YIELD OF *GREVILLEA ROBUSTA* IN THE MAIZE FIELDS OF KENYA

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MUCHIRI, M., MIINA, J. & PUKKALA, T. 2002. Yield of *Grevillea robusta* in the maize fields of Kenya. The study developed individual-tree diameter and height models for *Grevillea robusta* growing in the maize fields of central Kenya. This type of agroforestry farming has become very popular in the central highlands of Kenya, producing both staple food and wood for various purposes. The yield of wood of this kind of production system is most probably very significant but little investigated. This study used tree-level data from 24 temporary plots to model the dependence of tree diameter on tree age and competition by other trees. Competition was described with a competition index computed from the distances and diameters of neighbour trees. Another model was developed for predicting the tree height from tree age and diameter. The diameter model explained 65% of the variation in diameter if tree age was the only predictor and 68% if competition index was used as another predictor. The height model explained 82% of the variation in tree height. The models were utilised in a simulation model, which was run for two different initial stands, one representing a regular and the other an irregular spatial distribution of trees. In the case simulations covering 30 years, the mean annual volume increment of the rather sparse *Grevillea robusta* stands in agroforestry fields (about 200 trees ha^{-1}) ranged from 8 to 24 m^3 ha^{-1} $year^{-1}$. The highest yield for wood was obtained when the stand volume was left to increase significantly from its initial value, indicating that the current growing stock volumes are clearly too low for maximal wood production. However, higher stand volumes would most probably significantly decrease maize yields.

Key words: Agroforestry - competition index - spatial model - individual-tree model - simulation model - silky oak - silver oak - *Zea mays*

MUCHIRI, M., MIINA, J. & PUKKALA, T. 2002. Hasil *Grevillea robusta* di ladang jagung di Kenya. Kajian dijalankan untuk membina model diameter dan model ketinggian setiap pokok *Grevillea robusta* yang ditanam di ladang jagung di bahagian tengah Kenya. Perladangan hutan tani seperti ini digemari ramai di tanah tinggi bahagian tengah Kenya. Ia menghasilkan makanan asasi dan kayu untuk pelbagai kegunaan. Hasil kayu daripada sistem pengeluaran ini sangat penting tetapi kurang dibuat kajian. Kajian ini menggunakan data aras pokok daripada 24 petak sementara untuk membina model bagi kaitan diameter pokok dengan usia pokok serta persaingan

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daripada pokok lain. Persaingan diterangkan dengan indeks persaingan yang dikira daripada jarak dan diameter pokok-pokok bersebelahan. Satu lagi model dibangunkan untuk meramalkan ketinggian pokok daripada umur dan diameter pokok. Model diameter menerangkan 65% daripada perubahan dalam diameter jika umur pokok merupakan satu-satunya peramal dan 68% jika indeks persaingan digunakan sebagai peramal. Model ketinggian menjelaskan 82% daripada perubahan dalam ketinggian pokok. Model-model tersebut digunakan dalam model simulasi yang dijalankan terhadap dua dirian asal yang berbeza, satu mewakili taburan ruang biasa pokok, manakala satu lagi mewakili taburan ruang luar biasa pokok. Dalam simulasi kes yang merangkumi 30 tahun, min tambahan isipadu tahunan bagi dirian *G. robusta* yang agak jarang di ladang hutan tani (kira-kira 200 pokok ha^{-1}) berjulat daripada 8 hingga 24 m^3 ha^{-1} setahun. Hasil kayu yang tertinggi diperoleh apabila isipadu dirian dibiarkan untuk meningkat dengan bererti daripada nilai asalnya. Ini menunjukkan bahawa isipadu stok yang ditanam pada masa ini adalah terlalu rendah untuk pengeluaran kayu secara maksimum. Bagaimanapun, isipadu dirian yang lebih tinggi paling berkemungkinan akan menurunkan dengan bererti hasil jagung.

Introduction

Grevillea robusta is a native to subtropical Eastern Australia where it exists in scattered small stands in Queensland and New South Wales. It is commonly known as silky oak or silver oak. Its natural latitudinal range in Eastern Australia is 470 km, from 25° 50' S to 30° 10' S. The altitude range is from just above sea level (asl) near the coast to a maximum of 1100 m at the western extreme of its range some 160 km inland (Harwood 1992).

The first record of the species being introduced outside its natural range was in 1828 when the botanist Alan Cunningham dispatched seeds to England (Harwood 1989, Owino 1992). The species was one of the natural trees to be planted into cultivation systems within its country of origin (Lebler 1979). Since then, it has become very popular and is widely grown in agroforestry systems in East Africa and Central African highlands.

Grevillea robusta was introduced to Kenya in the late nineteenth century from India and Sri Lanka where the species had shown great potential as a shade tree in tea, coffee and cinchona plantations (Harwood 1989). By the mid-twentieth century the species had become the dominant tree for shade in coffee and tea plantations. Since then, the use of *G. robusta* as a shade tree has been declining rapidly. Nowadays the species is intensively planted as a multipurpose tree in agrisilvipastoral systems covering an estimated area of 750 000 ha in the central highlands around Mt Kenya. *Grevillea robusta* is so intensively planted in this region that it is the dominant component of the tree cover in some parts, and especially on eastern and southern slopes. It was estimated that *G. robusta* comprised 37% of 14 746 trees found in 254 farms which were randomly sampled in Embu district (Kamweti 1996). Tyndall counted 77 *G. robusta* trees ha^{-1} on farm land in Kirinyaga district (Akyeampong *et al.* 1999).

Most farmers in the central highlands of Kenya grow *G. robusta* for timber, poles and firewood for sale rather than as a source of providing their families with tree products and services. The species has successfully been planted on farms because it generally grows rapidly, is easy to propagate and establish, has good stem form, provides economically viable products and it is not significantly affected by pests and diseases. It develops proteoid roots, which increase its ability to harvest water and nutrients from low-fertility soils (Harwood & Booth 1992). It does not compete with adjacent crops as strongly as other species. This may be a consequence of its relatively light crown and deep root system (Mwihomeke 1992). The litter of *G. robusta* serves as organic mulch (Raju 1992). This tree can also tolerate pollarding and pruning of its roots (Harwood & Booth 1992).

The trees are either linearly or spatially arranged on farms where they are intercropped with agricultural crops such as maize (*Zea mays*), beans and bananas at various densities. The economic output of this type of farming system has not been analysed due to the lack of information on the growth of *G. robusta* in agricultural fields. Extremely high variation in stand density and spatial patterns of tree location call for distance-dependent individual-tree growth models (e.g. Lorimer 1983, Pukkala & Kolström 1987, 1991, Biging & Dobbertin 1995). None of the earlier studies on the yield and growth of *G. robusta* attempted to construct this type of models (e.g. Abebe 1992, Habiyambere & Musabimana 1992, Kalinganire & Zuercher 1992, Kamweti 1992, 1996, Okorio & Peden 1992, Otieno 1992, Ling 1993, Akyeampong *et al.* 1999, Kiriinya 1999).

The objective of this study was to construct distance-dependent individual-tree diameter and height models that could be used to predict the development of *G. robusta* trees in agroforestry systems. The models developed in this study were based on tree measurements on temporary plots. As the periodical growth of the measured trees was not known, we developed models that predicted the total diameter and height growth as a function of tree age and between-tree competition. The models were used to develop a simulation system, which enabled the simulation of the growth of *G. robusta* trees in the agroforestry system. Simulation examples are provided for two fields.

Materials and methods

Study site

The study was carried out on the eastern slopes of Mt Kenya in Meru south district, central highlands of Kenya, longitude 37° 40' E and latitude 0° 18' S and altitude 1400 m asl. The area is classified as agro-ecological zone of coffee (UM2) (Jaetzold & Schmidt 1982). The mean annual temperature is 18 to 20 °C. The rainfall pattern is bimodal with an annual mean of 1000 to 1600 mm. The first rainy season is from mid March to late May and the second is between mid October and end of December. Dry seasons are from January to mid March and mid August to mid October. Soils are volcanic, very deep, well-drained and dark reddish brown.

Fields and measurements

The study data were collected from 24 fields (small-scale farms) which were subjectively selected so as to collect tree (*G. robusta* and other species) data at varying spatial arrangements, densities and tree size (Table 1). The type of tree arrangement varied from random to linear; densities from low to high; and size from very small to very large (Table 2). The site characteristics were quite similar for all the fields and homogenous in each field. Most of the fields had maize intercropped with trees. One plot was measured in each field. The plots were rectangular and of varying sizes with the smallest being 0.012 ha (2 × 60 m) and the largest 0.63 ha (50 × 125 m). Trees were also measured in a 10-m buffer zone around the plot.

All trees in a plot were measured for the following variables: tree species, coordinates (x, y), diameter at 1.3 m (dbh), approximate age (for *G. robusta* only) and pollarding (pollarded or not). The age was given by the farmers and may not always be accurate. The total height was measured for every tenth tree starting with the first tree measured. Out of the 919 trees measured for dbh, 857 were *G. robusta*. Height was measured for 123 of trees.

Table 1 Characteristics of sample plots. Plots 10 and 13 represent dense rows of boundary trees.

Plot number	Plot area (m^2)	N (ha^{-1})	D (cm)	H (m)	T (year)	G (m^2 ha^{-1})
1	3600	189	14.0	10.2	7.8	6.3
2	1600	256	25.3	19.4	12.0	13.3
3	1920	125	28.9	20.2	13.0	9.3
4	2640	231	28.0	19.4	14.6	16.6
5	1600	225	22.9	18.0	13.6	10.2
6	3024	99	29.8	20.8	15.7	8.3
7	3200	225	29.2	21.7	16.8	16.3
8	4752	53	43.0	26.8	25.5	7.8
9	3200	169	28.8	21.8	18.0	12.2
10	166	2470	27.5	21.4	18.2	154.6
11	5300	143	24.2	16.7	11.0	8.9
12	2772	144	25.1	19.5	15.4	8.3
13	120	1917	25.2	18.8	15.0	96.8
14	625	192	23.1	22.1	11.3	8.5
15	1925	265	27.4	21.6	18.4	16.4
16	3600	236	25.9	21.1	18.4	13.6
17	2500	20	84.0	37.9	45.0	11.2
18	2500	160	25.1	19.4	15.7	9.2
19	2000	285	22.6	18.5	15.2	12.7
20	4200	83	30.4	19.8	17.5	8.3
21	6000	162	24.7	18.7	14.5	9.0
22	6250	203	24.3	18.9	16.2	11.4
23	750	280	8.8	9.0	5.4	2.6
24	400	275	8.8	8.0	7.3	4.2

N = number of trees, D = mean tree diameter, H = mean height, T = mean age of trees,
G = stand basal area

Table 2 Mean, SD and range of some variables in the study material for dbh and height models

Variable	Mean	SD	Minimum	Maximum
Dbh model				
Dbh (cm)	26.3	11.0	1.7	95.3
Age (year)	15.7	6.4	1.0	45.0
CI2	0.13	0.18	0.00	1.31
Height model				
Height (m)	18.7	8.6	1.6	40.2
Dbh (cm)	25.8	17.1	1.7	95.3
Age (year)	14.7	9.3	1.0	45.0

Regression modelling

The purpose was to prepare models that enabled the prediction of diameter and height development of trees in *G. robusta*-maize agroforestry fields, as a function of tree age and competition by other trees. The stand basal area and some distance-dependent competition indices were used to describe the competition that a tree faced. Due to the high within-field variation in stand density, the competition indices correlated better with diameter and height than with the distance-independent stand basal area. The following indices were tested (Hegyi 1974):

$$CI1 = \sum_{k=1}^{n} d_k / s_k \tag{1}$$

$$CI2 = \sum_{k=1}^{n} d_k^2 / s_k \tag{2}$$

where

d_k = diameter (cm),
s_k = distance (m) of competitor k and
n = number of competitors.

Both indices were tested using 6, 8 and 10 m competition distance (neighbour trees within 6, 8 or 10 m were included). *CI2* with 8-m competition distance correlated most strongly with diameter and was, therefore, used in the dbh model. Note that competition indices that included the diameter of the subject tree could not be used because, when predicting future diameters with the model, the diameter of the subject tree was unknown.

The fact that trees in the same field were correlated observations was taken into account in modelling. Both the diameter and height models were random parameter models with the following form:

$$d_{ij} = f_1\left(a_{ij}, CI2_{ij}\right) + p1_i + e1_{ij} \quad (3)$$

$$h_{ij} = f_2\left(a_{ij}, d_{ij}\right) + p2_i + e2_{ij} \quad (4)$$

where

d_{ij}, h_{ij} and a_{ij} = diameter (cm), height (m) and age (years) respectively of tree j in field i

$CI2_{ij}$ = competition index computed for tree j in field i

$p1_i$ and $p2_i$ = random field factors $p1_i \sim \mathrm{Nid}(0, \sigma^2_{p1})$ and $p2_i \sim \mathrm{Nid}(0, \sigma^2_{p2})$ and $e1_{ij}$ and $e2_{ij}$ = random tree factors $e1_{ij} \sim \mathrm{Nid}(0, \sigma^2_{e1})$ and $e2_{ij} \sim \mathrm{Nid}(0, \sigma^2_{e2})$.

It was found that the presence or absence of pollarding did not affect the relationship between tree age and diameter, and variables describing pollarding were therefore not needed predictors in the diameter model. The height model predicted the height of a non-pollarded tree. To enable the simulation of the temporal development of tree diameter, a distance-independent diameter model was also needed:

$$d_{ij} = f_3\left(a_{ij}\right) + p3_i + e3_{ij} \quad (5)$$

The models were estimated with the MIXED procedure of the SAS software (SAS/STAT 1992, Software Release 6.07). When developing the models, different transformations of both the predicted variable and predictors were tested in modelling, as well as different combinations of predictors. The models selected had the lowest residual variance among the tested ones, with an acceptable distribution of residuals.

Results

Models

The distance-independent and distance-dependent diameter models are as follows (*t*-values in parentheses):

$$\ln(d) = 4.668 - \frac{32.749}{(a+8)} \quad (6)$$

$$(102.6) \quad (-54.4)$$

$$\ln(d) = 4.744 - \frac{33.126}{(a+8)} - 0.398\ln(CI2+1) \quad (7)$$

$$(104.2) \quad (-56.1) \quad (-6.45)$$

where

d = dbh (cm),
a = tree age (years) and
$C12$ = competition index (equation (2)) computed using an 8-m competition distance.

The coefficients of determination (R^2) were 65.3% for the distance-independent model and 68.3% for the distance-dependent model. The root mean square errors (RMSE) were 6.46 cm for equation (6) and 6.18 cm for equation (7). The estimates for the between-field residual variance components were 0.0288 for equation (6) and 0.0275 for equation (7) (Table 3). For within-field variance the values were 0.0490 (equation (6)) and 0.0468 (equation (7)). From these variances it can be computed that a correction factor of (0.0288 + 0.0490)/2 = 0.0389 should be added to equation (6) and 0.037 to equation (7) when the models are used in a deterministic way and without knowing the random field factor.
The height model is

$$\ln(h) = \underset{(93.8)}{3.683} - \underset{(-29.3)}{1067.33}/((a+30)(d+10)) \qquad (8)$$

where h = tree height (m). This equation explained 81.9% of the variation in tree height. The RMSE of equation (8) was 3.67 m, the between-field residual variance estimate was 0.0082, and the within-field residual variance was 0.0326 (Table 3). The correction factor that should be added to the constant in a deterministic non-calibrated usage of the model was 0.0204.

According to the distance-dependent diameter model, increasing the between-tree competition decreased the diameter of a tree (Figure 1). Also, the height of a tree was affected, but not as much as the diameter (Figure 2).

Table 3 Residual variance components for random parameter models (equations (6) – (8))

Variance component or correction factor	Equation (6) (Model for *d*)	Equation (7) (Model for *d*)	Equation (8) (Model for *h*)
Between-field variance	0.0288	0.0275	0.0082
Within-field variance	0.0490	0.0468	0.0326
Total residual variance	0.0778	0.0743	0.0408
Correction factor for non-calibrated use	0.0389	0.0370	0.0204
Correction factor for calibrated use	0.0245	0.0234	0.0163

Correction factor for non-calibrated use should be added to the prediction if the model is not calibrated for a particular site or field. If the model is calibrated (the field factor is known), the correction factor for calibrated use should be added to the prediction.

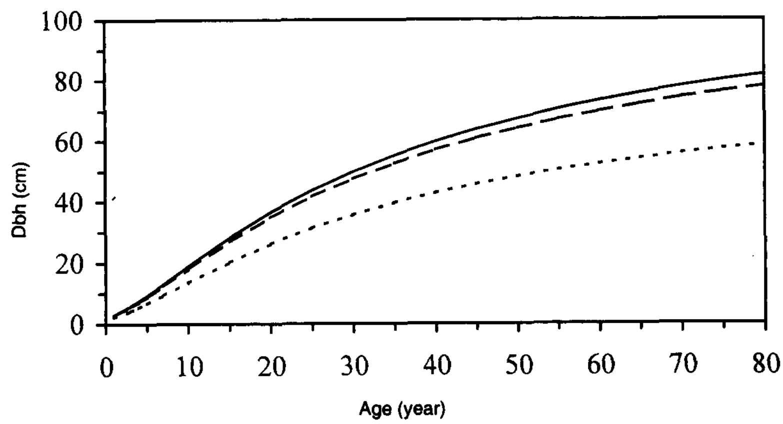

Figure 1 Development of the tree dbh as a function of age and between-tree competition. No competition *C12* = 0 (—); medium competition *C12* = 0.13 (- -); and heavy competition *C12* = 1.31 (···)

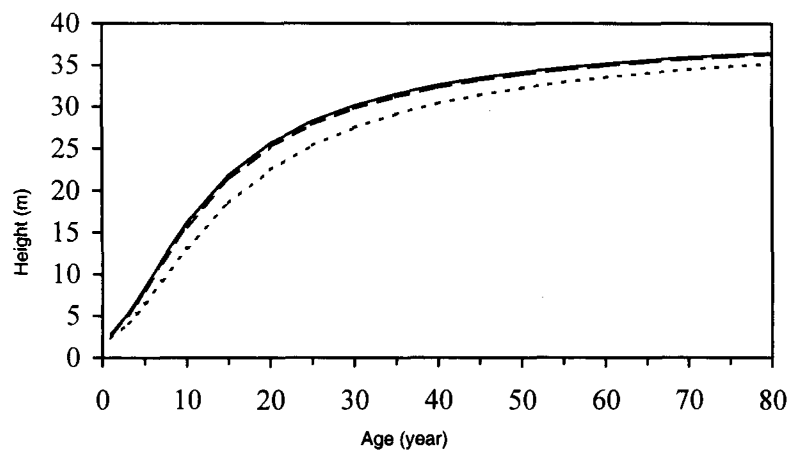

Figure 2 Development of the tree height as a function of age and between-tree competition. No competition *C12* = 0 (—); medium competition *C12* = 0.13 (- -); and heavy competition *C12* = 1.31 (···)

Simulation model

The diameter and height models were used in a simulation program that was developed to predict the growth of trees in the agroforestry field. Besides growth, the program was designed to allow the simulation of cuttings and planting of new trees. The simulation program was able to predict the wood production of a given *G. robusta* stand during any time period with any cutting and planting system.

The simulation model was initialised with an existing tree stand, with coordinates and age known for every tree. If age was unknown but dbh was known, the initial age (a) was predicted from the following equation, which we developed using the material of this study:

$$a = 0.560\, d - 0.0346\, d \times P \tag{9}$$

where $P = 1$ if the tree has been pollarded and 0 otherwise.

The development of tree dimensions was simulated as follows:

(1) increase tree ages by one year,

(2) compute dbh corresponding to the new age by using equation (6). Take the effect of competition into account by re-computing all diameters using equation (7), and repeat re-computing until diameters converge and

(3) compute tree heights corresponding to the new age and diameter using equation (8).

Simulation of thinning treatments was based on the thinning years and thinning intensities (per cent of basal area thinned) given by the user. The program removed trees, starting from the largest individual, until the harvest percentage was full.

The program did not consider mortality because in the agroforestry systems in subhumid highlands of Kenya, tree mortality is negligible after the trees are more than four years old (Milimo & Konuche 1983, Wanyiri *et al.* 2000). In the absence of a volume function for *G. robusta* (Ling 1993), the volume of every removed tree was computed with a function for *Eucalyptus grandis* (Mabvurira & Eerikäinen, pers. comm.):

$$\ln(v) = -3.872 + 0.389 \ln(d) + 2.681 \ln(h) + 1.350 \ln(d/(h - 1.3)) \tag{10}$$

where

v = stem volume in dm^3.

The program also allowed the planting of a user-specified number of new trees after a cutting. New trees are planted in places where the competition by existing trees is low. When searching for a place for a seedling, the program generated random x and y coordinates until it found a place where $CI1$ (equation 1) was less than a user-specified limit (0.3 in our simulations). The age of a seedling was taken as one year, its height as 1.3 m and dbh as 0 cm.

Case simulations

The simulation model was used to simulate the development of trees in two fields of the study material (Fields 1 and 16). Field 1 represented a uniform spatial distribution of tree locations whereas in Field 16 most trees were planted along field borders (Figure 3). Three management regimes were simulated for both fields: (1) a no-treatment schedule, (2) a schedule where 30% of the basal area was removed at 5-year intervals and 30 trees ha^{-1} were planted immediately after each thinning (thinning schedule 1), and (3) a schedule where the thinning percentage was 50% of basal area and the planting density was 50 trees ha^{-1} (thinning schedule 2) for 30 years.

In Field 1 the stand volume increased at a rate of about 17.7 $m^3 ha^{-1} year^{-1}$ in the no-treatment schedule, 7.5 $m^3 ha^{-1} year^{-1}$ in thinning schedule 1, and 3.5 $m^3 ha^{-1} year^{-1}$ in thinning schedule 2, during a 30-year simulation period (Figure 4). All three schedules maintained the number of trees ha^{-1} near the initial level of about 200 trees ha^{-1}. The mean annual removal was 10.0 $m^3 ha^{-1}$ in thinning schedule 1 and 10.7 $m^3 ha^{-1}$ in thinning schedule 2. The mean annual volume increment was 17.7 $m^3 ha^{-1}$ in the no-treatment schedule, 17.5 $m^3 ha^{-1}$ in thinning schedule 1 and 15.2 $m^3 ha^{-1}$ in thinning schedule 2.

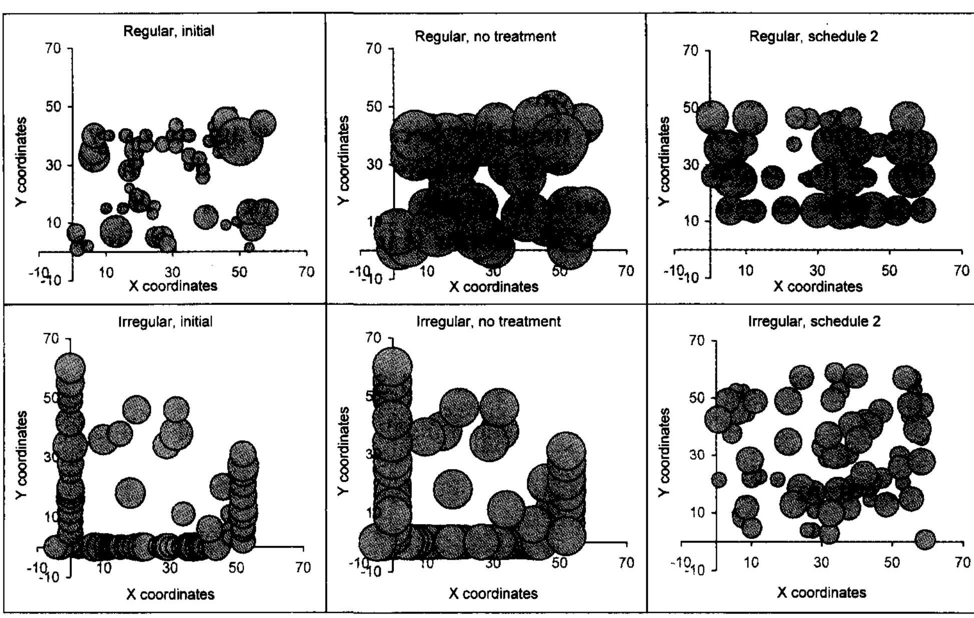

Figure 3 Dbh maps for trees in Fields 1 and 16: initial and two simulations after a 30-year simulation period. The diameter of the bubble is directly proportional to the tree dbh.

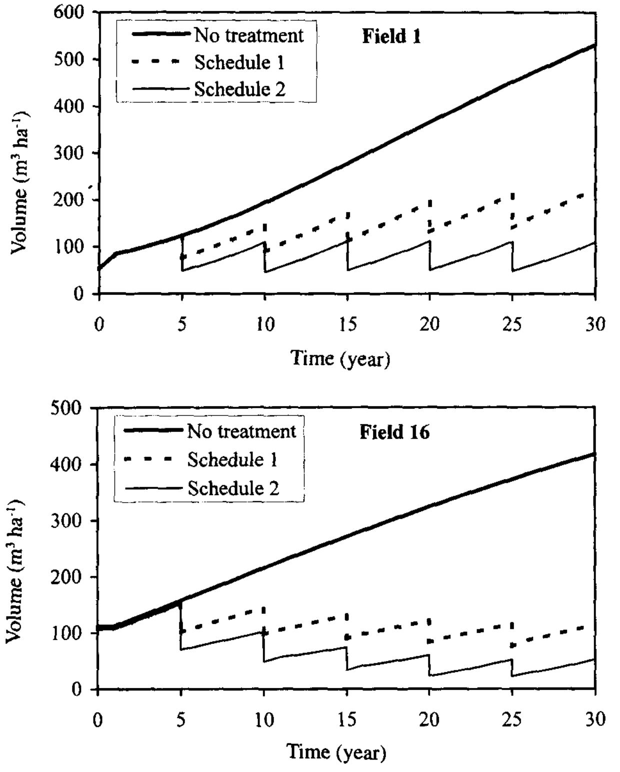

Figure 4 Development of the total stem volume ha^{-1} in Fields 1 and 16 with about 200 *Grevillea robusta* trees ha^{-1} during a 30-year simulation period

In Field 16 the trees were initially older and the growth rate was slower (the field factors $p1_i$ and $p3_i$ of equations (3) and (5) were negative). The stand volume increased at a rate of 13.9 m^3 ha^{-1} $year^{-1}$ in the no-treatment schedule, 3.8 m^3 ha^{-1} $year^{-1}$ in thinning schedule 1, and decreased by 1.8 m^3 ha^{-1} $year^{-1}$ in thinning schedule 2. The mean annual removal was 7.2 m^3 ha^{-1} $year^{-1}$ in thinning schedule 1 and 8.1 m^3 ha^{-1} $year^{-1}$ in thinning schedule 2. The mean annual volume increment of the 30-year simulation period was 13.9 m^3 ha^{-1} in the no-treatment schedule, 13.8 m^3 ha^{-1} in thinning schedule 1 and 8.5 m^3 ha^{-1} in thinning schedule 2.

Discussion

The data used to construct the models in this study were collected from temporary sample plots in *G. robusta*-agroforestry fields. The models were, therefore, static; periodical growth data of the measured trees were not available for modelling. The two individual tree diameter models presented, a distance-independent diameter model and a distance-dependent diameter model, were suitable for estimating dbh of any size or type of *G. robusta* tree in any spatial arrangement of trees. The height model was suitable for estimating the development of total height of only the unpollarded trees in similar fields. All the models were suitable for application in all site classes of *G. robusta* because site variation was taken into account in modelling through the random field factor (between-field variance component). The field factor makes it possible to calibrate the models for a particular site class or field (Lappi 1998, Eerikäinen 1999).

The distance-dependent diameter model which estimated dbh as a function of age and competition by other trees was better in terms of the coefficient of determination (68.3%) than the distance-independent diameter model which estimated dbh as a function of age (of 65.3%). However, the 3% improvement in the coefficient of determination may not be worth the extra effort and expense required to collect spatially referenced tree data (see Wimberly & Bare 1996).

The diameter models may overestimate the post-thinning diameter growth immediately after a heavy thinning because the predicted diameter depends only on tree age and post-thinning competition. Therefore, the models should not be used in simulations which include heavy thinning of dense stands. Fortunately, such thinning is not common in agroforestry fields.

The dbh values estimated by the distance-dependent diameter model (Figure 1) are within the range reported in other studies of *G. robusta*. The model predicted the dbh of a 10-year-old *G. robusta* tree growing in an agroforestry field and facing maximum between-tree competition as 13.6 cm, and 18.9 cm when there was no between-tree competition. A tree 20 years old and growing in similar conditions would have a dbh between 26.2 cm (maximum competition) and 36.5 cm (no competition). These figures compare quite well with 16.5 cm for a 10-year-old tree and 27.4 cm for a 20-year-old tree as reported by Okorio and Peden (1992). However, they differ from those estimated by Ling (1993) and Kalinganire (1996) for a 10-year-old tree. The former estimated dbh of a *G. robusta* tree at 10 years as 19.8 cm and the latter as 25.3 cm.

The distance-dependent height model (Figure 2) predicted the total height of a 10-year-old unpollarded *G. robusta* tree in an agroforestry field as 13.1 m when the competition was at maximum, and 16.1 m without competition. A 20-year-old tree would have a height between 22.5 m (maximum competition) and 25.6 m (no competition). These values are quite close to16 m at 10 years and 26 m at 20 years reported by Okorio and Peden (1992), but differ substantially from the estimates by Ling's model (1993) and those reported by Kalinganire (1996) for 10-year-old trees. The former estimated the mean height of 10 year-old *G. robusta* as 9.9 m and the latter reported it as 11 m.

For *G. robusta* trees between one and 30 years of age, growing and competing with other trees in an agroforestry field, the distance-dependent diameter model estimated a mean annual dbh growth of 1.7 cm when there was no competition and 1.2 cm with maximum competition. The distance-dependent height model estimated the mean height growth of the same trees as 1.1 m year^{-1} without competition and 1.0 m year^{-1} with competition. Thus, mean annual dbh growth was reduced by 29% when competition was at maximum while the mean annual height growth was reduced by 9%.

Kamweti (1992) reported the mean annual volume increment for a 10-year-old *G. robusta* plantation as 20.6 m^3 ha^{-1}, and Pierlot (in Kalinganire and Zuercher 1992), as 10 $m^3 ha^{-1}$ at 16 years for a stocking of 600 stems. In our simulations for two fields, the mean annual volume increment ranged from 8.5 to 17.7 m^3 ha^{-1}. These yield figures are very well in line with those of earlier studies when one takes into account that agroforestry fields represent lower stand densities than forestry plantations.

The models and the simulator developed in this study are of practical significance because they can be used to simulate wood yields of *G. robusta* for any specified cutting and planting system. They can also be used in optimising yields of a *G. robusta*-agroforestry system following the outline proposed by Pukkala (1998).

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References

ABEBE, T. 1992. Early growth performance of *Grevillea robusta* in southern Ethiopia. Pp. 111–116 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry*. ICRAF. English Press, Nairobi.

AKYEAMPONG, E., HITIMANA, E., TORQUEBIAUS, E. & MUNYEMANA, P. C. 1999. Multistrata agroforestry with beans, bananas and *Grevillea robusta* in the highlands of Burundi. *Expl Agriculture* 35: 357–369.

BIGING, G. S. & DOBBERTIN, M. 1995. Evaluation of competition indices in individual tree growth models. *Forest Science* 41 (3): 360–377.

EERIKÄINEN, K. 1999. Random parameter model for the relationship between stand age and tree height in Zambia. Pp. 151–165 in Pukkala, T. & Eerikäinen, K. (Eds.) Growth and yield modelling of tree plantations in south and east Africa. University of Joensuu, Faculty of Forestry. *Research Notes* 97: 151–165.

HABIYAMBERE, T. & MUSABIMANA, F. 1992. Effects of spacing on growth and production of *Grevillea robusta* in the semi-arid region of Bugesera in Rwanda. Pp. 99–102 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry, Proceedings of an International Workshop*. ICRAF.

HARWOOD, C. E. (Ed.) 1989. Grevillea robusta: *An Annotated Biography*. ICRAF. English Press, Nairobi.

HARWOOD, C. E. 1992. Natural distribution and ecology of *Grevillea robusta*. Pp. 21–28 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry, Proceedings of an International Workshop*. ICRAF. English Press, Nairobi.

HARWOOD, C. E. & BOOTH, T. H. 1992. Status of *Grevillea robusta* in forestry and agroforestry. Pp. 9–16 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry, Proceedings of an International Workshop*. ICRAF. English Press, Nairobi.

HEGYI, F. 1974. A simulation model for managing jack-pine stands. Pp. 74–90 in Fries, G. (Ed.) Growth models for tree and stand simulation. Royal College Forest. *Research Note* 30.

JAETZOLD, R. & SCHMIDT, H. 1982. *Farm Management Handbook of Kenya* . Volume II. Central Kenya, Ministry of Agriculture, Nairobi.

KALINGANIRE, A. 1996. Performance of *G. robusta* in plantations and on farms under varying environmental conditions in Rwanda. *Forest Ecology and Management* 80: 279–285.

KALINGANIRE, A. & ZUERCHER, E. 1992. Provenance trials of *Grevillea robusta* in Rwanda: interim results. Pp. 103–110 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry, Proceedings of an International Workshop.* ICRAF. English Press, Nairobi.

KAMWETI, D. M. 1992. Growth and utilization of *Grevillea robusta* around Mt Kenya. Pp. 73–80 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry, Proceedings of an International Workshop.* ICRAF. English Press, Nairobi.

KAMWETI, D. M. 1996. Assessment and prediction of wood yield from agroforestry systems in Kenya. Ph. D. thesis, University of Nairobi.

KIRIINYA, C. 1999. The best way to manage *Grevillea. Agroforestry Today* 11(1–2): 34–35.

LAPPI, J. 1998. Calibration of height and volume equations with random parameters. *Forest Science* 37(3): 781–801.

LEBLER, B. A. 1979. The grevilleas of south-east Queensland. *Queensland Agricultural Journal* 105: 177–187.

LING, E. 1993. *Socio-economic Evaluation of Intercropped* Grevillea *on Small-scale Farms in Kirinyaga District, Kenya.* Sveriges Lantbruksuniversitet Institutionen för Skogsekonomi. 42 pp.

LORIMER, C. G. 1983. Tests of age-independent competition indices for individual trees and natural hardwood stands. *Forest Ecology and Management* 6: 343–360.

MILIMO, P. B. & KONUCHE, P. K. A. 1983. *Interim Results of Registered Experiment 257/66. A Spacing Experiment of* Cupressus lusitanica *(Miller).* Draft technical note, Kenya Forest Department, Nairobi.

MWIHOMEKE, S. T. 1992. A comparative study of the rooting depth of *Grevillea robusta* interplanted with sugar-cane along contour strips. Pp. 117–124 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry, Proceedings of an International Workshop.* ICRAF. English Press, Nairobi.

OKORIO, J. & Peden, D. 1992. The growth performance of *Grevillea robusta* in the highlands of Uganda. Pp. 87–98 in Harwood, C. E. (Ed.) Grevillea robusta in *Agroforestry and Forestry, Proceedings of an International Workshop.* ICRAF. English Press, Nairobi.

OTIENO, H. J. O. 1992. Growth performance of *Grevillea robusta* in various-ecological zones of Siaya District, Western Kenya. Pp. 81–85 in Harwood, C. E. (Ed.) Grevillea robusta in *Agroforestry and Forestry, Proceedings of an International Workshop.* ICRAF. English Press, Nairobi.

OWINO, F. 1992. Trends in growing and utilization of *G. robusta* as an exotic. Pp. 17–19 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry, Proceedings of an International Workshop.* ICRAF. English Press, Nairobi.

PUKKALA, T. 1998. Modelling tree-crop interactions in agroforestry systems. Pp. 117–130 in Pukkala, T. & Eerikäinen, K. (Eds.) Modelling the Growth of Tree Plantations and Agroforestry Systems in Southern and East Africa. University of Joensuu, Faculty of Forestry. *Research Notes* 80.

PUKKALA, T. & KOLSTRÖM, T. 1987. Competition indices and the prediction of radial growth in Scots pine. *Silva Fennica* 21(1): 55–67.

PUKKALA, T. & KOLSTRÖM, T. 1991. Effect of spatial pattern of trees on the growth of a Norway spruce stand. A simulation model. *Silva Fennica* 25(3): 117–131.

RAJU, K. R. T. 1992. Silver oak (*Grevillea robusta*) a multipurpose tree for arid and semi-arid regions. Pp. 55–58 in Harwood, C. E. (Ed.) Grevillea robusta *in Agroforestry and Forestry, Proceedings of an International Workshop.* ICRAF. English Press, Nairobi.

WANYIRI, J. M., KAGOMBE, J. K. & MWANGEKA, N. 2000. *Review of the Implementation and Management of the Non-resident Cultivation in Kenya.* Final draft report, Kenya Forestry Department, Nairobi.

WIMBERLY, C. M. & BARE, B. B. 1996. Distance-dependent and distance-independent models of Douglas-fir and western hemlock basal area growth following silvicultural treatment. *Forest Ecology and Management* 89: 1–11.