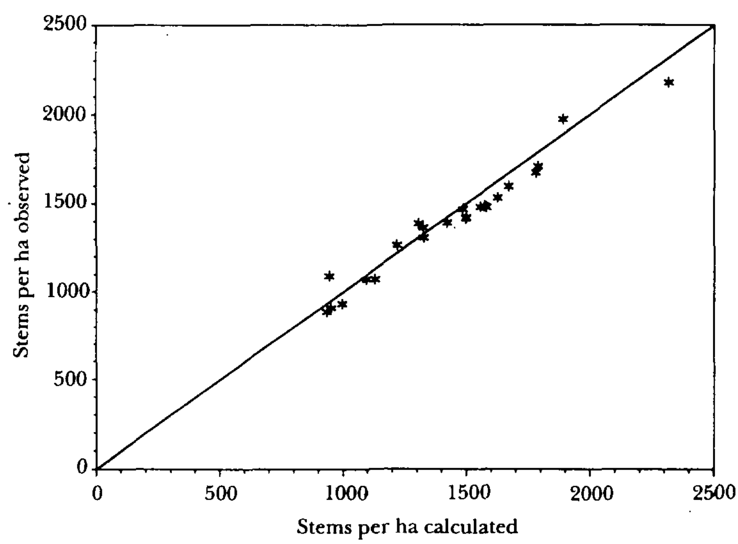

Figure 2. Comparison of observed and calculated survivals (eq. 4)

Even though equation (5) does not include all of the independent variables in the model of Pienaar *et al.* (1990b), the previously mentioned tendencies in basal area development are represented by the model. The result of the fit of equation (5) is presented in Figure 3. The correction factor ($s_{y.x}/2$; e.g. Crow & Schlaegel 1988) was not applied at the transformation, because it caused a bias over the whole range of the data.

Equation (5) may be converted to a basal area algebraic difference form with the same coefficients:

$$\ln(G_2) = \ln(G_1) + \beta_1 \left[\frac{1}{A_2} - \frac{1}{A_1}\right] + \beta_2 [\ln(h_{dom_2}) - \ln(h_{dom_1})] + \beta_3 [\ln(N_2) - \ln(N_1)] \quad (6)$$

where A_1, A_2 = stand ages (years) at the beginning and end of the period,
G_1, G_2 = basal areas ($m^2 ha^{-1}$) at ages A_1 and A_2,
h_{dom_1}, h_{dom_2} = dominant heights (m) at ages A_1 and A_2
N_1, N_2 = stems per hectare at ages A_1 and A_2.

Equation (6) should be used when measured stand data are available adding to the accuracy of the prediction. Equation (5) must be used when idealised basal area curves are generated, e.g. for different site indices.

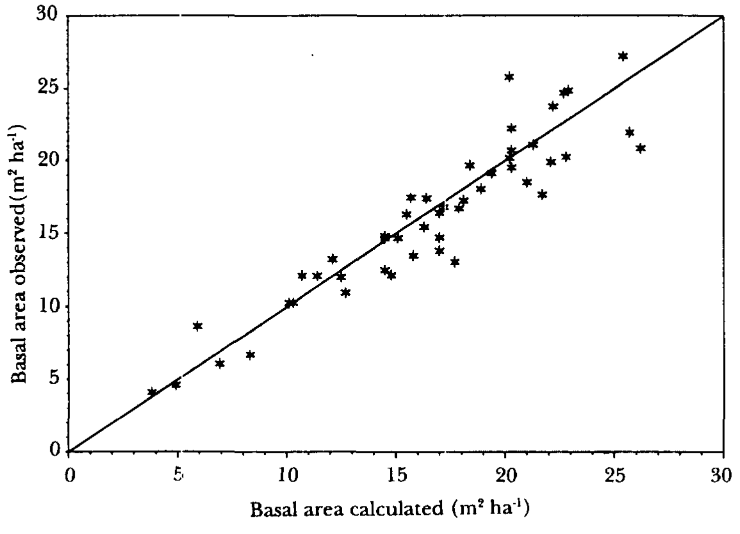

Figure 3. Comparison of observed and calculated basal areas (eq. 5)

Tree level diameter growth model

For the estimation of the exact yield of utilisable timber in a stand, a model that describes the diameter distribution is needed. Future stand tables are commonly derived by means of a diameter distribution method which ignores the availability of an observed initial stand table and predicts or recovers future distribution parameters from projected stand variables such as the number of surviving trees per hectare, basal area per hectare and dominant height (Pienaar & Harrison 1988).

With the model of Clutter & Jones (1980), an existing stand table such as would be available from most stand management inventories, can be projected using

$$\frac{g_{2_i}}{\bar{g}_2} = \left(\frac{g_{1_i}}{\bar{g}_1}\right)^{\left(\frac{A_2}{A_1}\right)^{\beta}} \quad (7)$$

where A_1, A_2 = stand ages (y) at the beginning and end of the period,
g_{1_i}, g_{2_i} = basal areas of the ith surviving tree (cm^2) at ages A_1 and A_2,
$\bar{g}_1, \bar{g}_2$ = average basal areas of the survivors (cm^2) at ages A_1 and A_2,
β = coefficient.

The coefficient is $\beta = 0.78592$, and the error of prediction in the model is $s_{y.x}$ = 0.213 or 21.3 % (n = 2615). The standard error of estimate for β is 0.00392.

Equation (7) is compatible with the empirical observations of individual tree basal area development (Pienaar & Harrison 1988). Over a short period of time, the relative tree size ($g_i/\bar{g}$) remains constant. Over a longer period of time the relative size of an individual survivor ($g_i/\bar{g}$), and therefore the relative contribution of smaller than average-sized survivors to the total basal area, decreases, whereas the relative size of the largest trees increases. For the same period length, the change in relative size decreases as age increases. Equation (7) is independent of stand density (stems per hectare) and of site quality.

For small trees (relative size less than 0.2), our model tends to produce a moderate underestimation. If the projection period is short and the range of diameters exceptionally large, then very small trees may show negative growth.

A projected stand table at age A_2 consistent with the projected per-hectare basal area is obtained (Pienaar *et al.* 1990a):

$$N_j g_{2_j} = G_2 \frac{N_j\left(\frac{g_{1_j}}{\bar{g}_1}\right)^{a}}{\sum_{j=1}^{k} N_j\left(\frac{g_{1_j}}{\bar{g}_1}\right)^{a}} \quad (8)$$

where N_j = number of survivors in dbh-class j (j=1,k) at age A_1,
g_{1_j} = basal area corresponding to midpoint of dbh-class j at age A_1,
g_{2_j} = basal area corresponding to midpoint of dbh of the N_j survivors at age A_2,
$\bar{g}_1$ = average basal area of the $N = \sum N_j$ survivors at age A_1,
G_2 = total basal area (m² ha⁻¹) at age A_2,
a = $(A_2/A_1)^{0.78592}$.

The stand table projection procedure requires a prior estimate of future survival N_2 (eq. 4) and a per-hectare basal area G_2 (eq. 6). In addition, the predicted total mortality must be identified in the initial stand table by dbh-class. This is accomplished by assuming that the probability that a tree in a given dbh-class will die during the projection interval is inversely proportional to its relative size defined as $g_{1_j}/\bar{g}_1$. Having identified the trees predicted to die during the projection interval, the relative sizes of the dbh-class midpoints are recalculated for the survivors only and are then projected according to equation (8) to obtain future dbh-class midpoints. The diameters of the survivors can further be distributed within dbh-classes by assuming that the trees are uniformly distributed around the projected dbh-class midpoint.

A worked example of stand projection

The procedure of projecting stand and tree parameters obtained from a stand inventory is illustrated in a stand which is 4 years of age at the inventory. The measured stand parameters are first projected up to the age of 5 years (Table 2). Then the initial stand table is projected such that it remains consistent with projected survival and per-ha basal area. First, mortality (N_1-N_2) is identified for each initial dbh-class (Table 3). From the surviving trees, a new initial stand table is constructed and the dbh-class midpoints are projected up to the age of 5 years (Table 4). A restriction was imposed that diameter growth may not be negative. The final diameter distribution was not transformed into one with integer class intervals.

Table 2. Current stand and with the growth models projected stand

	Current stand	Projected stand
A (y)	4.0	5.0
h_{dom} (m)	15.4	19.1 (eq. 2)
N (stems ha⁻¹)	1574	1507 (eq. 4)
G (m² ha⁻¹)	17.1	22.9 (eq. 6)

Table 3. Calculations to predict mortality (eq. 4) by dbh-class

Dbh-class	N_{1_j} ha^{-1} (1)	G_{1_j} (m^2 ha^{-1})	$\bar{g}_1/g_{1_j}$ (2)	(2)/Σ(2) (3)	(1)/Σ(1) (4)	(3)x (4)/Σ(3x4) (5)	Mortal. 67*(5)
2	62	0.019	34.50	0.420	0.039	0.383	26
3	77	0.054	15.33	0.186	0.049	0.212	14
4	62	0.078	8.63	0.105	0.039	0.096	6
5	31	0.061	5.52	0.067	0.020	0.031	2
6	77	0.218	3.83	0.047	0.049	0.053	4
7	46	0.177	2.82	0.034	0.029	0.023	2
8	15	0.075	2.16	0.026	0.010	0.006	0
9	46	0.293	1.70	0.021	0.029	0.014	1
10	139	1.092	1.38	0.017	0.088	0.034	2
11	201	1.910	1.14	0.014	0.128	0.041	3
12	170	1.923	0.96	0.012	0.108	0.029	2
13	248	3.292	0.82	0.010	0.158	0.036	3
14	108	1.663	0.70	0.009	0.069	0.014	1
15	139	2.456	0.61	0.007	0.088	0.015	1
16	46	0.925	0.54	0.007	0.029	0.004	0
17	46	1.044	0.48	0.006	0.029	0.004	0
18	15	0.382	0.43	0.005	0.010	0.001	0
19	31	0.879	0.38	0.005	0.020	0.002	0
21	15	0.520	0.31	0.004	0.010	0.001	0
	1574	17.1	82.24	1.0	1.0	1.0	67

Table 4. Calculations to project the stand table (eq. 8) after removal of predicted mortality

Dbh-class	N_j ha^{-1} survivors	G_{1_j} (m^2 ha^{-1})	$N_j(g_{1_j}/\bar{g}_1)^a$ (1)	(1)/Σ (1) (2)	$g_{2_j} = G_2(2)/N_j$	d_2
2	36	0.011	0.51	0.000	2.1	1.6(2.0)
3	63	0.045	2.34	0.001	5.4	2.6(3.0)
4	56	0.070	4.14	0.003	10.7	3.7(4.0)
5	29	0.057	3.64	0.002	18.3	4.8(5.0)
6	73	0.206	14.17	0.009	28.2	6.0
7	44	0.169	12.33	0.008	40.8	7.2
8	15	0.075	5.78	0.004	56.0	8.4
9	45	0.286	22.96	0.015	74.2	9.7
10	137	1.076	89.84	0.057	95.4	11.0
11	198	1.882	162.95	0.104	119.7	12.3
12	168	1.900	170.12	0.108	147.3	13.7
13	245	3.252	300.24	0.191	178.3	15.1
14	107	1.647	156.46	0.099	212.7	16.5
15	138	2.439	237.85	0.151	250.7	17.9
16	46	0.925	92.47	0.059	292.4	19.3
17	46	1.044	106.84	0.068	337.9	20.7
18	15	0.382	39.92	0.025	387.2	22.2
19	31	0.879	93.86	0.060	440.5	23.7
21	15	0.520	57.65	0.037	559.1	26.7
	1507	16.9	1574.06	1.0		

When the models are used, the limited data (Table 1) have to be given attention. By extrapolation beyond the range of the data on which the models are based, there is a risk of bias.

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