The GMIX3.2 forest model for estimating carbon sequestration by mixed species plantations in Ghana

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Introduction

GMIX 3.2 is a model which has been developed for Arborcarb Ltd to provide forecasts of timber volumes, biomass and sequestered carbon from plantations of mixed indigenous species in Ghana. Its purpose is to support financial and operational planning for such plantations, with special emphasis on valuation of sequestered carbon.

The model is based on a long history of permanent sample plot work in Ghana to establish typical species growth rates, together with other Ghanaian forestry research on crown dimensions, tree volumes, and biomass conversion factors. These methods and coefficients are detailed in this report.

GMIX 3 is an evolution of two earlier and similar models prepared for Arborcarb Ltd during 2008. The first, GMIX, was a simplified indicative model for general mixtures of indigenous species, completed during February 2008. The second version, GMIX 2, was finalised during June 2008 and provides individual functions for 33 indigenous species identified as appropriate for mixed-species plantations. GMIX 3.2, described here, adds calibration for four exotic species that may be used as project components: Cocoa (*Theobroma cacao*), Cedrela (*C. odorata*), Rubber (*Hevea brasiliensis*) and Teak (*Tectona grandis*). Additionally, to assist in species selection and planning, it adds a GIS tool which can display various map layers and species mixtures for inventoried forest reserves. An earlier version, GMIX 3.1, is identical to GMIX 3.2 except that it lacks calibration for the four exotic species.

Using the model

Installation

GMIX 3.2 comprises an Microsoft Excel workbook file with integrated Visual Basic modules, together with a number of directories containing map coverages and tree distribution data. In order to run, it also requires that the ESRI MapObjects 2 runtime library is installed on the target system. The system is designed to run on versions of Microsoft Windows XP and compatible systems with Microsoft Office 2003 or higher installed.

Assistance with installation can be provided by the author (contact denis@bio-met.co.uk) subject to Arborcarb Ltd prior authorisation.

Workbook contents

When GMIX3 is opened, it will show the tabs listed in the table below.

Worksheet	Description
Silviculture	Defines the species to be planted, their harvesting, and the site type being planted. The user can amend these settings to reflect the scenario being considered. The **Update** button on this sheet runs the model and updates the output tables and charts, based on the silviculture settings. The **Map Tool** button opens the mapping components.
YieldFig	A chart showing the three top line indicators of forest performance over the first one hundred years from planting. These are total tree carbon, standing basal area, and volume mean annual increment.
CarbonPools	A chart showing the carbon sequestered in various carbon pools over the first one hundred years from planting. This includes trees (above and below ground), deadwood and litter, wood products, and fossil fuel substitution.
YieldTable	This is the main output table from the model, and shows for each year the standing stock parameters (tree numbers, basal area, volume and biomass), timber yield and mean annual increment, and sequestered carbon in trees, deadwood, products and as fuel substitution.
SpeciesTable	A summary table of species composition by year. It can show one of the following parameters for each planted species: Basal area (m^2/ha), bole volume (m^3/ha), stocking (n/ha) or mean BA diameter (cm)
SizeClassBySpp	Gives more detail on species composition, with one row each per species and year giving total stocking, basal area, crown percentage, and tree nubers by diameter classes.
Parameters	This table gives the various coefficients that control the calibration of the model. This includes species parameters for 33 indigenous species and 4 exotics, and whole stand coefficients.

Running the model

A scenario for a model run is set up via the Silviculture sheet, as illustrated in Figure 1. The main areas on this that can be edited by the user are:

Figure 1 : Silviculture sheet used to set up a model scenario

Silvicultural Options

Planting Density				Site type		
2	x	2	m	2 - Moist Semi-deciduous	Map Tool	Update
equivalent to		2500	per ha			

	Species list			Planting			
	Trade name	Botanical Name	Code	Plant	%	⌘	N/ha
13	Edinam	Entandrophragma angolense	EA				
14	Sapele	Entandophragma cylindricum	EC	✓	10%	⌘	250
15	Candollei	Entandrophragma candollei	ECL				
16	Utile	Entandophragma utile	EU	✓	10%	⌘	250
17	Guarea	Guraea cedrata	GC				
18	Hyedua	Guibourtia ehie	GE				
19	Rubber	Hevea brasiliensis	HEV				
20	Niangon	Heritiera utilis	HU				
21	African Mahogany	Khaya anthotheca, grandifolia	KA				
22	African Mahogany	Khaya ivorensis	KI				
23	African Walnut	Lovoa klaineana, trichilioides	LOV				
24	Mansonia	Mansonia altissima	MAN	✓	16%		400
25	Odum	Milcia excelsa, regia	MIL				
26	Kusia	Nauclea diderrichii	NAU	✓	16%		400
27	Danta	Nesogordonia papaverifera	NES				
28	Dahoma	Piptadeniastrum africanum	P	✓	16%		400
29	Asoma	Parkia bicolor	PAR				
30	Afrormosia	Pericopsis elata	PER				
31	Asanfena	Pouteria altissima, robusta	POU				
32	Kyerere	Pterygota macrocarpa	PTM				
33	Otie	Pycnanthus angolensis	PYC				
34	Afina	Strombosia glaucescens	STG				
35	Ohaa	Sterculia oblonga	STO				
36	Wawabima	Sterculia rhinopetala	STR				
37	Teak	Tectona grandis	TEC				
38	Cocoa	Theobroma cacao	THE				
39	Emire	Terminalia ivorensis	TI				
40	Makore	Tieghemella heckelii	TIE				
41	Wawa	Triplochiton scleroxylon	TRI	✓	16%		400
42	Ofram	Terminalia superba	TS	✓	16%		400
43	Avodire	Turraeanthus africanus	TUR				
44			Total	7 sp.	100%		2500

Harvesting			
Year	Fell %	Dmin	Species
10	33%	20	MAN, NAU, P, TRI, TS
20	33%	20	MAN, NAU, P, TRI, TS

Other options		
Run model for	100	years

Planting density The general spacing for planting is given by entering values in cells C2 and E2, for example, 2 x 3 m, or 3 x 4 m plantings. The number of trees per ha will calculated from spacing in cell E3

Site type — Selecting from the drop down in cell H2 will specify a site type from moist evergreen, moist semi-deciduous, or dry semi-deciduous areas.

Planting mixture — This table is used to select which species to plant, and their proportions. Clicking in column D will toggle the tick mark on or off. Selecting several cells in column D will likewise toggle the tick mark on or off for all of them. Clicking on column F will toggle on or off the symbol ⌘. Where this is present, then a planting proportion (*eg.* 10%) in column G will be taken as a fixed value. Species without the ⌘ symbol are planted in equal proportions, and any values entered in column G will be overwritten. Double-clicking in column G causes the proportions to be re-calculated for any change in species selection or fixed planting proportions. This re-calculation also happens whenever the update button is clicked.
Column H shows the planting proportions in terms of trees/ha. It is calculated by the model from the percentage values and cannot be edited.

Harvesting — In this section, the percentage of stems to be felled in any given year can be specified. A minimum diameter can be imposed in column K, and species to be included in the harvesting in column L, listed using the codes from column C.
Note that clear felling can be specified, but the model will not simulate re-planting.

Other options — Although 100 years is the standard period of simulation for carbon credit calculations, shorter runs may be useful to quickly test different scenarios. The drop down in K23 can select runs of 25, 50 or 100 years.

Update button — The update button at L2 will run the model with the current settings. The *YieldFig*, *CarbonPools*, *YieldTable* and *SpeciesTable* sheets will be updated, with the *YieldTable* being made the active sheet while updating is progressing.

Map Tool — This button will bring up the mapping tool described on page 7.

Model outputs

The key output table for the model is the sheet *YieldTable*, illustrated in Figure 2 below. This sheet becomes active while the model is running, and will build line by line until the run is completed.

The contents of the various columns is as follows:

A Age from planting, shown in years.
B Stand basal area in m2/ha.
C Number of surviving stems per hectare.
D Diameter of the tree of mean basal area, in cm.
E Canopy percentage cover. This can be more than 100% because of the canopy layering, but will rarely exceed 150-160%.

Figure 2 Main output table from GMIX3

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	**Forest Standing Crop, Timber Yield and Sequestered Carbon**																			
2	**Stand parameters**					**Standing Trees**				**Harvest**		**Yield**		**Sequestered Carbon** (tons/ha CO2-equivalent)						
3	**Age**	**BA**	**Trees**	**Dg**	**Canopy**	**Volume, m3/ha**		**Biomass, t/ha**		**Fell**	**Volume**	**Yield**	**MAI**	**Tree bole**	**Tree**	**Tree**	**Dead**	**Wood**	**Wood**	**TOTAL C**
4	*yrs*	*m2/ha*	*n/ha*	*cm*	*%*	*Bole*	*Total*	*Wood*	*Total*	*% BA*	*m3/ha*	*m3/ha*	*m3/ha/yr*	**& crown**	**roots**	**TOTAL**	**Wood**	**Product**	**Fuel**	sequestered
5	1	0.3	1,667	1.6	16%	2.4	2.7	1.2	1.4			2.4	2.4	2.5	0.5	3.0				3.0
6	2	1.4	1,667	3.3	24%	11.0	13.1	5.6	6.6			11.0	5.5	12.1	2.4	14.5				14.5
7	3	3.1	1,667	4.9	35%	26.9	33.1	13.6	16.6			26.9	9.0	30.5	6.1	36.5				36.5
8	4	5.6	1,667	6.5	47%	50.7	63.8	25.6	32.0			50.7	12.7	58.7	11.7	70.4				70.4
9	5	8.6	1,667	8.1	62%	82.2	105.4	41.4	52.7			82.2	16.4	96.6	19.3	115.9				115.9
10	6	12.1	1,667	9.6	77%	119.9	156.0	59.8	77.3			119.9	20.0	141.7	28.3	170.1				170.1
11	7	15.8	1,665	11.0	92%	162.0	213.5	80.2	104.9			162.0	23.1	192.3	38.5	230.8	0.1			230.9
12	8	19.0	1,585	12.3	103%	200.0	266.4	98.2	129.9			200.0	25.0	238.1	47.6	285.7	11.7			297.4
13	9	21.0	1,406	13.8	108%	227.0	305.5	110.4	147.5			227.0	25.2	270.4	54.1	324.5	37.8			362.3
14	10	12.9	753	14.7	64%	141.8	192.3	68.7	92.5	31%	78.2	220.0	22.0	169.7	33.9	203.6	153.5	71.7	21.4	450.2
15	11	15.4	753	16.2	73%	173.8	237.6	84.0	114.0			252.1	22.9	209.1	41.8	250.9	108.5	65.0	21.4	445.7
16	12	18.1	753	17.5	83%	207.6	285.9	100.0	136.7			285.9	23.8	250.6	50.1	300.8	76.7	58.8	21.4	457.8
17	13	20.8	751	18.8	93%	242.5	336.1	116.5	160.3			320.8	24.7	293.9	58.8	352.7	54.8	53.3	21.4	482.2
18	14	23.1	731	20.1	101%	272.9	380.5	130.8	181.1			351.2	25.1	331.9	66.4	398.3	47.8	48.3	21.4	515.8
19	15	24.6	684	21.4	105%	295.2	413.9	140.9	196.1			373.4	24.9	359.5	71.9	431.4	55.6	43.7	21.4	552.2
20	16	25.5	625	22.8	107%	310.8	438.2	147.7	206.7			389.0	24.3	379.0	75.8	454.8	70.6	39.6	21.4	586.4
21	17	26.1	566	24.3	107%	322.5	457.2	152.6	214.8			400.7	23.6	393.8	78.8	472.6	85.7	35.9	21.4	615.6
22	18	26.6	512	25.7	107%	332.4	473.7	156.7	221.7			410.6	22.8	406.5	81.3	487.8	97.8	32.5	21.4	639.5
23	19	27.0	465	27.2	107%	341.4	488.9	160.5	228.2			419.6	22.1	418.4	83.7	502.0	106.2	29.4	21.4	659.0
24	20	15.9	273	27.2	63%	202.0	290.1	95.5	136.1	31%	110.3	390.6	19.5	249.6	49.9	299.5	258.5	127.8	51.6	737.3
25	21	17.5	273	28.5	68%	225.1	324.6	106.3	152.2			413.7	19.7	278.9	55.8	334.7	182.8	115.7	51.6	684.9
26	22	19.2	273	29.9	74%	248.8	360.1	117.4	168.7			437.4	19.9	309.2	61.8	371.0	129.2	104.8	51.6	656.7
27	23	20.8	273	31.1	80%	273.0	396.5	128.8	185.6			461.5	20.1	340.3	68.1	408.3	91.4	94.9	51.6	646.2
28	24	22.5	273	32.4	85%	297.7	433.8	140.3	202.9			486.2	20.3	372.0	74.4	446.4	64.6	86.0	51.6	648.7
29	25	24.2	273	33.6	91%	322.8	471.9	152.2	220.7			511.4	20.5	404.6	80.9	485.6	45.8	77.9	51.6	660.9

F Bole volume in m^3/ha over bark. This includes volume from the ground up to crown break. The is based on the volume equations of Wong & Blackett (1994).

G Total volume in m^3/ha over bark. This includes all bole and branch wood down to a 5 cm top diameter. It is calculated from the volume equations of Alder (1982).

H Bole volume expressed in tonnes/ha biomass, converted by the species average wood density.

I Above woody biomass (tonnes/ha), based on total volume (column G) multiplied by species wood density.

J Percentage of standing basal area removed in harvesting.

K Bole volume in m^3/ha removed in harvesting.

L Yield to date in m^3/ha, being the standing bole volume plus any bole volume removed .

M Mean annual increment (m^3/ha/yr) , or yield divided by stand age.

N Carbon, as CO2-equivalent tonnes/ha (t/ha CO_2-equiv.), sequestered in above ground wood (bole+branchwood).

O Estimated carbon sequestered in tree roots(t/ha CO_2-equiv.).

P Total carbon sequestered by trees (t/ha CO_2-equiv.) – the sum of N+O.

Q Carbon sequestered as logging debris, dead trees, litter and other woody dead material (t/ha CO_2-equiv.).

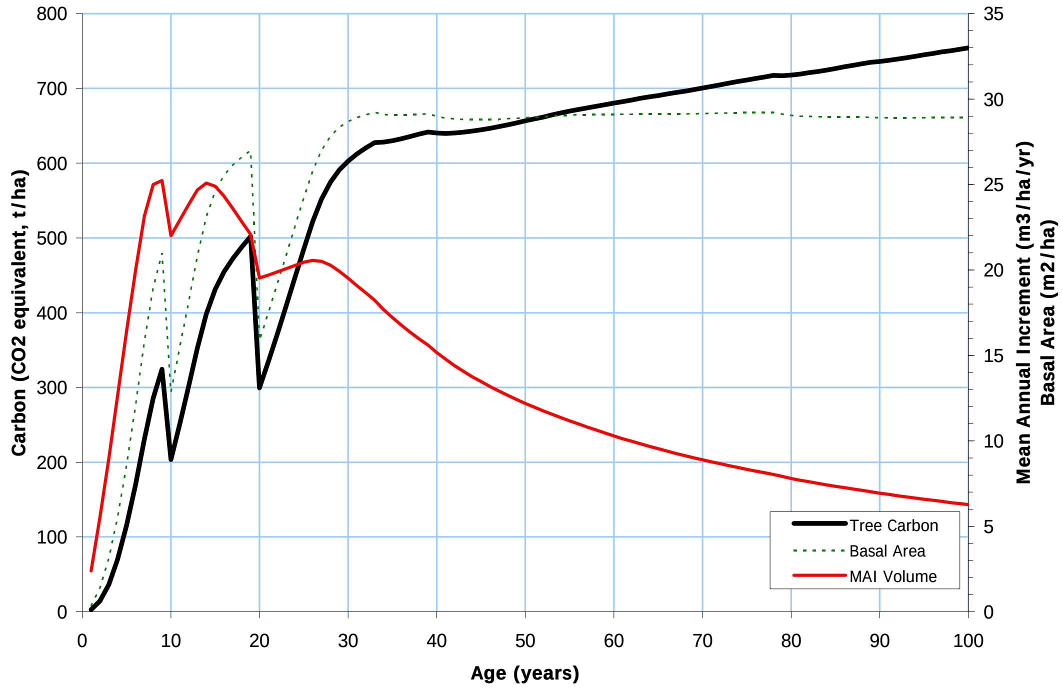
R Carbon sequestered as wood products such as timber, panel board, paper (t/ha CO_2-equiv.).

S CO_2-equivalent of fossil fuel substituted by using wood waste as fuel (t/ha CO_2-equiv.).

T Total of all sequestered CO_2, including fossil fuel substitution (sum of columns P-S).

Figure 3 below shows the chart from the GMIX3 *yieldfig* tab. It is designed to give top line indicators of total stand performance over the simulation period, including MAI (column M in Figure 2), basal area (column B) and total tree carbon (column P). It will be noted that the MAI curve, which is generally a smooth curve in conventional yield tables, shows dips after felling in GMIX3. This is due to the fact that the model accounts for felling damage, which is generally ignored by simpler models. Basal area will tend towards a limiting value which depends somewhat on species mix and site selection. Carbon will tend to accrue

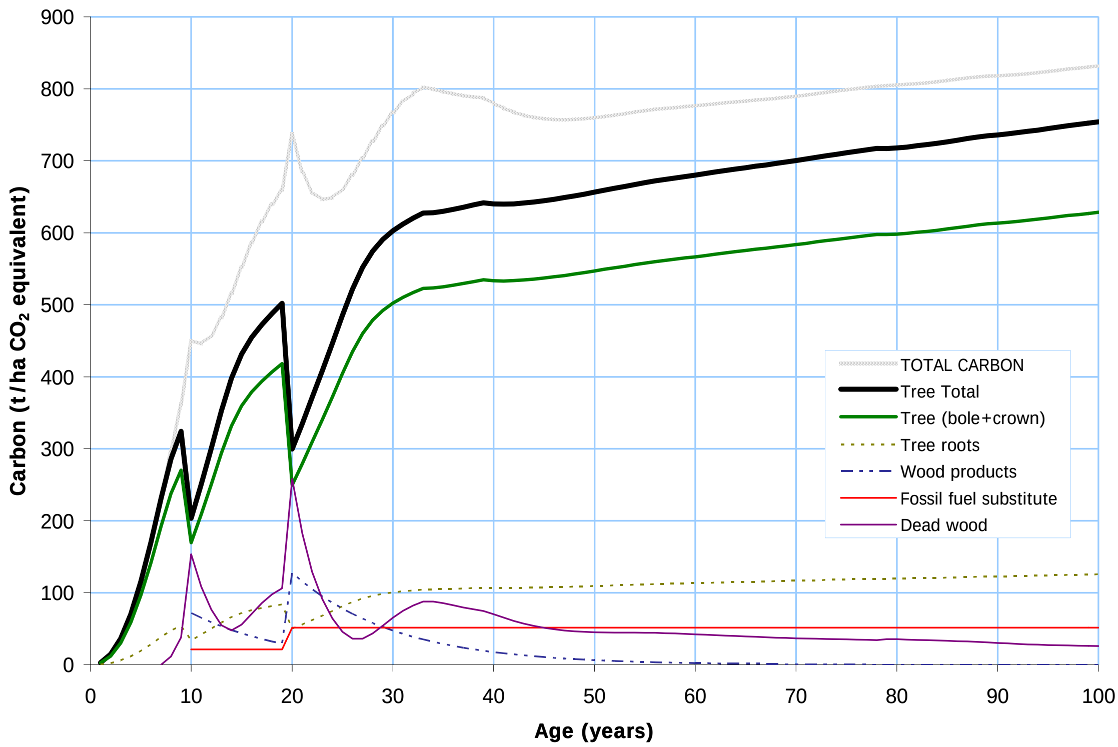
Figure 3 Chart of main yield indicators from GMIX3



proportionately with volume for the first 100 years, as trees will continue to gain in average height even at constant basal area.

Figure 4 shows the chart from the GMIX3 *CarbonPools* tab. The heavy black line shows the total tree carbon (column P on Figure 2). The green line shows above ground carbon

Figure 4 Chart of carbon pools over time from GMIX3



(column N). The pale gray line is the total sequestered carbon in all forms, including dead wood, products and fossil fuel substitution (column T). The spikes in sequestered carbon following harvest reflect accrual of carbon in products and deadwood (logging debris and conversion waste). These reduce over time back to zero as decay and respiration reduces deadwood and products.

Testing alternative scenarios

GMIX3 options are set on the *Silviculture* sheet, and the various output tables updated by clicking the Update button on that page. These results can be saved using the Excel File Save As... menu to save the resultant scenario under a suitable file title. In this way a number of scenarios can be tested and saved. The model output sheets do not contain any Excel formulae, and hence the pages can be cut and pasted as needed into other workbooks, reports and presentation formats.

Figure 5 Model coefficients from the GMIX3 parameters sheet

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Model coefficients**												
2	**Species coefficients**												
3	**Trade name**	**Botanical Name**	**Code**	**WE/ME**	**MS**	**DS**	**Guild**	**AD dom**	**AD int**	**AD sup**	**Dmax**	**Density**	**CAF**
4	Okoro	Albizia zygia	ALZ	25%	47%	29%	2	15.6	10.0	6.4	80	0.510	94%
5	Sonkyi	Allanblackia parviflora	ALL	90%	10%	0%	3	3.8	3.0	2.4	50	0.720	81%
6	Ceiba	Ceiba pentandra	CP	6%	33%	61%	1	31.6	16.2	8.3	185	0.350	120%
7	Celtis	Celtis mildbraedii, zenkeri	CEL	30%	51%	19%	3	6.1	4.9	3.9	65	0.780	88%
8	Daniella	Daniella ogea, thurifera	DAN	80%	17%	3%	1	10.7	5.5	2.8	115	0.465	104%
9	Sapele	Entandophragma cylindricum	EC	30%	59%	11%	2	5.8	3.7	2.4	130	0.640	108%
10	Utile	Entandophragma utile	EU	17%	49%	34%	2	5.6	3.6	2.3	135	0.673	109%
11	Edinam	Entandrophragma angolense	EA	33%	58%	8%	2	3.2	2.1	1.3	95	0.545	98%
12	Candollei	Entandrophragma candollei	ECL	40%	47%	13%	2	2.9	1.8	1.2	155	0.625	114%
13	Hyedua	Guibourtia ehie	GE	24%	71%	5%	2	3.0	1.9	1.2	70	0.710	90%
14	Guarea	Guraea cedrata	GC	48%	48%	4%	3	3.0	2.4	1.9	70	0.610	90%
15	Niangon	Heritiera utilis	HU	98%	1%	1%	2	4.7	3.0	1.9	80	0.625	94%
16	Mahogany	Khaya anthotheca/grandifolia	KA	26%	58%	17%	2	16.9	10.8	6.9	95	0.560	98%
17	Mahogany	Khaya ivorensis	KI	43%	38%	19%	2	16.9	10.8	6.9	130	0.560	108%
18	Walnut	Lovoa klaineana, trichilioides	LOV	60%	38%	2%	2	4.3	2.7	1.7	95	0.560	98%
19	Mansonia	Mansonia altissima	MAN	3%	43%	54%	2	5.4	3.4	2.2	70	0.625	90%
20	Odum	Milcia excelsa, regia	MIL	20%	19%	61%	1	17.7	9.0	4.6	145	0.655	112%
21	Kusia	Nauclea diderrichii	NAU	51%	41%	8%	1	7.0	3.6	1.8	115	0.735	104%
22	Danta	Nesogordonia papaverifera	NES	24%	44%	32%	3	4.6	3.7	2.9	65	0.740	88%
23	Asoma	Parkia bicolor	PAR	63%	25%	12%	2	5.2	3.3	2.1	115	0.480	104%
24	Afromosia	Pericopsis elata	PER	1%	87%	12%	2	11.9	7.6	4.9	120	0.704	106%
25	Dahoma	Piptadeniastrum africanum	P	57%	33%	10%	2	10.5	6.7	4.3	115	0.705	104%
26	Asanfina	Pouteria altissima, robusta	POU	29%	57%	14%	2	8.1	5.2	3.3	110	0.540	103%
27	Kyere	Pterygota macrocarpa	PTM	18%	61%	21%	2	6.4	4.1	2.6	90	0.625	97%
28	Otie	Pycnanthus angolensis	PYC	44%	44%	13%	2	14.2	9.1	5.8	85	0.480	95%
29	Ohaa	Sterculia oblonga	STO	30%	53%	17%	2	4.7	3.0	1.9	65	0.720	88%
30	Sterculia	Sterculia rhinopetala	STR	21%	61%	18%	2	5.3	3.4	2.2	60	0.720	86%
31	Afena	Strombosia glaucescens	STG	65%	34%	2%	3	1.9	1.5	1.2	35	0.992	73%
32	Emeri	Terminalia ivorensis	TI	33%	51%	17%	1	14.8	7.6	3.9	145	0.576	112%
33	Ofram	Terminalia superba	TS	17%	58%	25%	1	13.3	6.8	3.5	110	0.560	103%
34	Makore	Tieghemella heckelii	TIE	69%	29%	2%	2	7.1	4.5	2.9	155	0.640	114%
35	Wawa	Triplochiton scleroxylon	TRI	14%	42%	44%	1	17.3	8.8	4.5	135	0.385	109%
36	Avodire	Turraeanthus africanus	TUR	50%	49%	1%	3	5.1	4.1	3.3	75	0.560	92%
37	Cedrela	Cedrela odorata	CED	30%	60%	10%	1	14.3	7.3	3.7	130	0.560	108%
38	Cocoa	Theobroma cacao	THE	15%	70%	15%	1	8.0	4.1	2.1	15	0.625	57%
39	Rubber	Hevea brasiliensis	HEV	65%	30%	5%	1	12.3	6.3	3.2	50	0.530	81%
40	Teak	Tectona grandis	TEC	10%	40%	50%	1	10.2	5.2	2.7	145	0.750	112%
41													
42	**Whole stand coefficients**												
43	Crown diameter from tree diameter		0.828	0.1682									
44	Intrinsic growth variation		30%										
45	Limiting crown density		40%	90%	150%								
46	Bole volume equation			0.0004634	2.201								
47	Whole tree volume equation			0.0004900	2.280								
48	Root:Shoot Ratio		0.2										
49	Woody debris half-life, yrs		2										
50	Timber products half-life, yrs		7										
51	Felling damage per harvested m3		50%										
52	Processing conversion %		50%										
53	Fossil-fuel CO_2 equivalent per ton wood fuel		1.095										
54	Combustible processing residues, %		25%										
55	CO2-equiv:Biomass ratio		1.833										
56	Dominance multiplier for increment		1.25										
57	Crown radius scaling factor		0.3										

Any workbook saved from the original GMIX3.xls file will contain a complete copy of the original model. However, this will only run properly if all the sheets in the workbook are left with their original names and layouts.

GMIX3 mapping tool

General use of the mapping tool

When the Map tool button is clicked on the Silviculture sheet (See Figure 1) a display will come up as shown in Figure 6 below. The main controls and active features on this display are as follows (in approximate order of logical use):

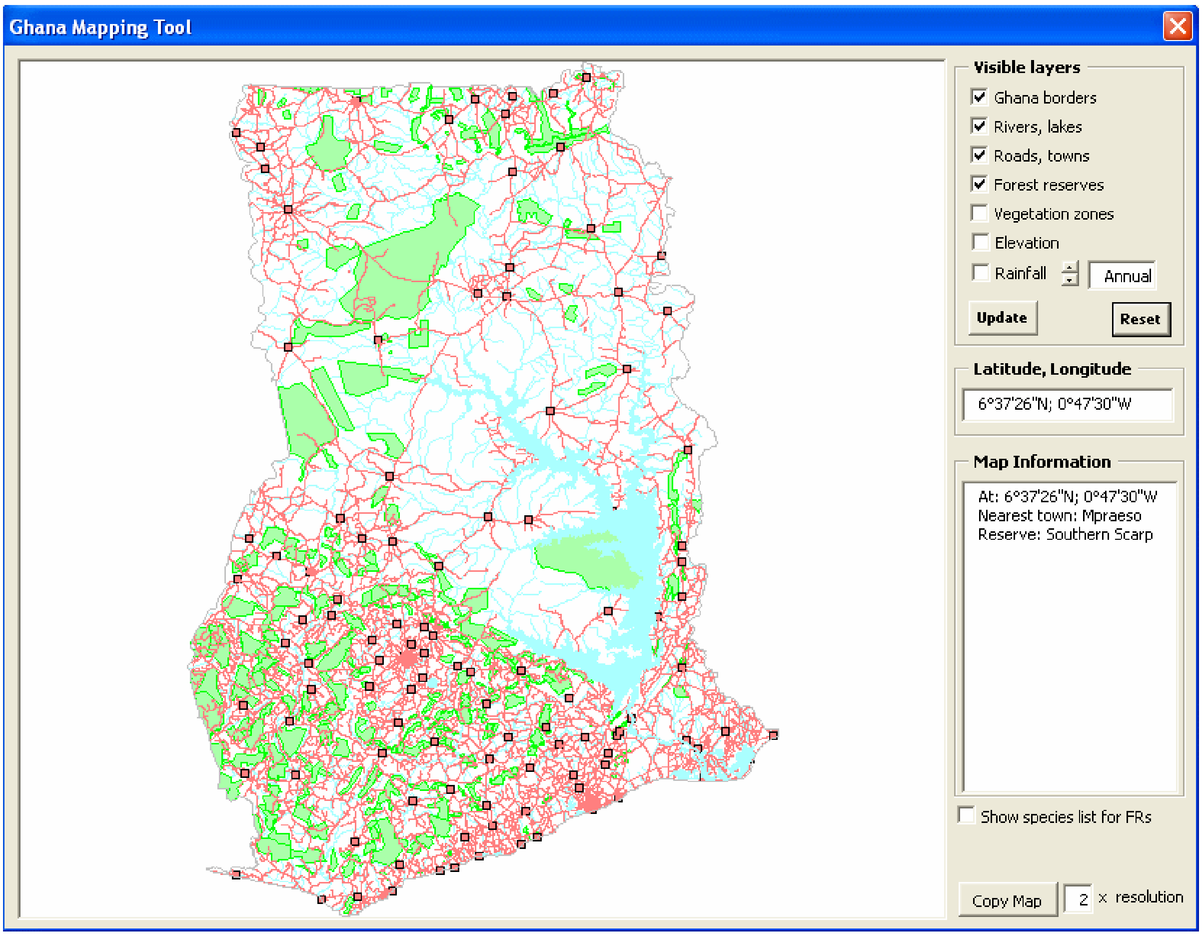
- Reset button: This will initialise the map and display in their correct order the map layers for borders, Lake Volta, rivers, forest reserves, towns and roads. The check boxes for these layers will be ticked.

- Longitude, Latitude: This will update with the current cursor position. Longitude and latitude can be used with Google Earth, for example, to locate a map feature on satellite imagery quite easily.

- Map Information: When the left mouse button is single clicked on the map, information relating to the current position will appear in this box. Only information relating to active (ticked) layers is shown.

- Zoom and Pan: Zooming in on the map is done by dragging a box with the left mouse

Figure 6 The GMIX3 mapping tool



button. When the mouse button is released, the map will zoom to the dragged area. To zoom out, double click on the map anywhere. This will zoom out to the previous view. Double clicking several times will zoom out to the full map. Dragging with the right mouse button held down will pan the map.

- Tick/Untick a named layer: When a layer is ticked, it will become visible. If the layer is a non-transparent one (this includes forest reserves, vegetation zones, elevation and rainfall), use the Update button to put the layers in their correct order, otherwise the ticked layer will hide underlying ones. When a layer is ticked, clicking on the map will bring up relevant information about that point from the layer, *eg.* rainfall, elevation, vegetation zone, name of forest reserve. Unticking a layer removes it from the map.

- Rainfall months: This shows the rainfall layer for the displayed month, or annually. These can be scrolled through rapidly to give an idea of seasonal change. Each month viewed will remain available for the map Information box until the rainfall checkbox is cleared.

- Update button: This will refresh the map and move the layers into their optimum order to view borders, hydrology, and infrastructure on top of the non-transparent layers.

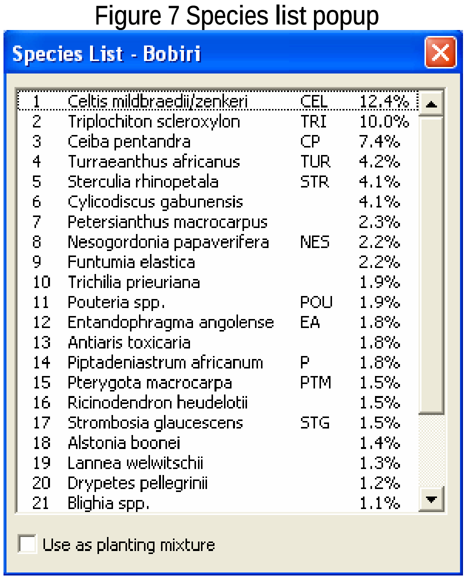
- Copy Map button: This will copy the visible map to the clipboard. The resolution can be increased to give a more detailed image For normal reproduction of maps in reports, 2x resolution is adequate. The highest resolution the system can support will depend on available RAM.

- Show Species list for forest reserves: If ticked, when the map is clicked, a popup will appear as discussed below to show a list of common species in the nearest forest reserve. If cleared, this behaviour is turned off.

Forest Reserve Species Lists

When the Show Species list for forest reserves check box is ticked, clicking on the map will produce a popup box similar to that shown in Figure 7.

Figure 7 Species list popup



This will give a list of species occurring in the nearest forest reserve, in order of abundance. The percentage basal area (equivalent approximately to percentage crown cover) of the species is listed as an abundance index. Species for which GMIX 3.2 is calibrated will have their 3-letter codes shown.

All species having an abundance index greater than 1% are listed. At the bottom of the list is indicated the total abundance (BA%) of the listed species.

Clicking the Use as planting mixture checkbox will result in the Silviculture sheet of the model being updated to show all the calibrated species in the list as a planting mixture.

The data source for these lists is the 1986-92 Forestry Department/DFID forest inventory. Not all reserves are included, especially outside the high forest zone. The list will always show species in the nearest reserve inventoried. This may be some considerable distance from the point actually clicked. By comparing the reserve name at the top of the box with the forest reserve name in the map information box, one can confirm whether or not the list refers to the actual point clicked inside any given forest reserve. Note that current stocking may differ from inventoried stocking due to subsequent forestry activities, fire damage and land use changes.

This list provides a means of identifying suitable potential species for sites. When using a list that applies to a different reserve or location, common sense must be applied in checking the similarity of seasonal rainfall, altitude and soils.

Technical specifications

General method and standards

The GMIX3 model is present as a VBA[1] program embedded within the GMIX3.xls workbook. It derives its coefficients from the data on the *Parameters* sheet, which is laid out as shown in Figure 5. Inputs, defining the initial state of the model, are set on the *Silviculture* sheet, as previously discussed (see page 2). The algorithms which define how the model functions are contained within the VBA program, and are described briefly in the various following headings.

The model complies with standards for calculation of total tree carbon and other ecosystem components. The IPCC (2006) has published guidelines and standards for National Greenhouse Gas Accounting (NGHA). The subset of these guidelines applicable to forestry are published in Volume 4 *Agriculture, Forestry and Other Land Use* (AFOLU). A set of standards for AFOLU projects in the Voluntary Carbon Sector (VCS, 2007) certification has also been published. IPCC (2006) identifies 3 tiers for methods and data sources for carbon calculations. Tier 1 are default global values and methods. Tier 2 are based on regional data, whilst tier 3 requires national data based on re-measurements on plots or experiments over 5 years or longer. VCS (2007) identifies aboveground biomass, belowground biomass, litter, dead wood and soil organic carbon and carbon in products as eligible carbon pools.

There are no specifically defined forest growth modelling methods in any of the IPCC standards. Rates of change of the various biomass pools are shown in, for example, Annex 2 of IPCC (2006) *Summary of Equations*, but no method of calculation is specified. Likewise, most FSC and similar based standards for sustainable forest management are unspecific about calculation methods for sustainable yield (see eg Washburn & Block, 2001). Certifiers will generally rely on adequate evidence for reliable empirical models or yield tables based on and validated by permanent sample plot (PSP) data.

There is a substantial history of modelling techniques in forestry (back to the 18th century) and the number of modern models is legion, at every level of sophistication, widely and routinely used for sustainable forest management. Alder (1995) describes methods for natural tropical forest modelling in a procedural manual prepared for the UK's Department for International Development (DFID). This manual updated an earlier version prepared for FAO in 1980 (Alder, 1980). The author has also prepared a procedural manual for permanent sample plots for natural tropical forest (Alder, 1992). Implemented forest growth models, used in sustainable forest management situations, developed by the author have included Brazil (Alder, 1996, Alder & Silva, 2000), Costa Rica (Alder, 1996), Ecuador (Alder

[1] VBA: Microsoft Visual Basic for Applications programming language, version 6.3.

& Montenegro, 1999), Guyana (Alder, 2001, 2002, Alder *et al* 2001) , Kenya (Alder, 1979), Papua New Guinea (Alder, 1998), and Uganda (Alder *et al*, 2003). The MYRLIN system, specifically designed for modelling natural forest management where local PSP data was limited, has been adopted by a number of small projects, particularly in South America (Wright & Alder, 2002).

Data sources

The majority of the data and coefficients applied for the GMIX3 model fall within the IPCC Tier 3 criteria. There has been extensive forestry research in Ghana since the mid-1970s, supported by FAO and DFID. In addition, Ghana has, through the Forest Research Institute of Ghana (FORIG), a long history of permanent sample plots in natural forest and of plantation trials and experiments.

The data used in the model includes tree increment data from three series of PSPs:

- PSPs established by the Forestry Department around 1968-72. These data for the basis of the GHAFOSIM model developed by the author in 1989 and of growth studies in 1992 (Alder, 1990, 1992).
- PSPs established by FORIG from 1947 onwards. This data is reviewed in Alder (1993), with further plot measurements being made on some plots by Foli (1993, 1999, 2005, Foli *et al*, 2003).
- PSPs established by the Forestry Department with DFID assistance from 1991, and re-measured in 1995 (Alder, 1995)

Altogether these PSPs comprise a substantial body of information about growth and yield of the 34 target species in the GMIX3 model. The FORIG plots are particularly relevant to plantation conditions as the experimental forest at Bobiri was largely cleared under the Tropical Shelterwood system in 1947-1955, leaving a uniform-age crop growing in the dry semi-deciduous forest zone which would likely be a primary target for rehabilitation plantings.

GMIX 3.2 also includes four exotic species: Cocoa (*Theobroma cacao*), Cedrela (*C. odorata*), Rubber (*Hevea brasiliensis*) and Teak (*Tectona grandis*). Data sources used in estimating parameters for these are as follows:

Cocoa	Zuidema *et al* (2005), Concha *et al.* (2007)
Cedrela	Alder (1996, 2001)
Rubber	Wauters et al (2008), ROCS-Ghana (2008)
Teak	Alder (1994)

DFID also maintained from 1986 onwards several ongoing projects which have provided inventory and ecological information about the major tree species and forest types. These have included volume equations (Wong & Blackett, 1994), ecological profiles (Hawthorne, 1995), as well as a substantial database of temporary inventory plots.

Local biomass equations are also available for Ghana, and represent Tier 3 coefficients for crown expansion factors. These were developed by the author as part of an FAO project (Alder, 1982, Alder & Stewart ,1982). These equations and results were incorporated in the global and regional default expansion factors published by FAO in 1996 (Brown, 1996).

Foli (2008) has recently undertaken a consultancy study reviewing all available and extant plantation trials. This extends considerably an earlier work for ITTO (Foli, 1999). This also provides important local and current, Tier 3 information on real-world growth and yield, and will also be incorporated into the GMIX3 model.

Conclusions

GMIX3 is a model for evaluation sequestered carbon and forest management options which is soundly based on a large body of growth and yield data from Ghana's indigenous forests. The major components of the model, evaluating timber volume and above ground biomass, conform to IPCC (2006) Tier 3 criteria. Tier 1 and 2 coefficients sourced from IPCC-recommended publications (*eg* Brown, 1996, Smith et al, 2002) are used to estimate below ground biomass, deadwood and carbon sequestered in products. The model is packaged as an Excel workbook, and will run on any system with Microsoft Excel installed.

Estimates from the model conform to general levels of sequestered carbon from closed canopy forest, but additionally allow multiple species interactions to be tested, especially in relation to other commercial outputs such as timber from intermediate fellings. As with any such model, it may be found in practice that specific sites or nursery stock may under-perform as a result of biotic factors such as disease or mineral deficiencies. Equally, stands may substantially exceed the estimates of the model in specific instances because of favourable circumstances. In general, the model assumes best practice nursery and planting silviculture, control of fire, and planting of mixtures rather than pure stands. Stands with few or single species will be subject to higher levels of biotic risk, and should be avoided except for species proven to be robust in this respect.

Disclaimer

Tree survival and growth can vary considerably as a result of variation in soils, hydrology and the biotic environment. Seed selection, silviculture and management also leads to great variation in yield. The information provided by the GMIX family of models represent average estimates from available information. Map coverages are based on digitised maps from 1965-1975 and are intended only as a guide. *Any reliance on model data or outputs is therefore entirely at the users own risk.*

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