

A carbon model for reforestation in the Udzungwa Corridor

Prepared under contract for the African Rainforest Conservancy, New York

by

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SUMMARY

The Udzungwa Carbon Model described in this report is in the form of a macro-enabled Excel workbook called [UCM \(v1.1\).xlsm](#). A copy of the model can be downloaded from bit.ly/arcucm11. It is based on the MYRLIN model developed from the analysis of permanent sample plots in several tropical regions. It has been calibrated for 8 species suggested for possible re-forestation work in the Udzungwa corridor area. The model shows carbon-dioxide capture for a single even-aged stand, planted as a mixture of species.

The model shows the main carbon pools, above-ground biomass, below-ground biomass, dead wood (coarse necromass), and carbon accrued in timber products. It does not show soil carbon or natural regeneration. It gives information on timber yields in terms of bole wood volume for the standing crop and intermediate thinnings, if any. The variables that the user can adjust are the planting density, the species mixture and proportions of each species, and the site quality. For harvesting, they include the timing, frequency and intensity of fellings, and selection of species to be felled.

For biomass estimation, the model uses allometric models recently developed in Tanzania for moist tropical forest. These give above ground biomass and bole volume, and below ground root biomass. Widely-used pantropical allometric equations are also compared.

The model allows additional species to be added, requiring some basic information about plant form (tree or palm), mature diameter, ecological guild and wood density, together with an estimate of site suitability. An overall site quality indicator can also be varied.

The model comprises various parameters contained in visible and hidden sheets, together with VBA code. The model is provided under an open source GNU Version 3 license.

The outputs comprise a main stand table that shows aggregate performance in terms of the normal stand parameters of age, basal area, mean diameter, stocking, bole volume, total volume, thinning volumes. It also shows biomass in tonnes CO₂-equivalent for the main carbon pools: Above ground, below ground, deadwood, and product carbon. Graphs are linked to this table which show these parameters visually. There are additional tables at the species level, including diameter distribution by species and year, stocking for each species, and volumes by species.

The model is intended as an early stage tool for feasibility assessment using best available information. The performance of tree species can never be known accurately until they are tried in situ. However, in aggregate, growth performance for mixtures of species that are known to be suited for the moist tropical forest medium altitude conditions prevailing at Udzungwa should conform to the models forecast behaviour, and it can therefore be a useful component of the planning process for this project area.

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I would like to thank Carter Coleman, of the African Rainforest Conservancy for the opportunity to undertake the work described in this report; also Fred Jailos and Theron Morgan-Brown for necessary background information and files for the study.

Abbreviations

AMR.....	Annual Mortality Rate
ARC.....	African Rainforest Conservancy
CO ₂	Carbon Dioxide
DBH	Diameter at Breast Height (1.3 m)
IPCC	Intergovernmental Panel on Climate Change
MAI.....	Mean Annual Increment
MYRLIN.....	Method of Yield Regulation with Limited Information
UCM	Udzungwa Carbon Model
VBA.....	Visual Basic for Applications

Disclaimer

This report presents the author's research, analysis, and findings as an independent consultant. Any errors or omissions are solely the responsibility of the author. It does not represent any policy or opinion of the African Rainforest Conservancy or any member of the organisation and should not be construed or referenced as such. While the author has attempted to provide decision tools with reference to the Udzungwa Corridor Project, they are based on limited information and of an interim nature, and the author can accept no responsibility or liability for any consequential outcomes based on the use of these tools.

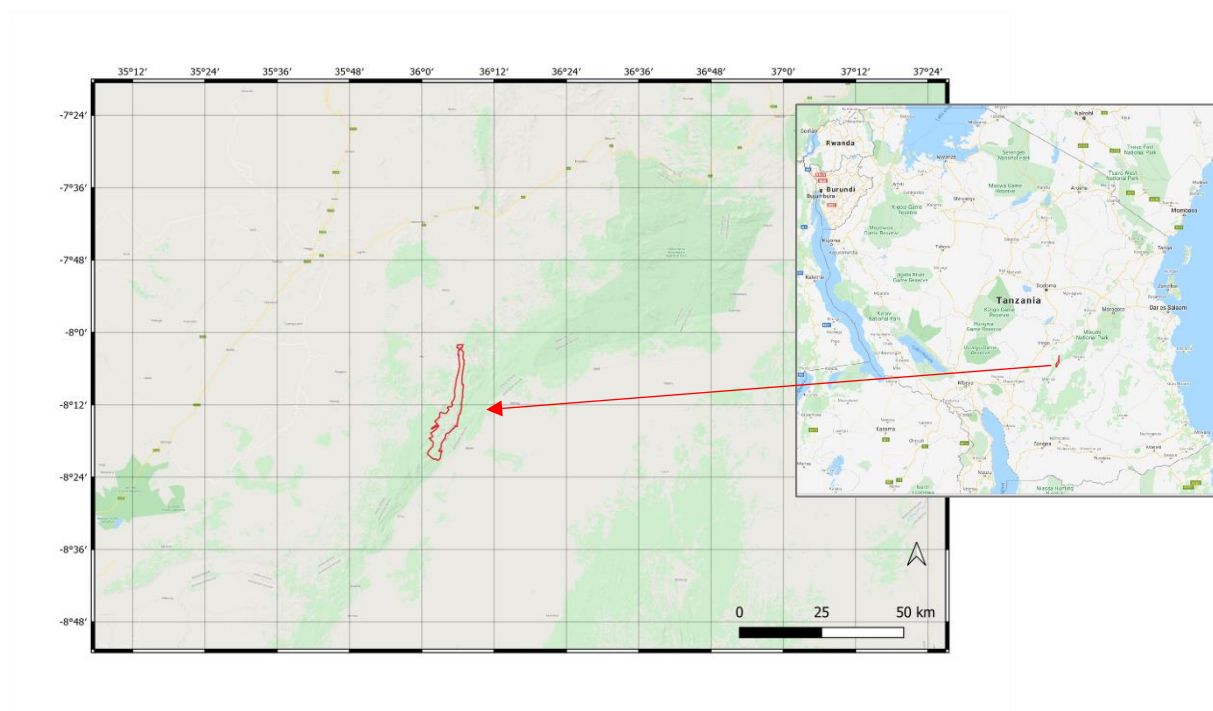
Support

The author offers email support *sine die* for the original model described here for use in its intended context as a planning tool for the Udzungwa Corridor project. This excludes substantive modifications to the model's internal design or outputs as documented here, or researching the calibration of new species. For support please email the author at post@denisalder.com.

1. Introduction

This report covers work done by the consultant at the request of the African Rainforest Conservancy (ARC) to investigate the carbon sequestration potential associated with re-forestation of Udzungwa corridor area shown in Figure 1. A recent survey report by Jailos (2020) describes the biology, soils and land use situation of the area. The main output from this consultancy is a carbon sequestration

Figure 1 : Location of Udzungwa Corridor project area



model for the Udzungwa corridor area, as a tool for use in estimating potential carbon offsets from re-afforestation. This model is contained in an Excel workbook called UCM (v1.1).xslm. This can be downloaded via the link bit.ly/arcucm11¹. This report explains the methodology, construction and use of this model, as well as giving examples of its application.

2. Species selection and growth data

2.1. Pre-selected species

The consultant was asked to consider the effect of planting eight species in various possible mixtures, as listed in Table 1. However, it was clear reviewing the report of Jailos (2020) that there may be changes and adaptations to this species list based on experience of farmers and agencies planting trees in the region, and it was in any case necessary from a growth modelling perspective to consider categories of species, in terms of growth rate, wood density, maximum size and ecology.

¹ This is an abbreviated link. The original full link is: <https://bio-met.co.uk/proj/arc/UCM%20%28v1.1%29.xslm>

Reviewing available information on the 8 species suggested that all are suitable for the area. Table 1 gives reference sources for each species that were used to develop growth models and assess suitability. The UCM model is designed to estimate the growth of mixed-species plantings, rather than monocultures as with a traditional plantation yield model.

Planting in mixtures will minimize risks from monocultures, particularly for Khaya and Milicia, which have known insect pests (*Phytolyma*, *Heteronygmia*) that are likely to be troublesome in pure stands but are not problematic when a minor proportion of a mixed stands. In both cases these pests only attack the young trees, and as these species are valuable timber trees that grow to large sizes, they are worth including as a minor proportion of mixtures in spite of this risk.

Table 1 : Initially proposed list of species for planting

Code	Species	Family	Sources
LET	Lettowianthus stellatus	Annonaciae	https://en.wikipedia.org/wiki/Lettowianthus https://www.iucnredlist.org/species/32853/132678597
COR	Cordyla africana	Fabaceae	http://pza.sanbi.org/cordyla-africana https://en.wikipedia.org/wiki/Cordyla_africana
MIL	Milicia excelsa	Moraceae	https://en.wikipedia.org/wiki/Milicia_excelsa
KHA	Khaya anthotheca	Meliaceae	https://pfaf.org/user/Plant.aspx?LatinName=Khaya+anthotheca https://en.wikipedia.org/wiki/Khaya_anthotheca
ERY	Erythrophleum suaveolens	Fabaceae	http://tropical.theferns.info/viewtropical.php?id=Erythrophleum+suaveolens https://en.wikipedia.org/wiki/Erythrophleum_suaveolens https://pfaf.org/user/Plant.aspx?LatinName=Erythrophleum+suaveolens
CRO	Croton megalocarpus	Euphorbiaceae	https://en.wikipedia.org/wiki/Croton_megalocarpus https://uses.plantnet-project.org/en/Croton_megalocarpus_(PROTA)
ACA	Acacia nilotica	Fabaceae	https://en.wikipedia.org/wiki/Vachellia_nilotica https://www.cabi.org/isc/datasheet/2342
ALB	Albizia gumifera	Fabaceae	https://uses.plantnet-project.org/en/Albizia_gumifera_(PROTA)

2.2. Growth characteristics

Growth and yield information on all the selected species is limited, but there is enough to calibrate a growth model based on the MYRLIN system (Alder et al, 2002a, b; Alder, 2020), using general indicators of tree mature size, ecology and wood density. MYRLIN is based on the analysis of many species from Permanent Sample Plots (PSPs) in the humid tropics (rainforest, moist tropical forest, and semi-deciduous forest). This analysis showed that species could be grouped based on mature diameter and mean diameter increment into groups that corresponded to their ecological guild (pioneer, light-demanding, intermediate, and shade tolerant), wood density (light, medium, dense), and their mature diameter. Table 5 in Alder (2020) gives a summary of the group characteristics, including mean diameter growth rate, mean annual mortality rate (AMR), mean wood density, and 95% percentile of the cumulative diameter distribution, corresponding to the mature diameter that the species typically achieves. This table is also embedded in the UCM model as sheet MYRLIN_ref.

In the carbon model, discussed in depth in the next section, a tool has been added that assigns the MYRLIN model based on a selection of characteristics. Figure 2 below shows the settings that have been applied for the target species. This tool is on sheet SpeciesList. Up to 20 species can be entered. The entries in columns A-D are typed in as text. Columns E-I are selected from a range of drop down options in each cell. Column J is completed automatically by a macro, using the decision tree options discussed in Alder (2020, Table 5).

Figure 2 : Growth model selection tool applied to the 8 selected species

	A	B	C	D	E	F	G	H	I	J
1	Species characteristics									
2	Code	Common name	Botanical name	Family	Form	Mature diameter	Ecological guild	Wood density	Site suitability	MYRLIN group
3	LET	Lettowianthus	Lettowianthus stellatus	Annonaceae	Tree	Medium (30-50 cm)	Light demanding	Light (0.35-0.5)	Normal, healthy	L2
4	COR	Mwumbe	Cordyla africana	Fabaceae	Tree	Large (50-80 cm)	Intermediate	Heavy (0.65-0.85)	Normal, healthy	M3
5	MIL	Mvule	Milicia excelsa	Moraceae	Tree	Very Large (80+ cm)	Light demanding	Medium (0.5-0.65)	Normal, healthy	L4
6	KHA	Mkangazi	Khaya anthotheca	Melaceae	Tree	Very Large (80+ cm)	Intermediate	Medium (0.5-0.65)	Normal, healthy	L4
7	ERY	Mucarati	Erythrophileum suaveolens	Fabaceae	Tree	Medium (30-50 cm)	Intermediate	Heavy (0.65-0.85)	Normal, healthy	M2
8	CRO	Msenefu	Croton megalocarpus	Euphorbiaceae	Tree	Large (50-80 cm)	Light demanding	Heavy (0.65-0.85)	Normal, healthy	L3
9	ACA	Mjungu	Acacia nilotica	Fabaceae	Tree	Large (50-80 cm)	Light demanding	Heavy (0.65-0.85)	Normal, healthy	L3
10	ALB	Mkenge	Albizia gumifera	Fabaceae	Tree	Large (50-80 cm)	Light demanding	Medium (0.5-0.65)	Normal, healthy	L3

3. Biomass and allometric functions

3.1. Bole and total volume

Tree bole and total volume are calculated using functions for Tanzania moist forest species taken from Masota et al (2014), Table 4. Bole volume is given by the equation:

$$V_{\text{bole}} = 0.0001364 D^{2.429} \quad \{\text{eqn. 1}\}$$

Total volume of the bole plus crown, down to a measurement limit of 2.5 cm diameter for branch wood, is given by :

$$V_{\text{total}} = 0.0006040 D^{2.190} \quad \{\text{eqn. 2}\}$$

The total volume equation was compared with the widely used pantropical equations from Chave et al (2005, 2014). The Masota equation gives lower values, but on the other hand is a locally determined (Tanzanian) Tier 3 equation according to IPCC terminology, that can be expected to be more accurate. The methodology was reviewed and also compared with the biomass equations in Malimbi et al (2016), based on the same data set for the moist tropical forest trees. The approach seems to be sound and of high quality. The Chave equation, often used for Tier 1 (generic) estimates in carbon accounting, is influenced by large data sets from Amazonia and SE Asia where trees tend to be taller and of higher volume for a given diameter. It has also been recently noted elsewhere that the Chave equation tends to give excessive values for some locales (Mundhenk et al, 2019).

In the above equations, V is wood volume overbark in m³, and D is tree diameter at 1.3 m, or above buttress where necessary, in cm.

3.2. Wood density and biomass

Once volume has been determined, biomass (B) is determined as the product of wood density and volume:

$$B = V \cdot \rho \quad \{\text{eqn. 3}\}$$

Here B is biomass in tonnes (metric tons), V is volume in m³, and ρ (rho) is the conventional symbol for wood density. In the model, the wood density is determined from the MYRLIN group, looked up from the table on the sheet MYRLIN_ref. Biomass above ground is determined from equations (2) and (3). For below ground biomass, a root expansion factor for tropical moist forest of 25% was applied, following Cairns et al (1997). Malimbwi et al (2016) give a root biomass equation for moist tropical forest in Tanzania that generally gives higher values than Cairns, but is based on a small sample of only 27 trees, so it was thought better to use the Cairns (*op. cit.*) coefficient, given its widespread acceptance for estimation of below ground biomass.

3.3. Sequestered carbon

The carbon content of biomass (C) is generally estimated by a coefficient of 0.5 (Brown, 1997; IPCC, 2006). For greenhouse gas inventories and most purposes related to carbon offsets, sequestered carbon is usually quoted as tonnes CO₂-equivalent. The ratio of CO₂-e to Carbon is 44/12, given by the relative atomic weights of CO₂ and C. Consequently, the ratio of tonnes CO₂-e to biomass is given by:

$$C_{\text{co2-e}} = 1.833 B \quad \text{\{eqn. 4\}}$$

It can be noted that if wood density is 0.545 (close to an average figure), then wood volume in m³ becomes numerically equivalent to tonnes CO₂-e. In general, we can expect the quoted above ground total tree volume to be close to above ground biomass in tonnes CO₂-e.

There is also often confusion in the literature about which units are being quoted: Volume, biomass, carbon content, or tonnes CO₂-equivalent. Even peer-reviewed publications are sometimes ambiguous, and misquoted figures are common. As a heuristic, the following points can be noted:

- Wood volume and tonnes CO₂-equivalent are numerically similar, with values for fully stocked forests around 300-600 m³/ha or t CO₂-e/ha over scales above 1 ha. Higher values occur on small plots or from yield tables, but are rarely achieved over a wider area.
- Biomass is typically around half of wood volume, depending on wood density, and may be 150-300 t/ha for fully stocked forests.
- Tonnes of carbon will be half this again, around 75-150 t/ha. Tonnes CO₂-equivalent is 44/12 or 3.67 times tonnes carbon. Tonnes CO₂-equivalent is often misquoted as tonnes carbon, causing significant confusion and understatement of figures.

In this report, depending on context, volume (m³), biomass (t) or tonnes CO₂-equivalent (t) are used, but tonnes carbon is not used in any of the reported data. For GHG accounting and carbon offset calculations, tonnes CO₂-equivalent is the primary unit that should be used.

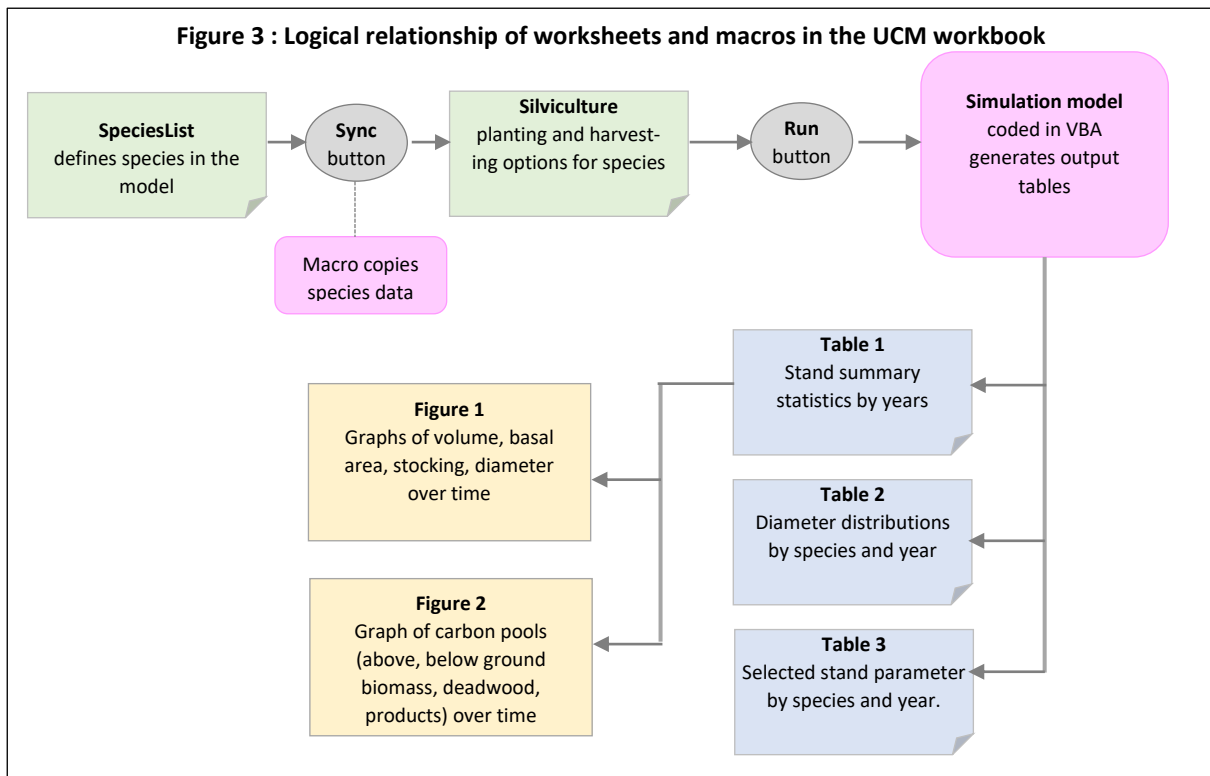
4. UCM growth model

4.1. Workbook description

The Udzungwa Carbon Model (UCM) is constructed as an Excel workbook, with worksheets for the input and output of data, some charts based on the output tables, and program code in the VBA language which provides the main functionality of the model. Figure 3 shows the logical arrangement of the worksheets and macro components in the model. The names in bold correspond to worksheet names in the Excel workbook.

The SpeciesList sheet is used to define the names and characteristics of the species recognised by the model. Not all the species need to be used in any given scenario, or run of the model. On this sheet is a Synchronize button which invokes a macro to copy the species names and codes to the Silviculture sheet. Here, the planting density and mixture can be specified, as well as the harvesting schedule, if any. There is a Run Model button which invokes the growth modelling macro. This regenerates the output tables on sheets Table1, Table2, Table3 and the charts linked to Table1, on sheets Figure1 and Figure2.

The following sections give a more detailed description of the content and usage of each worksheet.



4.2. Setting the species data for the model : SpeciesList sheet

Figure 4 shows the appearance of the SpeciesList sheet. This allows for up to 20 species to be recognised by the model. A three-letter species code, local or trade name, botanical name, and botanical family should be given in columns A-D. In column E, the tree form must be given. This can be specified as *Tree* or *Palm*, via the drop-down list in the cells.

In column F the relative size range of the tree at maturity, in terms of diameter, should be given. The drop-down menu allows for the choices *Small (below 30 cm)*, *Medium (30-50 cm)*, *Large (50-80 cm)*, *Very Large (80+ cm)*. For new species, this information can be obtained from literature, from local knowledge, or from inventory data if available. For many species, entering the Latin name in the site PlantUse will be found to give good information for this and other required characteristics. Wikipedia also often gives good information, but local experience and inventory data is the best source relative to local growing conditions.

Column G specifies the ecological guild. This refers to the light requirements of the species, and has 4 options: *Pioneer*, *light-demanding*, *intermediate*, and *shade bearer*. Again, this can be often

obtained from the botanical description or local knowledge of the ecology and occurrence. Pioneers, in the sense use here, require disturbed sites and bare soil for their regeneration, and are rare or absent in mature forest, only being found in secondary forest, roadsides and agricultural areas. Light-demanders are species that typically regenerate in forest gaps and clearings, and are rare in the forest understorey: they do not survive for long in shade. In inventory data of mature forest, they will be rare in the smaller size classes. Shade-bearers on the other hand are common in the understorey and mid-canopy; they have a typically J-shaped (exponential) diameter distribution in inventory data. They can survive for long periods and actively grow in the lower canopy. They are often trees with darker, high density timber. The intermediate trees are a large group of species, perhaps numerically the most common in mixed native forests, which are somewhat shade-tolerant and do occur in the understorey and mid-canopy, but are less able to persist and grow in such conditions. Most well-known plantation species are pioneers or light-demanders: It is unusual for a shade bearer or intermediate species to grow successfully under monoculture conditions. The most successful monoculture species in the tropics are all pioneers, such as Eucalyptus, Acacia, Pine and Cupressus species.

Figure 4 : Screen shot of the SpeciesList sheet

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Species characteristics												
2	Code	Common name	Botanical name	Family	Form	Mature diameter	Ecological guild	Wood density	Site suitability	MYRLIN group	References		
3	LET	Lettowianthus	Lettowianthus stellatus	Annonaceae	Tree	Medium (30-50 cm)	Light demanding	Light (0.35-0.5)	Normal, healthy	L2	https://en.wikipedia.org/wiki/Lettowianthus		
4	COR	Mwumbe	Cordyla africana	Fabaceae	Tree	Large (50-80 cm)	Intermediate	Heavy (0.65-0.85)	Normal, healthy	M3	http://za.wikipedia.org/wiki/Cordyla_africana		
5	MIL	Mvule	Milicia excelsa	Moraceae	Tree	Very Large (80+ cm)	Light demanding	Medium (0.5-0.65)	Normal, healthy	L4	https://en.wikipedia.org/wiki/Milicia_excelsa		
6	KHA	Mkangazi	Khaya anthotheca	Meliaceae	Tree	Very Large (80+ cm)	Intermediate	Medium (0.5-0.65)	Normal, healthy	L4	https://en.wikipedia.org/wiki/Khaya_anthotheca		
7	ERY	Mucarati	Erythrophleum suaveolens	Fabaceae	Tree	Medium (30-50 cm)	Intermediate	Heavy (0.65-0.85)	Normal, healthy	M2	http://proflora.org.za/species-profile/erythrophleum-suaveolens		
8	CRO	Msenefu	Croton megalocarpus	Euphorbiaceae	Tree	Large (50-80 cm)	Light demanding	Heavy (0.65-0.85)	Normal, healthy	L3	https://en.wikipedia.org/wiki/Croton_megalocarpus		
9	ACA	Mjungu	Acacia nilotica	Fabaceae	Tree	Large (50-80 cm)	Light demanding	Heavy (0.65-0.85)	Normal, healthy	L3	https://en.wikipedia.org/wiki/Acacia_nilotica		
10	ALB	Mkenge	Albizia gumifera	Fabaceae	Tree	Large (50-80 cm)	Light demanding	Medium (0.5-0.65)	Normal, healthy	L3	https://uses.plantnet-project.org/en/species/Albizia_gumifera		
11													
12													
13													
14													
15													
16													
17													
18													
19													
20													
21													
22													
23													
24	Instructions for use												
25	• Enter details of all species to be recognized by the model. Use average values where information is not available.												
26	• Click the 'Synchronize' button to reflect any changes here to the Silviculture sheet.												
27	• Do not extend the list of plantable species beyond 20 species (row 22). If this is needed, contact the author (denis.alder@gmail.com) for assistance.												
28													
29													
30													
31													
32													

Column H requires information about the wood density, in the categories *Very light (<0.35)*, *Light (0.35-0.5)*, *Medium (0.5-0.65)*, *Heavy (0.65-0.85)*, or *Very dense (0.85+)*. This can be obtained from the same reference sources noted above, or the online [wood density database](#). Local knowledge is also generally sufficient, soft white woods being very light, dark, hard woods being very dense, the majority of timber species being medium, and those of known high durability and distinct colour being heavy. The very dense woods are generally not millable, but used for crafts and carving.

As the selections in columns E-H are made so column J, showing the MYRLIN Group, will update automatically. This corresponds to the decision tree and table described in [Alder \(2020, Table 5\)](#). This table is also present in the UCM workbook as a hidden sheet called MYRLIN_ref. This can be viewed if required (using the Excel *unhide sheet* menu), but is not normally shown as the user does not need to interact with it.

Column I contains drop-down values for Site Suitability, with the choices *Vigorous growth*, *Normal*, *Poor growth*, *Unsuited*. These are primarily for sensitivity analysis, with Normal being the default option. Species that experience has shown do not do well can be marked as Poor growth or

Unsuited, depending on the degree of failure. Vigorous growth may apply to species that are clearly very suited to a site, based on experience.

Once all the settings have been made and the species list completed, then the Synchronize button can be used to copy the species list in the correct order to the Silviculture sheet. This button also resets the Silviculture sheet with respect to planting and harvesting options.

4.3. Setting planting and harvesting options : The Silviculture sheet

The Silviculture sheet, with some typical options, is shown in Figure 5. Possible options are described below. The Run Model button, when clicked, will run the growth model using the current settings. In doing so, any existing data on the output sheets Table1, Table2 and Table3 are overwritten, and the graphs on the sheets Figure1 and Figure2 will update automatically.

Figure 5 : The Silviculture sheet

	A	B	C	D	E	F	G	H	I	J	K	L
1			Planting Density					Site type				
2	Silvicultural Options		2	x	3	m		2 - Average				
3			equivalent to		1667	per ha						
4												
5	Species list		Planting				Harvesting					
6	Common name	Botanical Name	Code	Plant	%	⌘	N/ha	Year	Fell %	Dmin	Species	
7	Lettowianthus	Lettowianthus stellatus	LET	✓	20%	⌘	333	10	100%		ACA	
8	Mwumbe	Cordyla africana	COR	✓	13%		222	20	30%			
9	Mvule	Milicia excelsa	MIL	✓	40%	⌘	667					
10	Mkangazi	Khaya anthotheca	KHA									
11	Mucarati	Erythrophleum suaveolens	ERY	✓	13%		222					
12	Msenefu	Croton megalocarpus	CRO									
13	Mjungu	Acacia nilotica	ACA	✓	13%		222					
14	Mkenge	Albizia gumifera	ALB									
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27			Total	5 sp.	100%		1666					

Other options

Run model for **100** years

Run Model

On this sheet, the species available to the model are listed in columns A-C, rows 7-26. This is pre-set, and updated by using the Synchronize button on the SpeciesList sheet, as described in section 4.2.

4.3.1. Planting

The planting density is set by changing cells C2 and E2, which indicate planting spacing. When this is given, the number of plants per hectare will be updated automatically in cell E3.

The species to be planted are set by clicking in the column D7:D26. This will cause a tick to appear, or if repeated, to disappear again. When this column is ticked, that species will be planted.

The percentages to be planted of each species are by default equal, and in this case, column E7:E26 can be left blank. However, double clicking anywhere on this column will show the calculated percentages, or update them if there has been a change to the species selection in the meantime.

A fixed percentage can be assigned to one or more species by clicking on column F7:F26, when the symbol ⌘ will toggle on or off. If present, whatever % value is entered to the left will be held

unchanged, and the remainder allocated equally among other species. This is shown in the example, with 40% of plantings pre-set as *Milicia*, 20% pre-set as *Lettowianthus*, and the remainder automatically allocated equally.

The N/ha column is calculated automatically when the % values are updated. The cells highlighted in yellow could be left blank – the values have been filled in by the automatic algorithm

In most practical situations of scenario analysis, only total spacing (usually 2 x 3 or 3 x 3) is set, and the required species ticked. When the Run button is clicked, all the planting densities of the species are calculated, regardless of whether they have been updated on the visible sheet using the above tools.

Species which are not ticked will not be planted.

4.3.2. Harvesting

If any harvesting is to be done, then the year and the percentage of trees to be removed should be entered in the Harvesting box, in the columns Year and Fell%. The species to be harvested can be listed by the 3-letter code. If the species is blank, all species will be harvested equally. A minimum diameter constraint can also be imposed on trees to be harvested.

If a 100% harvesting is done without any species constraint, it becomes a clear felling. In this case, the run will terminate after all the trees are harvested. If 100% harvesting is specified with a species constraint, then only the listed species will be removed, and the remainder left to grow.

In the example in Figure 5, 100% of the Acacia is harvested at year 10, leaving the remaining trees. In year 20, 33% of the remainder (1 tree in 3) are removed.

4.4. Output tables and charts

Three output tables are generated, on sheets called Table1, Table2 and Table3. Of these, Table1 shows the performance of the whole stand, while Table2 and Table3 give breakdowns by species. The charts on sheets Figure1 and Figure2 are linked to the data on Table1. Figure 6 below shows the appearance of Table1 in the model.

Column A shows stand age. Column B is stand basal area in m²/ha, which is of interest to forest managers. Column C is the stocking of live trees, in trees per ha. Column D gives the quadratic mean diameter, or diameter of the mean basal area tree as it is often called. Column E shows estimated crown closure, which is useful information for deciding on thinning regimes. At closure values greater than about 90%, self-thinning, or death of understorey trees, will start to occur. Column F and G give bole and total wood volumes in m³/ha. In columns H and I, these are converted to above ground biomass in t/ha, again for boles and whole trees. Columns J and K show thinnings as a percentage of basal area, of interest to silviculturists, and in terms of wood volume extracted, less branchwood and felling waste.

Columns L and M show the yield, which is the total of bole volume including any intermediate removals, as a gross figure in column L, and as mean annual increment (MAI, yield/age). MAI is important if managing a forest estate under a clearfelling regime, as it determines the production of the whole estate once a balanced age class distribution is reached, with equal areas in all age classes from planting to final felling. MAI x estate area then gives the total production of the estate per annum. It is often quoted as a relative indicator of production when comparing plantation species.

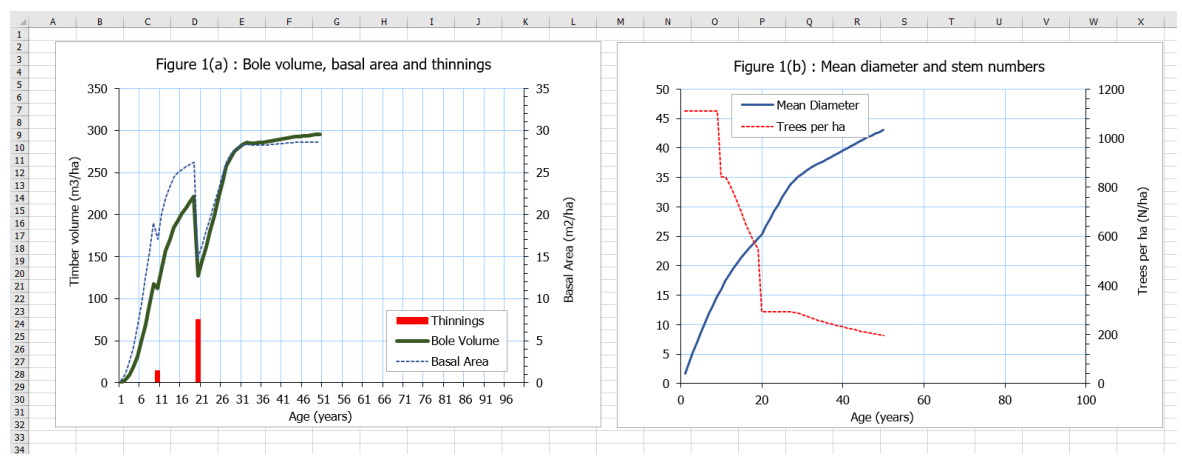
Figure 6 : Main output table from the model

Table 1 : Forest Standing Crop, Timber Yield and Sequestered Carbon																			
Stand parameters					Standing Trees				Harvest		Yield		Sequestered Carbon (tons/ha CO ₂ -equivalent)						
Age	BA	Trees	Dg	Canopy	Volume, m ³ /ha		Biomass, t/ha		Fell	Volume	Yield	MAI	Tree	Tree	Tree	Dead	Wood	TOTAL	
Yrs	m ² /ha	n/ha	cm	%	Bole	Total	Wood	Total	% BA	m ³ /ha	m ³ /ha	m ³ /ha/yr	bole &	roots	TOTAL	Wood	Product	C	
11	7	12.4	1,111	11.9	67%	69.1	159.7	28.9	67.2			69.1	9.9	123.3	30.8	154.1			154.1
12	8	15.7	1,111	13.4	79%	92.3	206.4	38.4	86.5			92.3	11.5	158.6	39.7	198.3			198.3
13	9	19.0	1,111	14.8	91%	117.8	256.1	48.8	107.0			117.8	13.1	196.1	49.0	245.1	0.1		245.2
14	10	17.1	842	16.1	78%	112.3	236.1	46.0	97.6	12%	14.7	127.0	12.7	178.9	44.7	223.6	52.6	13.5	289.7
15	11	20.1	842	17.4	89%	137.2	282.1	56.0	116.3			152.0	13.8	213.2	53.3	266.5	37.2	12.2	315.9
16	12	22.1	813	18.6	95%	156.8	315.4	64.0	130.1			171.5	14.3	238.4	59.6	298.0	32.1	11.1	341.2
17	13	23.3	775	19.6	98%	170.4	336.8	69.6	139.0			185.1	14.2	254.8	63.7	318.5	38.8	10.0	367.4
18	14	24.5	739	20.5	101%	184.6	359.1	75.4	148.2			199.4	14.2	271.7	67.9	339.6	50.2	9.1	398.9
19	15	25.0	694	21.4	101%	193.5	370.8	79.1	153.1			208.2	13.9	280.8	70.2	350.9	66.9	8.2	426.1
20	16	25.4	652	22.3	101%	201.0	380.0	82.2	157.0			215.7	13.5	287.9	72.0	359.9	79.8	7.5	447.2
21	17	25.7	614	23.1	101%	208.1	388.3	85.1	160.6			222.8	13.1	294.5	73.6	368.1	88.3	6.8	463.2
22	18	26.0	580	23.9	101%	214.8	396.1	87.9	164.0			229.6	12.8	300.7	75.2	375.9	93.6	6.1	475.6
23	19	26.2	550	24.6	101%	221.3	403.4	90.7	167.2			236.1	12.4	306.6	76.6	383.2	96.6	5.5	485.4
24	20	14.8	292	25.4	56%	127.3	229.6	52.2	95.3	33%	75.1	217.2	10.9	174.6	43.7	218.3	233.4	73.9	525.6
25	21	16.4	292	26.7	61%	144.1	256.7	59.0	106.4			234.0	11.1	195.1	48.8	243.9	165.0	66.9	475.8
26	22	18.0	292	28.0	67%	161.7	284.6	66.2	117.9			251.6	11.4	216.1	54.0	270.1	116.7	60.6	447.4
27	23	19.6	292	29.2	72%	179.9	313.1	73.6	129.5			269.7	11.7	237.5	59.4	296.8	82.5	54.9	434.2
28	24	21.2	292	30.4	77%	198.6	342.0	81.2	141.4			288.5	12.0	259.3	64.8	324.1	58.3	49.7	432.1
29	25	22.9	292	31.6	82%	217.9	371.5	89.0	153.5			307.7	12.3	281.5	70.4	351.8	41.3	45.0	438.1
30	26	24.6	292	32.7	87%	237.7	401.4	97.0	165.9			327.5	12.6	304.1	76.0	380.1	29.2	40.8	450.0
31	27	26.2	292	33.8	93%	257.5	431.0	105.1	178.1			347.3	12.9	326.4	81.6	408.1	21.4	36.9	466.4
32	28	27.1	290	34.5	95%	267.6	446.6	109.4	184.8			357.4	12.8	338.7	84.7	423.4	19.3	33.4	476.2
33	29	27.7	286	35.1	97%	274.8	457.5	112.5	189.5			364.7	12.6	347.4	86.9	434.3	22.3	30.3	486.8
34	30	28.0	280	35.7	98%	279.7	464.3	114.6	192.6			369.5	12.3	353.1	88.3	441.4	28.0	27.4	496.9
35	31	28.2	274	36.2	98%	283.2	468.7	116.2	194.8			373.0	12.0	357.1	89.3	446.3	34.3	24.9	505.5
36	32	28.3	268	36.7	99%	286.0	472.0	117.5	196.4			375.8	11.7	360.1	90.0	450.1	39.8	22.5	512.5
37	33	28.3	262	37.0	98%	285.1	470.6	117.5	196.3			375.0	11.4	359.9	90.0	449.9	41.5	20.4	511.8
38	34	28.2	257	37.4	98%	285.1	470.4	117.7	196.7			374.9	11.0	360.6	90.1	450.7	41.8	18.5	511.0

Columns N to S give sequestered carbon in units of tonnes CO₂-equivalent per ha. This is the most relevant data for carbon accounting. Above and below ground biomass are shown in columns N and O, with the total in column P. Deadwood, Wood products, and the overall total are shown in column S.

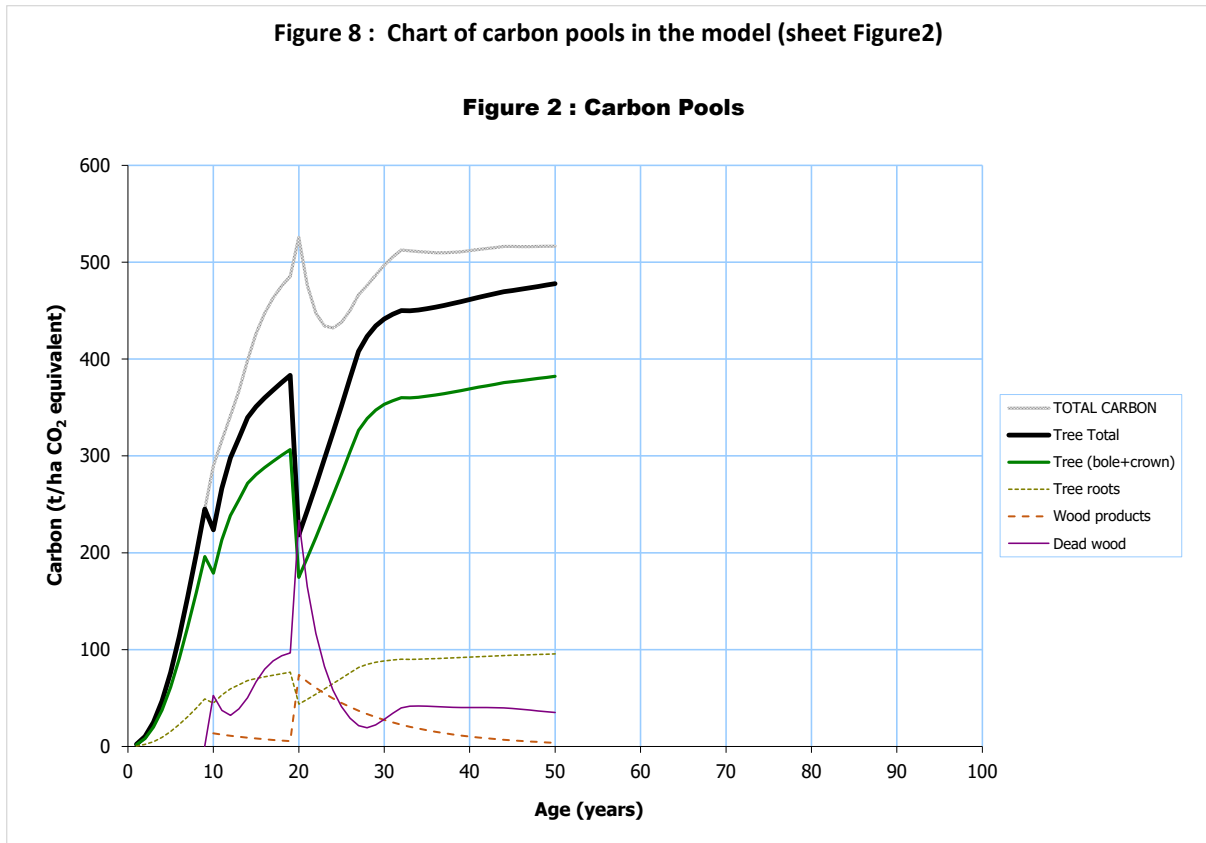
On the sheet Figure1 are two charts, as shown below in Figure 7. The left one, shown as (a), gives a graphical representation of tree basal area (column B), bole volume (column F) and harvested volume (column K). The right-hand chart (b) illustrates tree numbers per ha (column C) and mean diameter (column D) from model Table 1 (see Figure 6 above).

Figure 7 : Charts on model sheet Figure1 of some forest parameters over time



Sheet Figure2 is a chart of the carbon pools, tracking columns N-S of table 1 in the model. This is illustrated in Figure 8 below.

Figure 8 : Chart of carbon pools in the model (sheet Figure2)

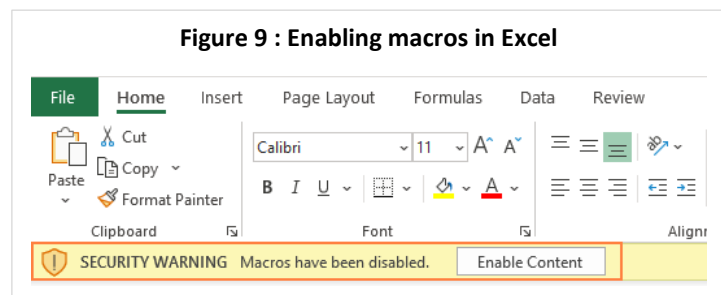


5. Using the model

5.1. Enabling macros

When the workbook is opened in Excel, macros must be enabled for it to function properly. If the buttons or other controls described are not responsive, then it is because macros have not been enabled.

How macros are enabled will depend on your security settings. In the default situation, a bar will appear with a button to enable macros. This must be clicked before proceeding (see Figure 9). There are two alternative situations. With macros automatically enabled (low security), the bar shown in Figure 9 will not appear and macros will work normally without any action on the user's part. With high security, macros will be disabled completely. In this case you need to change the security settings before you can use the model. The method varies with different Excel versions, but [this site](#) gives a good description with the more recent versions.



5.2. Running and saving scenarios

Trials with different planting densities, species selection and mixtures, and harvesting options constitute scenarios. Scenarios can be saved if required simply by saving the workbook under a different name.

If the workbook is saved as an .xlsx file rather than .xlsm (macro-enabled workbook), then the macros will be lost and it will not function, although all the saved tables and charts will be unchanged. This can be a useful way of saving scenarios for reference so they cannot easily be altered. However, an .xlsm version must be saved for the model to function with different options.

5.3. Adding or changing species

Species can be added or modified as described in section 4.2. After adding or deleting species, or changing their names, the **Synchronize** button must be used to ensure the *Silviculture* sheet has the same data, or the model will not function correctly.

5.4. Hidden and protected sheets

All the workbook sheets are protected. This restricts cells which can be altered to those where user data input is expected. If this is problematic, protection for a sheet can be turned off from the Excel menu. Note that the growth model macro automatically protects the sheets when it is run, so if it has been turned off, it will be found to have been turned on again.

There are also several hidden sheets containing parameter settings used by the program. These can be unhidden from the Excel menu, but this is not recommended for normal use. The hidden sheets are also protected.

5.5. Viewing the model code

The model code is provided under an open source license, and may be copied or modified freely, subject to attribution to this document. No responsibility is accepted for the performance of modified versions. The license details can be read at <http://www.gnu.org/licenses>, version 3.

The model code can be accessed by pressing Alt-F11 (PC) or Fn- \square -F11 (Mac). The main growth model code is in the module *CarbonModel*, but the module *Utilities* and sheets *SpeciesList* and *Silviculture* also have code that are required for full functionality. Coefficients for the various functions are read from the hidden sheets *Options+*, *Parameters*, and *MYRLIN* ref.

5.6. Getting help

If the model does not appear to be working properly, please email a copy of the workbook, together with a screen shot of the error message found, plus any explanation of the circumstances of the error. Emails should be sent to post@denisalder.com with 'UCM Error' in the subject line.

6. Conclusions

The Udzungwa Carbon Model described in this report is in the form of a macro-enabled Excel workbook called [UCM \(v1.1\).xlsm](#). A copy of the model can be downloaded from bit.ly/arcucm11. It is based on the MYRLIN model developed from the analysis of a large number of permanent sample plots in several tropical regions (Alder et al 2002b, Alder, 2020), and has been calibrated for the 8 species suggested for possible re-forestation work in the Udzungwa corridor area by ARC. The model is designed to show carbon-dioxide capture for a single even-aged stand, planted as a monoculture or in mixtures.

The model shows the main carbon pools, above-ground biomass, below-ground biomass, dead wood (coarse necromass), and carbon accrued in timber products. It does not show soil carbon or natural regeneration that may occur in older plantations, and does not calculate tree height. It also gives information on timber yields in terms of bole wood volume, both of the standing crop, and of intermediate thinnings. The variables that the user can adjust in reviewing stand management options are the planting density, the species mixture and proportions of each species, and the site quality. For harvesting, the user can decide the timing, frequency and intensity of fellings, and select which species should be felled on each occasion.

For biomass estimation, the model uses allometric models recently developed in Tanzania by Masota et al (2014) and Malimbwe et al (2016) for moist tropical forest. These give above ground biomass and bole volume, and below ground root biomass. The widely-used allometric equations of Chave et al (2005, 2014) and Cairns et al (1997) are also compared, and the Cairns model incorporated into the below-ground calculations.

The model allows additional species to be added, requiring some basic information about plant form (tree or palm), mature diameter, ecological guild and wood density which is entered into a decision tool on the [SpeciesList](#) sheet of the model, together with an estimate of site suitability. The site suitability and also the overall site quality indicator on the [Silviculture](#) sheet can be used to test risk should species performance be sub-optimal.

The model comprises various parameters contained in visible and hidden sheets, together with VBA code which can be access in Excel via the VBA Editor. The model is offered under an open source GNU Version 3 license, which implies that it may be copied and adapted as required, provided that the origin is cited. The hidden sheets in the model can be exposed via the Excel menus without requiring a password.

The outputs comprise a main stand table that shows aggregate performance in terms of the normal stand parameters of age, basal area, mean diameter, stocking, bole volume, total volume, thinning volumes. It also shows biomass in tonnes CO₂-equivalent, as normally used for GHG accounting, for the main carbon pools: Above ground, below ground, deadwood, and product carbon. Graphs are linked to this table which show these parameters visually. There are also additional tables showing details at the species level, including diameter distribution by species and year, stocking for each species, and volumes by species.

The model is intended as an early stage tool for feasibility assessment using best available information, and needs to be supplemented by and adjusted for locally obtained growth measurements as the plantation program proceeds. The performance of tree species can never be known accurately until they are tried in situ, and may vary significantly with seed source, local site conditions, nursery practice, and planting and tending methods. However, in aggregate, growth

performance for mixtures of species that are known to be suited for the moist tropical forest medium altitude conditions prevailing at Udzungwa can be expected to conform to the models forecast behaviour, and it can therefore be a useful component of the planning process.

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Oxford, 3rd August 2020

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