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A yield model for Caribbean Pine in Uganda

Based on 2003-2017 data from Global Woods estates at Kikonda, Uganda

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Executive summary

This report presents a growth and yield model for even-aged plantations of Caribbean Pine (*Pinus caribaea var. hondurensis*) grown in Uganda on the estates of Global Woods (GW), at Kikonda Forest Reserve. The model is an update of one published in 2003 (denisalder.net/pdf/uymdoc.pdf), incorporating new data from permanent sample plots (PSPs) established in forests planted from 2002-2017 using improved seed and silviculture.

The PSPs are of circular design, 250 m², with all trees measured for diameter at 1.3 m (dbh), two largest diameter trees for dominant height, and three other trees systematically for mean height. There were 357 plots in the analysis, with 1247 plot x measurements, and ranged in age from 2 years to 15 years. In total, there were 21,579 tree measurements included in the analysis.

Height growth on the PSPs was found to follow the site index curves of the 2003 model. However, whereas in 2003 the old forest at Kikonda had an average site index of 12.7 m, with the new GW plantings using improved Queensland seed, average site index was 20 m, with a range from 17-23 m. This represents a substantial increase in yield with improved seed and silviculture.

New taper functions had been developed by GW in 2015. For the present model, these were encoded in VBA for Excel and incorporated to calculate volumes over and under bark to variable user-specified top diameters and minimum log lengths.

Stand structure was represented in the model by five quintiles or cohorts, representing the 10%, 30%, 50%, 70% and 90% points of the diameter distribution. A function of quintile diameter was developed dependant on dominant height (as a site-scaled metric of age), quintile percent (as a proxy for competitive status), and stand mean spacing. This function had an R^2 of 93.7% with 6,220 data points (plots, measurements, and quintiles). This equation was used directly to estimate the initial diameter distribution, and in finite difference form as a diameter increment function to update the cohort diameters in each one-year time step.

To allow the taper function to be applied to diameter cohorts, a diameter-height allometric model using stand quadratic mean diameter (mean basal area diameter), cohort diameter, and stand dominant height to predict cohort height was developed.

The model allows thinnings of varying intensity with a bias to smaller trees (low thinning), and calculates an adjusted residual diameter distribution and thinnings diameter distribution accordingly. Thinning bias depends on thinning intensity, being more marked with lighter thinning.

The model is constructed as an Excel workbook with VBA macros. The user can specify simulation from planting or actual stand data, and may specify variable thinnings and merchantable volume criteria. The output includes age, dominant height, basal area, diameter distribution quintiles, total volume, merchantable volume in 2 classes, mean annual volume increment, thinning numbers, diameter distribution and volumes.

The report includes model code in VBA and some versions of the functions and R code used to generate graphs of functions and data in the report. This is an interim report and will be updated with additional material on compatibility functions for the FORSAT model in the near future.

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Acknowledgements

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List of abbreviations and acronyms

AM........................Ata Marie Group Ltd
BA..........................Basal area
BAF........................Basal area factor
CAI........................Current Annual Increment (m^3/ha/yr)
CRS........................Coordinate Reference System
dbh........................Diameter at breast height (1.3m)
FR..........................Forest Reserve
GIS........................Geographical Information System
GPS........................Global Positioning System
GW........................Global Woods AG, Uganda
MAI.......................Mean Annual Volume Increment (m^3/ha/yr)
PC..........................*Pinus caribaea*, Caribbean Pine
PSP........................Permanent Sample Plot
R............................R statistical analysis and programming language
SDI........................Stand Density Index
SI...........................Site Index
SQL........................System Query Language
TOR.......................Terms of Reference
UFRP.....................Uganda Forestry Rehabilitation Project (World Bank 1989-91)
UTM......................Universal Transverse Mercator
VBA.......................Visual Basic for Applications
VI..........................Valid International Ltd, UK

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Algebraic and forestry symbols

The following list gives the standard algebraic symbols used in the text. As far as possible we have followed the recommended standards of IUFRO. Units used are shown in brackets.

A ....An asymptotic coefficient, used in various equations
a ....Intercept coefficient in a 2-parameter regression equation
b ....Slope coefficient in a 2-parameter regression equation
d ....Tree diameter at breast height (1.3 m) in cm.
D_g ....Stand mean basal area (or quadratic mean) diameter (cm).
d_q..........Diameter corresponding to a percentile q of the diameter distribution
e............The mathematical constant 2.71828…
F ....A cumulative frequency
f ....Form factor
f(*x*)........Any function of x
G ....Stand basal area (m^2/ha)
g ....Tree basal area (m^2)
h ....Individual tree height (m)
H_{10} ....Dominant height at a specified age, *eg.* 10 years.
H_d.........Stand dominant height (m)
k ....A shape coefficient, used in various equations
m..........A scale coefficient, used in various equations
n ....Number or count of items, *eg.* number of trees on a plot.
N ....Stocking, or trees per ha.
P ....A probability or proportion
p ....Percentile point of a probability or frequency distribution
q ....A quintile, or one of 5 designated percentiles from a distribution
S ....Site index, generally H_d at a specified base age.
t ....Stand age, in years.
Δ...........finite difference, annual change [delta]
Σ...........Summation operator [sigma]
α...........Intercept coefficient in linear equation forms [alpha]
β ....Slope coefficients in linear equation forms [beta]
π ....The mathematical constant 3.14159… [pi]
θ ....Logit transform of q or $\log_e(q/(1-q))$ [theta]
ζ ....Stand density, either as mean spacing or SDI [zeta]

Disclaimer

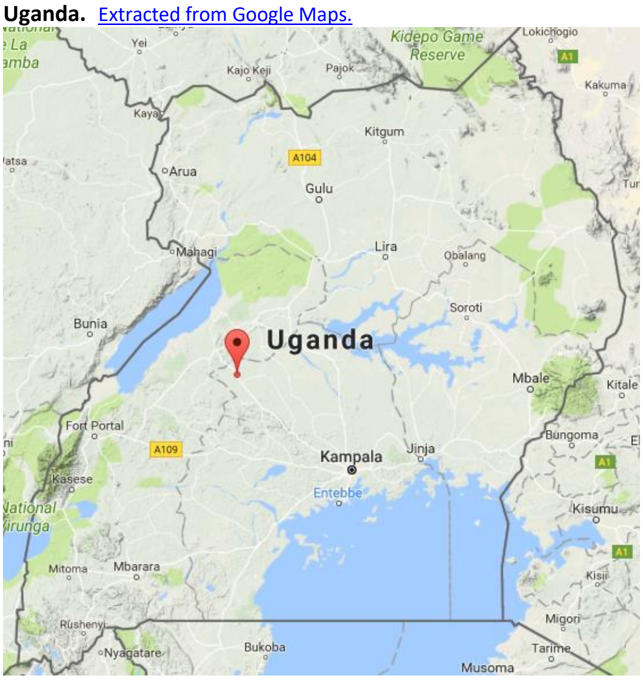
This report details research undertaken over a short time line and deals with complex statistical analysis of uncertain data. As such, it may, despite the best endeavours of the authors, contain errors and omissions. Additionally, projections from this material are instantiations of probability functions and inherently subject to uncertainty. Users should bear these factors in mind in applying the results and mitigate risks accordingly. Valid International Ltd necessarily disclaims any responsibility for outcomes arising from the use of this report or the models, functions and equations presented in it.

Background

This report details the development of a management tool for estimating the growth and yield of Caribbean Pine (*Pinus caribaea*) grown at the estates of Global Woods AG, near Kikonda, Uganda, situated at about 1°12'31"N, 31°33'35"E, at an altitude of 1,115 m, on the Kampala-Hoima Road. The Terms of Reference (TOR) for the study are given in Annex A.

As the TORs detail, the study is intended to be an update to the model developed by Alder *et al* (2003). That model operated as an Excel spreadsheet, using various VBA macros to provide the bespoke modelling functions. The 2003 model was based largely on temporary plots in older pine stands, and on whole-tree volume functions derived in 1989-91. For the present update, permanent sample plots (PSP) established and remeasured by GW over the period 2003 to 2017 were available, providing a much stronger basis for analysing dynamic trends. Additionally, it was desired to incorporate tree taper functions developed for GW by Ata Marie (AM) forestry consultants in 2015 (Ata Marie, 2015), instead of the 1989-91 whole tree volume equations used in the 2003 model.

Figure 1 : Location of General Woods plantations at Kikonda, Uganda. Extracted from Google Maps.



These different features meant that, rather than simply re-calibrating the 2003 model for the new data, a partial re-design of the system was necessary to incorporate some extra techniques. However, as far as possible, the look and feel of the 2003 model has been retained as indicated in the TOR. It is therefore packaged as a single spreadsheet representing the projected growth for a single even-aged stand. This can be done either from the time of planting, or for older stands, from a base of known age, height, and stocking, and optionally, diameter distribution.

Approach to analysis

The original permanent sample plot data were provided as a series of Excel workbooks from years 2009 to 2017, but including previous measurements back to 2002 for some of the older plots. These data were extracted into a single workbook, and then exported to a MySQL database for data checking and reconciliation. A copy of the clean database was also made in Access for provision to GW.

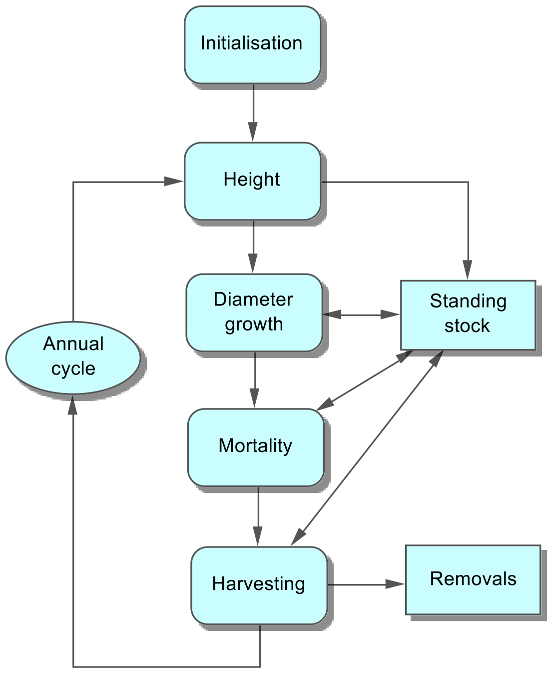
For analysis purposes, the R statistical system was used. R is a powerful statistical package and programming language that is open-source, freely available and widely used by many research institutions and universities. Information and downloads for various operating systems (Windows, Apple OS, Linux) are available at the site R-project.org. All the graphics in this report (except a few copied from the 2003 report for comparison) have been produced in R, with the relevant code included in Annex B.

The detailed analysis for the growth functions are described in the respective sections. These were generally tested in R, and then re-written in VBA to work with the Excel model. The VBA code for the model is listed in Annex C.

In general, the methods followed in this report are consistent with the considerable literature on the empirical modelling of even-aged forest plantations, which is summarised in text-books such as Clutter et al (1983) and Burkhart and Tomé (2012). It is also consistent with the author's past contributions in this field, notably Alder (1979, 1980), Alder & Montenegro (1999).

Logical structure of the model

Figure 2: Overview of model structure



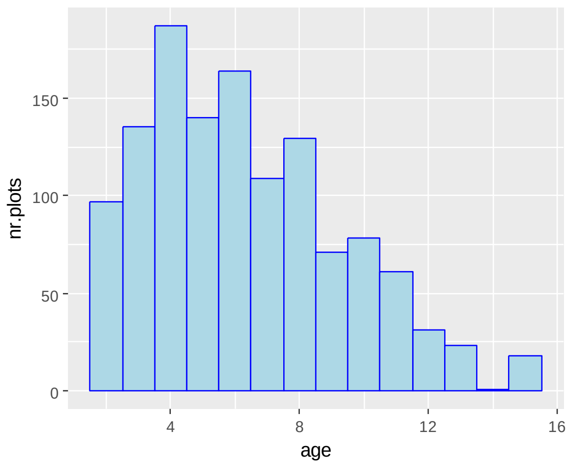
An overview of the logical structure of the model is illustrated in Figure 2. There is an initialisation phase, when parameters supplied by the user are read and various internal variables set up. The model then moves into an annual loop of repeated processes. Firstly, stand dominant height is calculated from a height-age function. Then, diameter increment is calculated, relative to the existing forest stock. This is influenced by the current dominant height, the stand density, and the competitive position of the cohort. The growing stock for the model is divided into 5 cohorts of similar size, each representing 20% of the trees. Mortality due to inter-tree competition is calculated. Then any harvesting due, in the form of thinnings, are estimated. This involves adjustment of the diameter distribution to allow for the fact that a silvicultural thinning will be biased to remove smaller trees. During these processes, the output worksheet is updated with current age, height, mean diameter, diameter quintiles (20% fractions of the diameter distribution), standing volume. merchantable volumes, and volumes and numbers of thinnings. Mean annual increment of volumes, both total and merchantable, are also calculated. All processes are carried out by VBA code, with inputs from and outputs to a single Excel worksheet. The entire software is listed in Annex C.

The permanent sample plot data

The main data source used for this model were permanent sample plots established in the compartments of GWs forest lease at Kikonda Forest Reserve. The plots are of 250 m2 circular design (8.92 m radius), and are measured annually or biannually for diameter at 1.3 m height (dbh). The two largest trees are measured for height, whose mean is dominant height. Additionally, 3 other trees across a range of diameters are measured to estimate mean height.

At the time the data analysis commenced, in July 2017, there were 357 PSPs in the data set. The distribution of observations by age is shown in Figure 3. The oldest plots were 15 years of age (2002-2017). In all there were 1247 plots x measurements, with 21,579 tree measurements, an average of 17 trees per plot per measurement. These data refer only to PSPs in Caribbean Pine.

Figure 3 : Age distribution of PSP measurements

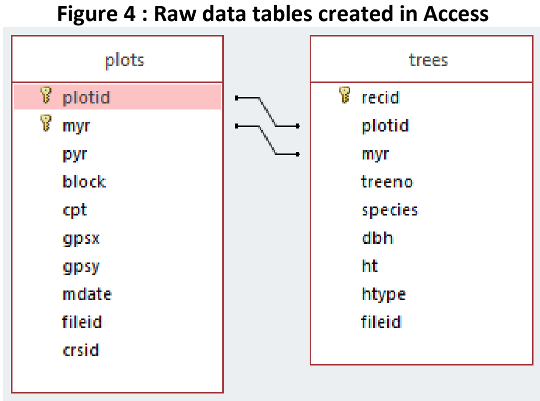


Age	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Plots	97	135	187	140	164	109	129	71	78	61	31	23	1	18

The data was provided in the form of Excel worksheets and was combined for analysis purposes into two linked tables. During this reformatting process, data was screened for errors, with various corrections being made to plot identification, heights and diameter. Some data, which could not be corrected, were excluded from the analysis, but these were relatively few in number. The above statistics, and those presented further on, refer only to cleaned data admitted for analysis.

Data structures and preliminary calculations

Figure 4 : Raw data tables created in Access



In the first stage of importation from Excel, raw data tables were created in MySQL, which were later exported to Access as a reference dataset for archival. The structure of these tables were as shown in Figure 4. The plots table contains one record per plot (plotid) and measurement year (*myr*), with year planted (*pyr*), forest block and compartment (*cpt*), GPS coordinates (*gpsx, gpsy*), measurement date, and a reference to the original Excel data file (*fileid*) and coordinate reference system (CRS, *crsid*). In the end it was found that only one CRS is used throughout (UTM zone 36N, WGS 84), so this latter information is essentially invariant.

For the individual tree measurements, plot and measurement year were used as linking data for the correct header record, then tree number (*treeno*), species code (*species*), diameter at 1.3 m (*dbh*), total height (*ht*), type of height measurement (*htype*) and originating Excel data file (*fileid*) were recorded.

Calculations were then made in MySQL to produce plot-level statistics commonly required for forest growth and yield analysis. At the same time, non-*Pinus caribaea* data were filtered out. *Pinus caribaea* (PC) accounted for 93% of the PSP dataset, with the remained comprising Eucalyptus (3.6%), *Maesopsis eminii* (1.0%), and *Pinus oocarpa* (2.2%). For this report, in all figures and tables, only PC data is included.

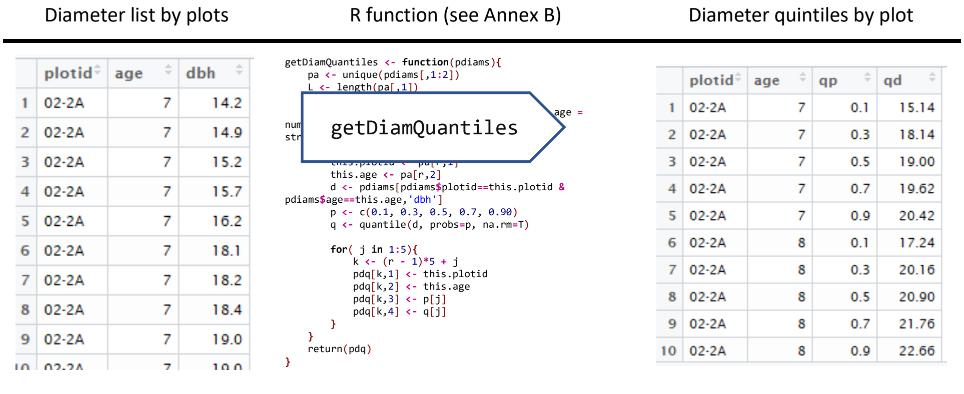
The plot summary file was then exported to R, together with a tree list for each plot. The data structure of the plot summary is shown in Figure 5. `nha` is the stocking stems per hectare, `gha` is the basal area in m2/ha, `dg` is the diameter of the mean basal area tree, or quadratic mean diameter, in cm, `hdom` is dominant height, in m, and `hlor` is Lorey's mean height, in m.

Figure 5 : Plot summaries imported as an R dataframe

	plotid	age	nha	gha	dg	hdom	hlor
1	02-2A	7	760	20.59	18.57	13.65000	12.98
2	02-2A	8	760	25.62	20.72	15.12887	14.66
3	02-2A	9	760	28.20	21.74	13.90000	14.83
4	02-2A	11	800	32.59	22.78	19.85000	20.59
5	02-2A	13	600	31.76	25.96	21.55000	21.91
6	02-2A	15	600	35.53	27.46	23.75000	24.28
7	02-2B	7	840	22.04	18.28	13.75000	13.22
8	02-2B	8	840	25.11	19.51	16.73768	16.26
9	02-2B	9	880	31.21	21.25	17.95000	17.00
10	02-2B	11	880	36.91	23.11	19.80000	19.39

The diameter list for each plot was analysed to derive 5 percentile diameters for each plot, or quintiles, for the 10%, 30%, 50% (median), 70% and 90% points of the diameter distribution. The function `getDiamQuantiles` in Annex B was written to do this, making the transformation as illustrated in Figure 6.

Figure 6 Processing diameter list to get diameter quintiles by plots



Diameter quintiles were selected as five points of the cumulative diameter distribution, at the 10%, 30%, 50%, 70% and 90% frequency points. The 10% point, for example, is a diameter such that 10% of trees will be smaller, and 90% larger. The 50% point is the median of the distribution, with half the trees smaller, and half larger. These quintiles were used to represent stand structure, providing both a compact description of the diameter distribution, and a method of analysing diameter increment in a situation where individual trees were not uniquely identified in the PSPs between successive measurements. The quintiles also represent cohorts of trees of similar competitive status, and are therefore compatible with the wide family of cohort-based forest models (Burkhart & Tomé, 2012). The methodology was adapted from Alder's (1979) model for East African conifers.

Dominant height

Tree and stand height are key variables for forest growth and yield estimation. Stand height is usually indicated by dominant height, which is the mean height of the dominant trees. There are various definitions, but a common one is the mean height of the 100 largest diameter trees per ha (West, 2009). Dominant height is an important indicator of site productivity, and provides a metric that is largely independent of stand density (unlike stand mean height) and incorporates effects of both site productivity and stand age.

For the GW PSP dataset, the two largest diameter trees on each 250 m^2 plot were measured for height. This corresponds to 80 trees per ha, a little less than the conventional definition of 100 trees/ha, but close enough to be effectively the same.

Mean height and Lorey's height

On the PSPs, three additional trees over a range of diameters were measured to provide a basis for estimating mean height. Mean height is influenced by stocking, tending to be less at lower stocking, and as such is rarely used as a key variable in stand modelling. Lorey's height is the mean height weighted by tree basal area or diameter squared (which has numerically the same effect). For the present study, Lorey's height was calculated, as shown in Figure 5 in the column `hLor` but neither arithmetic mean height nor Lorey's used in the analysis.

However, these additional height trees are extremely important for development of the height-diameter relation that is necessary to apply the volume taper model for stand volumes. This is discussed in the section on height-diameter function.

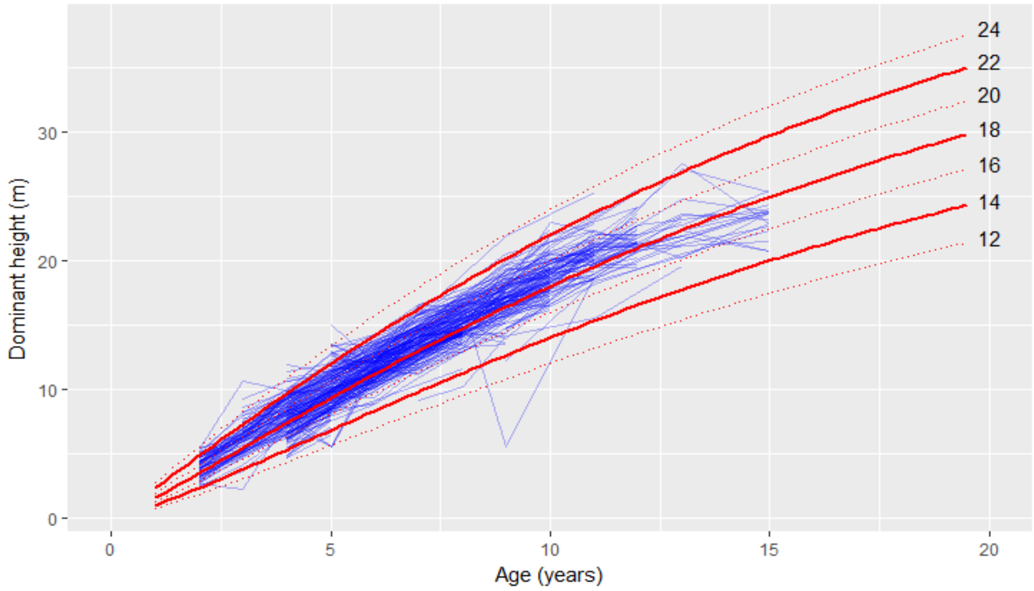
Site Index and the dominant height-age curve

Site Index is defined as dominant height at a given base age, and is a key indicator of site productivity. For the 2003 Uganda Caribbean Pine model (Alder et al., 2003) a base age of 10 years was selected after the usage of Kingston (1972), and site index curves developed based on the Chapman-Richards function. Those curves used a composite of datasets including curves developed by Kingston (1972) and temporary sample plot data from the UFRP inventories of 1989-91, and covered stands from 2 to 32 years of age.

The same system of site index curves were plotted with the GW PSP data (Figure 7). It can be seen that they provide a very good fit to the data. It is notable however, that with the original datasets, median site index for Uganda was about 14 m, whereas for the GW data, it is around 20 m. This reflects the fact that the GW stands were established with improved seed and have been more carefully managed. Indeed, in Table 3 of the 2003 report, Kikonda FR is shown as having a median site index of only 12.7 m, so the improvement in growth rates with the new hybrids planted by GW is considerable.

As the 2003 model continues to provide a good fit to the height-age-site index trends, it was adopted for use in the current model without modification. The original equations and their derivation are described in the 2003 report, but they are reproduced here for reference and completeness.

Figure 7 : Height growth from PSPs and site index curves
Blue lines are PSP data, Red lines are the site index model, site index values shown at right



The dominant height-age function is given by:

$$H_d = A.[1 - \exp(-k.t)]^{1/(1-m)}$$

where:

$$m = -0.01784\ H_{10} + 0.4847$$

$$k = 0.0606$$

$$A = H_{10} / [1 - \exp(-k.10)]^{1/(1-m)}$$

{eqn. 1}

In these equations, A, m and k are coefficients, H_d is dominant height, and H_{10} is site index or dominant height at the base age of 10 years.

In Annex B, the R function *`sicurv(age, si)`* calculates dominant height for a given age, using equation 1 above. In Annex C the equivalent VBA function is given for use in Excel, called `Hdom(age, si)`. There is also a VBA function to calculate site index, given height and age, `getSI(hdom, age)`. Both the VBA functions can be used as worksheet functions in Excel. The VBA functions form part of the model, whilst the R version was used during analysis.

Height-diameter function

The height-diameter function predicts individual tree height given its diameter. It is used as part of the volume calculation process, to calculate the height for each of the cohorts (quintile diameters) in the model so that the volume taper function could be applied. The relationship between height and diameter for individual trees within a given stand depends on the mean height and diameter of the stand. After some experimentation, and bearing in mind variables that were available to use within the model, the best relationship was found to be:

$$h = H_d\,(0.5385065 + 0.3713323 * d/D_g) \qquad \{eqn.\ 2\}$$

where h is individual tree or cohort height, H_d is dominant height of the stand, d is individual tree or cohort dbh, and Dg is quadratic mean diameter. This equation had an R^2 of 95.2% and standard error of predicted height value of 1.2 m. There were 6,121 height-diameter observations in the regression. In the VBA code for the model, it is represented by function `treeHeight(Hd, dg, dbh)`, the parameters being, respectively, dominant height, quadratic mean diameter, and tree or cohort dbh.

Diameter growth model

Diameter development over time was modelled as a function of dominant height, stand density and competitive status. In this relationship, dominant height is used as a combined variable for stand age and site. Competitive status was taken as the quantile position, such as the 10%, 30%, 50% etc fraction of the stand, and therefore corresponding to the P-values of the diameter quintiles. Stand density was measured as mean spacing per tree, or √(10,000/N), N being trees per hectare.

The function fitted by regression, after some experimentation with different models, was:

$$ln(d) = \beta_0 + \beta_1.\eta + \beta_2.\zeta + \beta_3.\theta + \beta_4.\eta.\theta + \beta_5.\eta.\zeta + \beta_6.\theta.\zeta + \beta_7.\eta.\theta.\zeta \qquad \{eqn.\ 3\}$$

where:

- d is cohort or quintile diameter, in cm
- $\beta_0 \ldots \beta_7$ (beta) are coefficients fitted by regression, as shown in the table at the right
- η (eta) is a transformation of dominant height H_d, in m:
  $\eta = 1/\sqrt{H_d}$
- θ (theta) is the logit transformation of the quantile q of the diameter distribution that the cohort represents:
  $\theta = \ln(q/(1-q))$
- ζ (zeta) is stand density, as mean tree spacing in m, from stems per hectare N:
  $\zeta = \sqrt{(10000/N)}$

Coefficients	
β_0	4.308092
β_1	-5.739368
β_2	0.066883
β_3	-0.065630
β_4	0.497234
β_5	-0.098210
β_6	0.017257
β_7	-0.049239

This equation, although it looks complex, is simply a form of the Schumacher equation:

$$ln(y) = a + b.\ x^{-k}$$

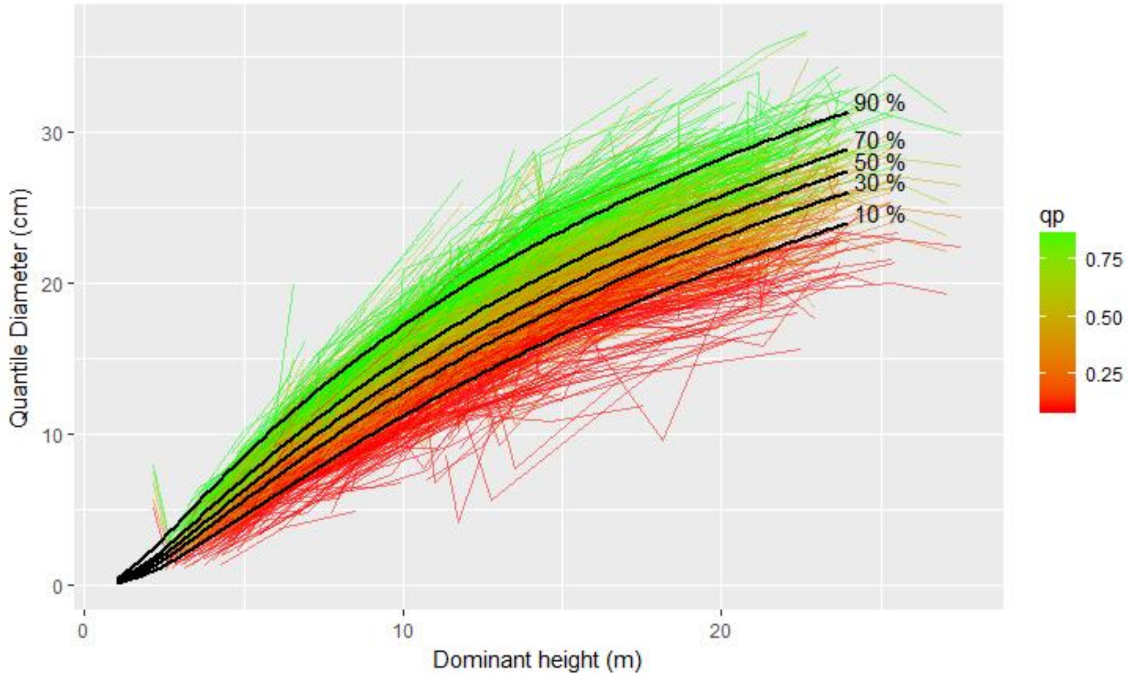
(Burkhart & Tomé, 2012, p. 116), with interaction terms for competitive status θ and stand density ζ. The regression fitted with an R^2 of 93.7% to 6,220 data points (357 plots, 1244 plots x measurements, 5 diameter quantiles per plot). All the coefficients are very highly significant at $P<0.001$.

Figure 8 shows the shape of the curve for the various quintiles of the diameter distribution, overlaid on the PSP data set, with colours corresponding to quintiles (red 10% shading through yellow 50% to green 90%). In this graph, the sample plot data for all stand densities are included, whereas the function plots (black lines) are only for a single density, of 3.5 m (816 trees per ha). The plot is produced using the R function `draw.diamGrowth` listed in Annex B.

The VBA function ***`qDiam(Hd, qp, nha)`*** in Annex C calculates diameter for a given dominant height `Hd` , quintile point `qp`, and stocking of `nha` trees per ha. This can be used as a worksheet function if required.

Equation 3 predicts diameter, and is premised on constant stocking over the history of the stand. It can be used to initialise the diameter distribution at a given point in time (assuming prior constant stocking). To reflect the dynamic effect of thinnings and changes in stand density over time, a diameter increment function is required.

Figure 8 : Quintiles of diameter distribution as a function of stand dominant height.
The plotted function (black, equation 3) is for stands of 3.5 m spacing (816 tph) whereas the data includes all densities. Colours correspond to diameter distribution quintiles.



Diameter increment

Equation (3) must be differentiated with respect to time to estimate diameter increment. This is done in the model by a finite difference method in the VBA function `qDiamInc`. Equation (3) can be re-written as:

$d_q = f_3(H_d, p_q, N)$ {eqn.4}

with d_q being the diameter for quintile q, H_d is stand dominant height at a given point in time t, p_q being the corresponding percentile point in the diameter distribution (10%, 30% etc), and N the stocking in trees per ha.

The site index equation (1) can also be shown in simplified form as:

$H_d = f_1(t, S)$ {eqn. 5}

where t is stand age and S is site index.

Annual diameter increment Δd_q for a cohort can therefore be calculated by combining these equations:

$\Delta d_q = f_3(f_1(t+1, S), p_q, N) - f_3(f_1(t, S), p_q, N)$ {eqn. 6}

This calculation is carried out in VBA function `qDiamInc` listed in Annex C.

In the model, equation (3) is used to estimate diameters for the first year, as part of the initialisation process. Thereafter, diameter increments are calculated from equation (6) and added to the previous year's diameter for that cohort. In this way, dynamic effects on diameter distribution due to harvesting are preserved.

Ata Marie Taper Functions

In the 2003 Caribbean Pine model (Alder et al, 2003), stand volume functions were developed based on tree volume measurements made as part of the UFRP 1989-91 inventory (Alder, 1990). However, for the present update, local and current volume and tree taper functions developed in 2015 for GW by Ata Marie forestry consultants (Ata Marie, 2015) were used. These were provided in the form of printed equations in the report, and had to be coded and tested for use in the model. Both R and VBA versions of the functions were developed and are listed in Annexes B and C.

The use of the taper models imposed constraints on the design of the model. Whilst the 2003 model used stand-based functions, and could therefore be relatively simple in design, the current version necessarily had to predict heights and diameters by cohorts, in order to use these tree-based taper models. This added flexibility and power to the model, but also increased complexity.

Table 1 below shows the R and VBA functions developed based on the Ata Marie taper model.

Table 1 : Functions implemented in R and VBA based on the Ata Marie taper models

Function description	R version Annex B	VBA (Excel) version Annex C
Function returns diameter overbark (dob) at a point hm metres above ground for tree of ht m total height and dbh cm diameter at 1.3 m. Note the R and VBA versions have parameters in a different order.	dobTaper(hm, ht, dbh)	dobTaper(ht, dbh, hm)
Returns diameter inside bark at a specified height. The parameters are the same as for dobTaper. Not coded in R.	n/a	dibTaper(ht, dbh, hm)
Solves for and returns height to specified merchantable top diameter. For both R and VBA versions, ht is tree total height (m) and dbh is tree dbh in cm. For the R version, dob is the required overbark top diameter. For the VBA version, dm is the required top diameter. If ub is 0 or omitted, dm is overbark. If ub is 1, dm is underbark top diameter.	hmTaper(dob, ht, dbh)	hmTaper(ht, dbh, dm [,ub])
Volume in m^3 over bark for a tree of total height ht m and diameter dbh cm. In the VBA version, an optional parameter hm gives merchantable height in m, in which case volume to that height is given. The R version only gives tree total volume.	vobTaper(ht, dbh)	vobTaper(ht, dbh [, hm])
As for vobTaper above, except gives volume inside bark.	vibTaper(ht, dbh)	vibTaper(ht, dbh [, hm])

The R versions were used primarily for testing and graphical analysis, and are available for developing possible regression models involving volume or merchantability criteria from the PSP dataset. The VBA versions are those used in the stand model. The hmTaper function for deriving merchantable from top diameter uses a numerical solution method. In the R version, it uses the uniroot library function. In the VBA version, a bisection algorithm (Stark, 1970) has been implemented. All the VBA functions can be used as simple Excel worksheet functions provided the TaperFunctions module, as listed in Annex C, has been attached and macros enabled.

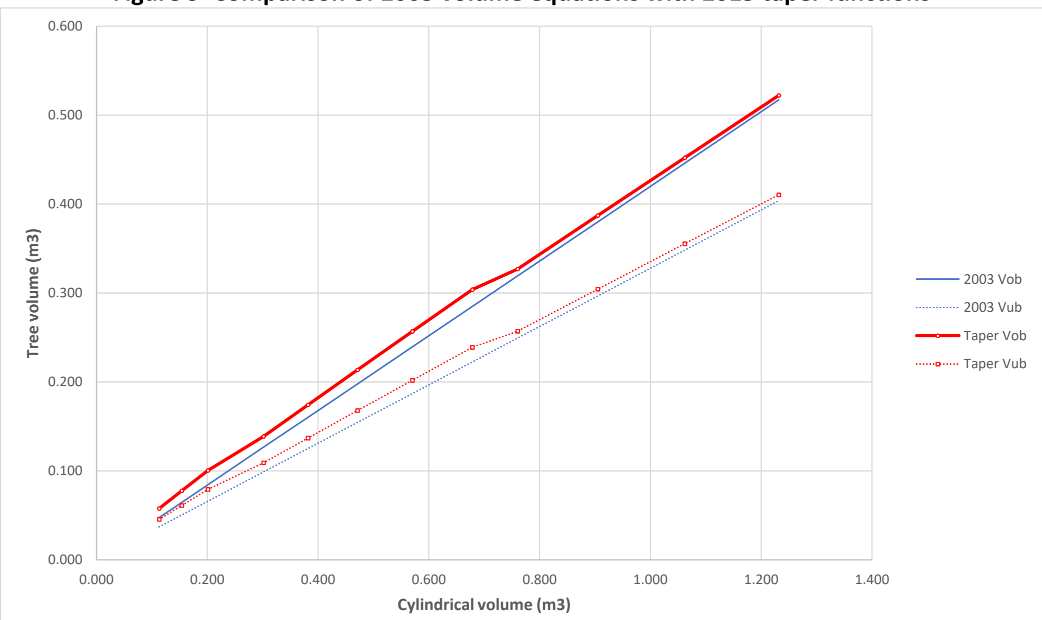
Performance of the taper model

To test the taper functions, whole tree volumes were calculated with them and compared with the tree volume equations used in the 2003 *Pinus caribaea* model. Table 2 and Figure 9 shows the results. A range of diameter and heights were used representative of the spread of the PSP data, and cylindrical volumes calculated from them. The 2003 equations are simple form factors, of 0.420 x cylindrical volume for overbark, and 0.328 for underbark volume. The taper function is a very complex calculation, but the results are closely comparable, with the taper functions giving slightly higher volumes, especially for smaller trees. Figure 9 shows the same information in graphical form.

Table 2 : Comparison of Ata Marie (2015) Taper Equation with Alder et al (2003) volume equations

			2003 Equations		*AM Taper Model*		*Difference %*	
Ht	**Dbh**	**CylVol**	**Vob**	**Vub**	**Vob**	**Vub**	**Vob**	**Vub**
10	12	0.113	0.048	0.037	0.058	0.045	21%	23%
10	14	0.154	0.065	0.050	0.078	0.061	20%	21%
10	16	0.201	0.084	0.066	0.101	0.079	19%	20%
15	16	0.302	0.127	0.099	0.139	0.109	10%	10%
15	18	0.382	0.160	0.125	0.174	0.137	9%	9%
15	20	0.471	0.198	0.155	0.214	0.168	8%	9%
15	22	0.570	0.239	0.187	0.257	0.202	7%	8%
15	24	0.679	0.285	0.223	0.304	0.239	7%	7%
20	22	0.760	0.319	0.249	0.327	0.257	2%	3%
20	24	0.905	0.380	0.297	0.387	0.304	2%	3%
20	26	1.062	0.446	0.348	0.452	0.355	1%	2%
20	28	1.232	0.517	0.404	0.522	0.410	1%	2%

Figure 9 Comparison of 2003 volume equations with 2015 taper functions



Self-thinning

Self-thinning, or mortality cause by overcrowding, occurs at high stand densities. The GW PSP data set has few stands at such high densities. The 2003 model, which incorporated data from older stands, had a self thinning model in the form of the equation:

$$N = 232093\ H_d^{-1.6055} \qquad \{eqn.\ 7\}$$

Here N is limiting stocking, in trees per ha, and H_d is dominant height.

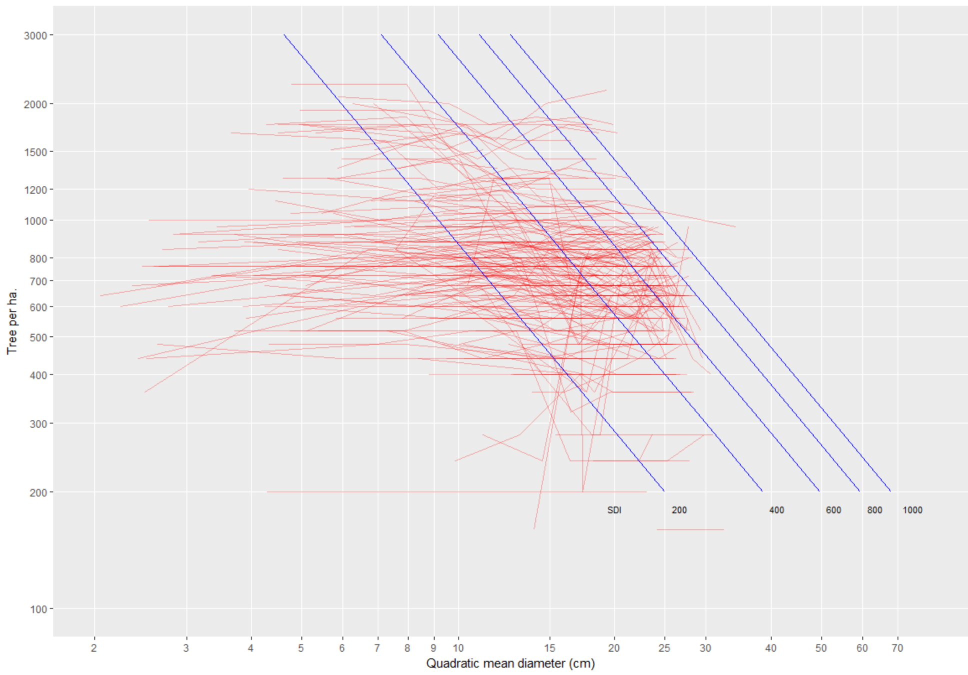
In the absence of better information about self-thinning from the new plantations, this function has been retained for the updated model, and will be found implemented in the VBA function `SelfThin(nha, hd)`, which returns either nha, the current stocking, or a lower value derived from equation (7) if self-thinning occurs. Self-thinning will only happen at densities above those of normal plantation management, but it is retained in the model in order to provide realism if high planting densities or long unthinned rotations are specified.

Stand density index

Reineke (1933) observed that when a graph of stocking is plotted against stand mean diameter on logarithmic scales, self-thinning occurs on lines with a slope of approximately -1.605. From this the idea of a stand density index (SDI) has been widely adopted (Clutter et al, 1983). The SDI is calculated relative to a base diameter, usually 25 cm dbh, using the relation:

$$Dg = [SDI.25^{1.605}/N]^{1/1.605} \qquad \{eqn.\ 8\}$$

Figure 10 : A Log-Log plot of Stocking versus Diameter for the PSP data, with lines of constant Stand Density Index. *Self-thinning would probably occur at an SDI of around 1200.*



where 25 is the base diameter chosen, and 1.605 is the slope of the self-thinning or Reineke line. Figure 10 shows the stocking-diameter relationship for the PSPs with lines of constant SDI.

Thinning ratio

When a selective thinning from below is applied, as is normal good practice in plantation management, smaller trees are preferentially removed. This has not been analysed empirically for the current model, but an assumed function based on Alder (1979) is applied. This applies a greater thinning bias the lighter the thinning, with heavy thinnings being more uniform in their effect. This function has the form:

$$p_a = p_i^{1/L} \qquad \{eqn. 9\}$$

where the p_a is a percentile of the diameter distribution after thinning for the same diameter point as the p_i percentile before thinning, and L is the leave fraction, or ratio of stocking after thinning to stocking before thinning.

Equation (9) is applied in the model to recalculate the percentiles for the remaining stand for the pre-thinning quintiles. A Weibull function is then fitted to these in order to interpolate the diameter points for the standard quintile values (10%, 30%, 50%, 70%, 90%). The diameter distribution of thinnings is also calculated as the difference between the before and after thinning diameter distributions. These calculations are carried out in the VBA routine `doThinning`.

Appearance of the model

This version of the model is constructed as an Excel 2016 workbook with VBA macros. The file is called Uganda GW Pine Model 2017 (v1.2).xlsm[1]. When the workbook is opened it will be seen to have a single sheet called `Model`, as per the screen shot in Figure 11.

Figure 11 : Screen shot of the model in Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	Global Woods Uganda - Forest model for Caribbean Pine																					Update
2	**Initial conditions for projection**						**Site index**		**Planting**		**Survival**		**Merchantable volume**		*Class 1*	*Class 2*			**Thinning Basis**		Custom	
3	1. From planting (per G3:K3)						20	m	1100	n/ha	85%		*Minimum top diam. (cm ub)*		10	20			*Threshold level*		600	
4									**Final year**		30	*yrs*	*Minimum log length (m)*		2	2			*Trees to remove*		33%	
5																						
6	**Crop before thinning**			Dg	BA	**Diameter distribution quintiles, cm**					**Standing Volume m3**			**MAI (m3/ha/yr)**			**Thinning Specs.**			**Thinned Volume (m3)**		
7	Age	Hdom	N/ha	cm	m2/ha	10%	30%	50%	70%	90%	OB, Tot	UB, cl.1	UB, cl.2	OB, Tot	UB, cl.1	UB, cl.2	SDI	Ratio	N/ha	OB, Tot	UB, cl.1	UB, cl.2
8	2	4.1	935	4.9	1.8	3.3	4.1	4.7	5.4	6.6	5			2.3			69					
9	3	6.3	935	8.7	5.5	6.4	7.5	8.4	9.3	11.0	19			6.4			171					
10	4	8.5	935	12.0	10.5	9.2	10.7	11.7	12.8	14.7	45	12		11.1	3.1		287	20%	187	7	0	0
11	5	10.6	748	15.3	13.7	12.3	13.8	15.0	16.3	18.3	67	39		14.8	7.9		339					
12	6	12.7	748	17.8	18.6	14.6	16.3	17.5	18.9	21.0	104	67		18.4	11.2		433					
13	7	14.6	748	20.0	23.4	16.6	18.4	19.7	21.1	23.3	145	100		21.7	14.4		522					
14	8	16.5	748	21.9	28.1	18.4	20.3	21.6	23.1	25.3	191	137	17	24.7	17.2	2.2	604					
15	9	18.3	748	23.5	32.6	20.0	21.9	23.3	24.8	27.1	240	178	41	27.4	19.9	4.6	679					
16	10	20.0	748	25.0	36.8	21.4	23.4	24.8	26.3	28.6	291	223	79	29.8	22.3	7.9	749					
17	11	21.6	748	26.3	40.7	22.7	24.7	26.1	27.6	30.0	343	269	121	31.8	24.5	11.0	813					
18	12	23.2	748	27.5	44.4	23.8	25.8	27.3	28.8	31.2	396	314	170	33.6	26.2	14.2	872	33%	247	112	89	35
19	13	24.6	501	29.6	34.4	26.0	27.9	29.4	30.9	33.1	322	258	166	33.9	26.8	15.5	656					
20	14	26.0	501	30.6	36.7	27.0	28.9	30.4	31.9	34.1	361	291	200	34.2	27.2	16.8	692					
21	15	27.4	501	31.5	38.9	27.9	29.8	31.3	32.8	35.1	399	323	229	34.5	27.5	17.6	725					
22	16	28.6	501	32.3	41.0	28.6	30.6	32.1	33.6	35.9	436	354	262	34.7	27.8	18.6	755					
23	17	29.8	501	33.0	42.9	29.4	31.3	32.8	34.4	36.7	473	385	292	34.8	27.9	19.2	783					
24	18	30.9	501	33.7	44.7	30.0	32.0	33.5	35.1	37.4	509	415	321	34.8	28.1	19.8	809					
25	19	32.0	501	34.3	46.4	30.6	32.6	34.1	35.7	38.0	544	444	350	34.8	28.1	20.3	833					
26	20	33.0	501	34.9	47.9	31.2	33.2	34.7	36.3	38.6	577	474	377	34.8	28.2	20.6	856					
27	21	33.9	501	35.4	49.4	31.7	33.7	35.2	36.8	39.2	610	501	403	34.7	28.1	20.9	876					
28	22	34.8	501	35.9	50.7	32.1	34.2	35.7	37.3	39.7	642	528	428	34.5	28.1	21.1	895					
29	23	35.6	501	36.3	52.0	32.6	34.6	36.2	37.8	40.1	672	553	452	34.3	28.0	21.2	913					
30	24	36.4	501	36.7	53.1	33.0	35.0	36.6	38.2	40.5	701	578	475	34.1	27.8	21.3	930					
31	25	37.2	501	37.1	54.2	33.3	35.4	36.9	38.6	40.9	729	601	497	33.9	27.6	21.3	945					
32	26	37.9	501	37.5	55.3	33.7	35.7	37.3	38.9	41.3	755	624	518	33.6	27.5	21.3	959					
33	27	38.5	501	37.8	56.2	34.0	36.1	37.6	39.2	41.6	781	646	538	33.3	27.3	21.2	973					
34	28	39.2	501	38.1	57.1	34.3	36.4	37.9	39.5	41.9	805	666	557	33.0	27.0	21.1	985					
35	29	39.8	501	38.4	58.0	34.5	36.6	38.2	39.8	42.2	828	686	575	32.6	26.8	21.0	997					
36	30	40.3	501	38.6	58.7	34.8	36.9	38.5	40.1	42.5	850	705	592	32.3	26.5	20.9	1008					

There is a button labelled **`Update`** positioned in cell V1. Clicking on this button will run the model with current parameter settings. A warning message appears that the current outputs will be overwritten. Clicking **`Cancel`** aborts the update, **`OK`** will clear the sheet and display the recalculated results with current settings. The various specifications for the simulation are in the white areas in rows 2:4, and for thinnings, in column R from row 8.

Input Options

The initial conditions of the stand to be projected or simulated can be defined in three ways, according to the option selected in call A3. These are:

(1) From planting. In this case, the site index should be set in call G3. Appropriate values would be between 17 and 23, with 20 being a median value and suitable default value for Kikonda forest with the improved *P. caribaea* hybrids planted since 2002. Planted stocking and survival should also be set in cells I3 and K3, with 1111 stems/ha (3 x 3 m spacing) and 85% survival being suggested defaults.

[1] Link address http://bit.ly/2ynRAIp. If inaccessible, email denis@validinternational.org for assistance. The file should be downloaded and run in Excel on the local computer. Do not attempt to use the online version of Excel – it will not run the macros.

(2) From stocking and dominant height data at a given age. In this case, the initial age, dominant height and stocking should be given in cells A8:C8. The model will calculate site index from this information and over-write any value in cell G3. The planted stocking and survival values in cells I3 and K3 will be ignored and can be blank, which is recommended if the output is to be used in a report. When run in this mode, the diameter distribution at the initial age is estimated from equation (3).

(3) From stocking, dominant height and diameter distribution at a given age. This is as for (2), but additionally the 10%, 30%, 50%, 70% and 90% points of the diameter distribution are required in cells F8:J8. These can be calculated in various ways, but one simple approach is to list all the diameters for all the inventory plots in the target stand, and then apply the Excel function *PERCENTILE.EXC(data-range, percentile)*[2]

Apart from these initial conditions, the final year of the simulation should be specified in cell K4. It is recommended that this should not exceed 50 years, as being an unreasonable extrapolation of current data.

Volume specifications

Volume calculations from the model are output in three columns. For the standing crop, these are columns K:M and for thinnings, columns T:V, both from row 8. Total volume over bark is always shown, and then merchantable volume in two classes. The specifications for these classes are given in P3:Q4. The top diameter under bark must be given. The classes do not have any required order, so class 1 may have a large, smaller or equal top diameter to class 2. A minimum length can also be given, but this is optional, and may be left blank. If given, trees whose height to the specified top diameter is less than the minimum length will not be counted as part of that merchantable volume class.

Merchantable volume is calculated under bark. It includes a deduction for stump height, set at 25 cm.

Note that the minimum length is not applied by fixed log-length sections like some bucking algorithms. If the minimum is 3 m, and a tree has a merchantable height of 4 m, then the entire 4 m length (less 25 cm stump allowance) will be used. In a bucking algorithm, the excess 1 m would be discarded.

If the under bark top diameters are zero or left blank, total under bark volume to the tip is calculated.

Thinning specifications

Cell U2 has a drop-down list of options for specifying thinning. These allow for no thinning (None), thinning by Basal Area or SDI control, or a custom thinning. If None is selected in cell U2, then any other specifications are ignored, any contents in column R8 downwards will be deleted, and no thinning will be done.

If Basal Area or SDI control are specified, thinning will be done when the threshold value in cell U3 is reached, which may be given in either m2/ha (for Basal Area control) or SDI units. The thinning intensity is given in cell U4.

For Custom thinnings, the values in U3 and U4 are ignored. Instead thinnings are performed at the intensity and age specified according to the entries in column R, from row 8. For

---

[2] A sample spreadsheet *How to get percentiles of diameter distribution.xlsx* can be downloaded from http://bit.ly/2xrBHUp that illustrates the method.

example, Figure 11 shows thinnings of 20% (1 in 5 stems) at age 4, and 33% (1 in 3 stems) at age 12.

If the Custom thinning is specified as 100%, a clear felling is assumed, and simulation will stop at that point.

Conclusions

This report describes the updating of the Uganda Caribbean Pine yield model from the version of Alder et al (2003) to a current version, specifically applicable to the Global Woods (GW) plantations at Kikonda Forest Reserve using improved hybrids.

For this purpose, permanent sample plot (PSP) data was provided by GW and cleaned and analysed by Valid International (VI). There were found to be 1247 plot-measurement years, with 21,579 tree measurements. The cleaned version of this dataset was archived as an Access database and supplied to GW as a reference copy (see Figure 3).

The site index curves (dominant height on age) from the 2003 model were found to be applicable and have been retained (Figure 7), although the median site index of the new plantings was found to be 20 m, as compared with 13 m on the same site for the previous cycle of plantings with locally collected seed. This represents a very considerable increase in productivity.

A requirement for the new model was to incorporate taper and volume functions developed for GW by Ata Marie (2015), in place of the older UFRP volume functions used in the 2003 model. A comparison (Figure 9 and Table 2) showed that the two give very similar results for whole tree volumes, with the taper functions being some 10% higher (depending on relative dimensions), but the taper functions are much more flexible in use for calculations with constraints on log lengths and diameters. The equations for the taper functions were encoded as R and VBA functions, as listed in Annex B and C, with versions for calculation of merchantable height and volume to different top diameters over and under bark.

To use these equations in the model required a different strategy to the whole stand model based on direct estimation of stand volume from stocking and dominant height used in the 2003 model. Instead a function was developed to predict percentiles of the diameter distribution. The model was structured to use five percentiles (quintiles), representing the 10%, 30%, 50%, 70% and 90% points of the diameter distribution, following the methodology of Alder (1979). A function to predict these directly at constant stocking, for unthinned stands was developed (equation 3), and then modified as a partial difference equation (equation 6) for use in thinned stands.

The model also required a local height-diameter function to relate tree heights to diameters for stands of a given dominant height and mean diameter (equation 2). This allowed the taper function to be used to estimate volumes for each of the quintiles.

As agreed in the TOR (Annex A), the model was represented in the form of an Excel workbook. The input and output format is shown in Figure 11, and the underlying VBA code for the model is given in Annex C.

During the development process of the current model, GW proposed that it should be compatible with the South African FORSAT estate modelling system. It was not possible to incorporate this objective without additional work, as there are some significant differences in the required functions. However, the scope of the required amendments have now been reviewed and discussed with technical specialists involved[3], and if the necessary additional work is agreed, a revision to this report will be produced with compatibility functions described in an additional section.

The current version of the model (GW Uganda Carib Pine Model v 1.2) is however fully usable as a planning tool as supplied, and can be combined with inventory summaries to

[3] Wille Brink (willie@mto.group) and Gerard Lindner (gerard@microforest.co.za). 20 September 2017.

produce estate projections using Excel. In this context, it should be a useful addition to GW's forest planning capabilities.

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Upgrading of the Uganda Pine Growth Model

Terms of Reference

1 Background

Global-Woods AG (GW) has some 8,000 ha of plantations established in Uganda near Kikonda, of which some 93% are Caribbean Pine, and 7% Eucalyptus. The oldest stands are from 2002. The forest is FSC certified and managed currently with a view to saw log production. The current management tool used for yield forecasting is the model of Alder et al (2003).

GW now wish to update that model to take into account new growth data available from 2002 on their own plantations, and specifically have a model that is sensitive to the effects of thinning, and that also can calculate optimal schedules as well as providing 'what-if' type simulations. The database for the modelling comprises about 320 permanent sample plots (PSPs) of 250 m2 circular design with approximately annual measurements. There is also an unspecified quantity of temporary sample plots (TSPs). The work would be in two packages, firstly for Caribbean Pine, which comprise the bulk of the estate, and then later on for Eucalyptus.

2 Key tasks

- Review and summarise the PSP and TSP datasets (to be provided as an Access database and ancillary files) and fit revised functions for height, diameter and volume.
- Analyse spacing and thinning responses and develop models particularly that are sensitive to and accurately reflect thinning response.
- Revise the structure and calibration of the model (currently coded in Excel/VBA) to incorporate these updated functions as well as incorporating a revised taper function to be provided by global-woods.
- Add additional code to the model to incorporate a 'goal-seeking' or optimizing mode to find best management practices to maximize production and value to a given minimum size (DBH) or to maximise rate of volume growth per hectare.
- Write a technical report and user manual (one document in two parts) for the model, being particularly clear about the justification of thinning response assumption used.
- Support via skype and email the use of the model. This support would not include updates or extensions to the model, but only its use as originally specified.
- Make any necessary corrections or bug-fixes to deal with problems that may arise during operation.
- The model would be designed to run in MS Excel, compatible with versions 1997-2003 and 2007-2016 (ie as .xls or .xlsm files).

3 Deliverables

1. The forest model, in the form of an Excel workbook with VBA macros, compatible with Excel 1997-2003 (.xls) and 2007-2016 (.xlsm).

2. A report, comprise technical reference detailing the data analysis and model structure and equations, and a user guide intended for management.

4 Timeline

This work will take place over a total of 15 days over a period of 3 months.

Annex B : R code used for analysis and graphics

R code included here is for figures shown in the report produced in R (the equivalent figure number is commented) and for functions equivalent to those used in the model and referred to in the report.

```r

# fitted functions forming part of the model

sicurv <- function(age, si){
  # Uganda P.caribaea height function.  Gives height
  # for <age> and site index <si>
  # see p.16 in Alder et al.(2003)
  m <- -0.0178*si + 0.4847
  k <- 0.0606
  A <- si/(1-exp(-k*10))^(1/(1-m))
  h <- A*(1-exp(-k*age))^(1/(1-m))
  return(h)
}

treeHeight <- function(hdom, dg, dbh){
# gives individual tree height (ht, m) from tree dbh (cm), stand dominant height
(Hdom, m)
# and stand quadratic mean diameter dg (cm)
rd <- dbh / dg
        rh <- 0.5385065 + 0.3713323 * rd
        ht <- rh * hdom
return(ht)
}

qDiamHd <- function(hd, qp, mpt){
#static function for diameter quantiles.  Returns diameter in cm for
#quantile qp (0-1) of the diameter distribution, dominant height hd m and spacing mpt
m/tree
# regression coefficients
b <- c(4.308092, -5.739368, 0.066883, -0.06563, 0.497234, -0.09821, 0.017257, -
0.049239)
bias <- exp(0.1461 ^ 2 / 2) # Meyer's correction for bias, logarithmic equation
lqp <- log(qp / (1 - qp))    # logit transform for quantile
invh <- 1 / sqrt(hd)         # transformation for dominant height
# R formula for regression:
# lnqd ~ invh + mpt + lqp + invh.lqp + invh.mpt + mpt.lqp + invh.lqp.mpt
lnD <- b[1] + b[2] * invh + b[3] * mpt + b[4] * lqp + b[5] * invh * lqp +
      b[6] * invh * mpt + b[7] * lqp * mpt + b[8] * invh * lqp * mpt
return(exp(lnD) * bias)
}


# taper equation components from Ata Marie (2015) report

dobTaper <- function(hm, ht, dbh){
# gives Diam overbark hm metres above ground for tree of ht m height and dbh cm
# diameter. See page 11 (sect 3.2, eqn. 3) of report
ltip <- ht - hm
b2 <- 6.28018
g1 <- 4.42443
g2 <- 1.52747
b1 <- (1-(b2/(dbh*ht)^0.3)*(1-1.3/ht)^g2)/((1-1.3/ht)^(g1/ht^0.2))
dob <- sqrt(dbh^2*(b1*(ltip/ht)^(g1/ht^0.2)+(b2/(dbh*ht)^0.3)*(ltip/ht)^g2))
return(dob)
}

hmTaper <- function(dob, ht, dbh){
# gives height to overbark diameter dob for tree total height ht and dbh.
# This is inverse of dobTaper, solved numerically using R uniroot function.
hm <- 0       # default height if function fails
   f <- function(h){return(dobTaper(h, ht, dbh) - dob)}
   try(hm <- uniroot(f, lower=0, upper=ht, tol=0.001)['root'], silent=T)
   return(as.numeric(hm))
}

```

```
vobTaper <- function(ht, dbh){
# whole tree volume overbark
b2 <- 6.28018
g1 <- 4.42443
g2 <- 1.52747
b1 <- (1-(b2/(dbh*ht)^0.3)*(1-1.3/ht)^g2)/((1-1.3/ht)^(g1/ht^0.2))
vob <- 3.14159246  * dbh^2/40000 * ((b1/(ht^(g1/ht^0.2) * (g1/ht^0.2+1))) *
(ht^(g1/ht^0.2+1)) + b2 * ht^(g2+1)/((dbh * ht)^0.3*ht^g2 * (g2+1)))
return(vob)
}

vibTaper <- function(ht, dbh){
# whole tree volume inside bark
b2 <- 6.28018
g1 <- 4.42443
g2 <- 1.52747
a0 <- 0.682537
a1 <- 0.524777
a2 <- -0.487183
t1 <- g1/ht^0.2
t2 <- (dbh*ht)^0.3
b1 <- (1-b2/t2*(1-1.3/ht)^g2)/(1-1.3/ht)^t1
vib <- 3.14159246  * dbh^2/40000 * (
                a0 * b1 / (ht^(t1+0)*(t1+1)) * ht^(t1+1)
        +       a1 * b1 / (ht^(t1+1)*(t1+2)) * ht^(t1+2)
        +       a2 * b1 / (ht^(t1+2)*(t1+3)) * ht^(t1+3)
        +       a0*b2/(t2*ht^(g2+0)*(g2+1))*ht^(g2+1)
        +       a1*b2/(t2*ht^(g2+1)*(g2+2))*ht^(g2+2)
        +       a2*b2/(t2*ht^(g2+2)*(g2+3))*ht^(g2+3))
return(vib)
}

##############################################################################
########### functions only used for analysis and documentation ##############

draw.taper <- function( ht, dbh){
# test plot of the taper function
# set scales to ht,  basal diam rounded to nearest 5
dbase <- dobTaper(0, ht, dbh)
hmax <- floor(ht/5+1)*5
gmax <- floor(dbase^2*0.007854+1)*100    #basal area of tree base in sq cm, rounded up
to nearest 100
# data points of taper function
h <- seq(from=0, to=ht, by=ht/50)
d <- dobTaper(h, ht, dbh)
g <- d^2*0.7854 #basal area in sq cm
tpf <- data.frame(d,g, h)
# create basic plot
a <- data.frame(x=c(0, gmax), y=c(0, hmax))
fig <- ggplot(a, aes(x=x, y=y)) + geom_point(shape=3)
# add taper function
fig <- fig + geom_line(data=tpf, mapping=aes(x=g, y=h), colour='red', size=1.5,
linetype='solid')
# add green lines for total height, dbh
fig <- fig + geom_hline(yintercept=1.3, colour='green',
                 size=0.5, linetype='solid')
fig <- fig + geom_hline(yintercept=ht, colour='green',
                 size=0.5, linetype='solid')
gbh <- dbh^2*0.7854
fig <- fig + geom_vline(xintercept=gbh, colour='green',
                 size=0.5, linetype='solid')
# add blue line joining tip of tree to dbh point
fig <- fig + geom_abline(intercept=ht, slope=(1.3-ht)/gbh , colour='blue',
                 size=0.5, linetype='solid')
# add captions
 fig <- fig + labs(x="Basal area (sq.cm)", y="Height (m)")
 fig <- fig + ggtitle("Global Woods Taper Function")
 return(fig)
}

# Figure 7 in report

draw.sicurv <- function(pdata){
# draws a system of site index curves using ggplot
```

```
# age range for graph
agemin <- 0; agemax <- 20;
# SI curve values to be plotted (from, to, by)
simin <- 12; simax <- 24; siby <- 2;
# height scale
hmin <- 0; hmax <- 40;
# initialise the plot
a <- data.frame(x=c(agemin, agemax), y=c(hmin, hmax))
fig <- ggplot(a, aes(x=x, y=y))
 # add data from plots
 fig <- fig + geom_line(data=pdata, aes(x=age, y=hdom, group=plotid), colour="blue",
alpha=0.3)
# draw the height index lines
alt=T   # toggle for alternate thick sold and thin dashed lines
for (si in seq(simin, simax, by= siby)){
        # styles for alternate lines
        if(alt){
                asize = 0.5; astyle="dotted"; acol="red" ; alt=F
        }else{
                asize = 1; astyle="solid"; acol="red" ; alt=T
        }
        fig <- fig+stat_function(fun=sicurv, xlim=c(1, agemax-0.5), args=list(si=si),
colour=acol,
                 size=asize, linetype=astyle)
        h = sicurv(agemax, si)
        fig <- fig + annotate("text", x = agemax , y = h , label = si)
 }
 # title and axis labels
 fig <- fig + labs(x="Age (years)", y="Dominant height (m)")
 #fig <- fig + ggtitle("Figure 7 : Global Woods PSPs on 2003 Site Index Model")
 # return ggplot object as a result
 return(fig)
}


# Figure 8 in report

draw.diamGrowth <- function(){
# plot of diameter for quantile dq on Hdom with colours for stand density (spacing)
# Maximum spacing to include
fig <- ggplot(data=pdxq[pdxq$qd<40,], aes(x=hdom, y=qd, group=plotidx, colour=qp))
fig <- fig + geom_line(alpha=0.5)
fig <- fig + scale_color_gradient(low="red", high="green")
# title and axis labels
fig <- fig + labs(y="Quantile Diameter (cm)", x="Dominant height (m)")
# draw the height-diameter lines for quantiles
for (pq in seq(0.1, 0.9, by= 0.2)){
fig <- fig+stat_function(fun=qDiamHd, xlim=c(1, 24), args=list(mpt=3.5, qp=pq),
colour="black",
         size=1, linetype="solid")
d = qDiamHd(25, pq, 3.5)
fig <- fig + annotate("text", x = 25 , y = d , label = paste(pq*100, "%"))
}
return(fig)
}


getDiamQuantiles <- function(pdiams){
# goes through the plot summary list and gets the diameter
# distribution quantiles (10%, 30%, 50%, 70%, 905) from the pdiams data frame.
# This should be a list of diameters (dbh) for each plotid and year (age)
# Returns a dataframe with plotid, age, qp (quantile), qd (quantile diameters)
 #
# get list of unique plotid-age values and preallocate output space
pa <- unique(pdiams[,1:2])
L <- length(pa[,1])
Lq <- L*5       # space for 5 quantiles
pdq <- data.frame(plotid = character(Lq), age = numeric(Lq), qp = numeric(Lq), qd =
numeric(Lq), stringsAsFactors = FALSE)
# work through plots and ages
for(r in 1:L){
        # current plotid and age
        this.plotid <- pa[r,1]
        this.age <- pa[r,2]
```

```
                        # get diameter list for current plot and age
                        d <- pdiams[pdiams$plotid==this.plotid & pdiams$age==this.age,'dbh']
                        # get the quantiles of the diameter distribution
                        p <- c(0.1, 0.3, 0.5, 0.7, 0.90)
                        q <- quantile(d, probs=p, na.rm=T)
                        # copy them into the correct row position of output dataframe
                        for( j in 1:5){
                                k <- (r - 1)*5 + j
                                pdq[k,1] <- this.plotid
                        pdq[k,2] <- this.age
                        pdq[k,3] <- p[j]
                        pdq[k,4] <- q[j]
                }
                }
                return(pdq)
        # that should be it!
        }

        # Figure 10 in report

        figLogNLogD<- function( ){
        # plot of diameter for quantile dq on Hdom with colours for stand density (spacing)
        # Maximum spacing to include given as <spc>
        fig <- ggplot(data=pdx, aes(x=dg, y=nha, group=plotid))
        fig <- fig + geom_line(alpha=0.3, colour="red")
        # title and axis labels
        fig <- fig + labs(y="Tree per ha.", x="Quadratic mean diameter (cm)")
        # Stand Density Index lines
        # data points for sdi 200-1000, stocking 300 to 1500 sph
        sdi_data <- data.frame(sdi=numeric(35), nha=numeric(35), dg=numeric(35))
        i=0
        for (s in seq(from=200, to=1000, by=200)){
        for(n in c(200,300,600,1000,1500,2000,3000)){
                i <- i + 1
                sdi_data[i,] <- c(s, n, fnInvSDI(n, s))
         }
        }
        #browser() #debugging
        # add sdi lines
        fig <- fig + geom_line(data=sdi_data, mapping=aes(x=dg, y=nha, group=sdi),
        colour='blue', size=0.5, linetype='solid')
        # annotate SDI lines at top
        n=180
        for(s in unique(sdi_data$sdi)){
        d = fnInvSDI(n,s)
        if(s>=1000) d <- d*1.03
        fig <- fig + annotate("text", x = d , y = n, size=3 , label = s)
        }
        fig <- fig + annotate("text", x = 20 , y = n, size=3 , label = "SDI")
        # log scales with custom tick marks
        fig <- fig + scale_y_log10(limits=c(100,3000),
        breaks=c(100,200,300,400,500,600,700,800,1000,1200,1500,2000,3000),
        minor_breaks=NULL ) +
        scale_x_log10(limits=c(2,80), breaks=c(2,3,4,5,6,7,8,9,10,15,20,25,30,40,50,60,70),
        minor_breaks=NULL)
        return(fig)
        }

        fnSDI <- function(d, sdi){
        # calculates points on the Stand Density Index line for a given SDI
        # base diameter for SDI is 25 cm
        n <- (sdi*25^1.605)*d^-1.605
        return(n)
        }


        fnInvSDI <- function(n, sdi){
        # calculates points on the Stand Density Index line for a given SDI
        # base diameter for SDI is 25 cm.  Inverse form, returns d given n
        d <- ((sdi*25^1.605)/n)^(1/1.605)
        return(d)
        }
```

Annex C: Workbook structure and VBA code for the model

This includes the VBA code in the model. It can be seen by typing Alt-F11 in Excel. It is divided into 3 modules, as per the section headings.

Module GrowthFunctions

This module includes new equations developed as part of this project, and some old equations from the 2003 model. All these functions are self-contained and can be used in Excel as worksheet functions if desired.

```
Option Explicit

'--------- New functions for 2017 model from GW PSP data -------------

Function qDiam(Hd As Double, qp As Double, nha As Double) As Double
'static function for diameter quantiles.  Returns diameter in cm for
'quantile qp (0-1) of the diameter distribution, dominant height hd m and stocking
nha trees/ha
Dim mpt As Double   'average spacing, metres/tree
Dim lqp As Double   'logit transform of qp
Dim invh As Double  'transform of hdom: 1/sqr(hdom)
Dim b As Variant    'array of coefficients
Dim lnD As Double   'predicted value is ln(dbh)
Dim bias As Double  'bias correction for log-transformed dependant variable
b = Array(4.308092, -5.739368, 0.066883, -0.06563, 0.497234, -0.09821, 0.017257, -
0.049239)
bias = Exp(0.1461 ^ 2 / 2)
mpt = Sqr(10000 / nha)      'transformation for n/ha
If mpt > 10 Then mpt = 10  'to avoid high values at very low stocking
lqp = Log(qp / (1 - qp))    'transformation for quantile
invh = 1 / Sqr(Hd)          'transformation for dominant height
'R formula for regression:
'lnqd ~ invh + mpt + lqp + invh.lqp + invh.mpt + mpt.lqp + invh.lqp.mpt
lnD = b(0) + b(1) * invh + b(2) * mpt + b(3) * lqp + b(4) * invh * lqp + _
      b(5) * invh * mpt + b(6) * lqp * mpt + b(7) * invh * lqp * mpt
qDiam = Exp(lnD) * bias
End Function


Function qDiamInc(si As Double, age As Double, qp As Double, nha As Double) As Double
'Diameter increment for site index si, age in years, diameter quantile qp,
'and stocking nha.  Returns increment in cm year.  Uses finite difference method
'based on qDiam function.
Dim Hd(0 To 1) As Double 'dominant heights over 1 year interval
Dim dbh(0 To 1) As Double 'estimated dbh at start and end of period
Dim t As Integer    'time index
For t = 0 To 1
    Hd(t) = Hdom(si, age - 1 + t)   't=0 is last year, t=1 this year
    dbh(t) = qDiam(Hd(t), qp, nha)
Next t
qDiamInc = dbh(1) - dbh(0)
End Function


Function treeHeight(Hd As Double, dg As Double, dbh As Double) As Double
   ' gives individual tree height (ht, m) from tree dbh (cm) and stand
   ' dominant height (hd, m) and mean basal area diamtere (dg, dm)
   Dim rh As Double, rd As Double   'relative height, relative diameter
   rd = dbh / dg
   rh = 0.5385065 + 0.3713323 * rd
   treeHeight = rh * Hd
End Function

Function getSDI(nha As Double, dg As Double) As Double
'gets Stand Density Index
```

```
Const Dindex = 25       'index diameter for SDI
Const Rcoeff = 1.605    'Reineke coefficient
getSDI = nha * (dg / Dindex) ^ Rcoeff
End Function

'------------ Functions adopted from old Alder et al 2003 model ---------------
'Note that only Hdom, GetSI and selfThin are used in the GW model.
'V50bha, V10ubha and dg are retained as worksheet functions available
'for comparative analysis but are not used by the model itself.

Function Hdom(si As Double, age As Double) As Double
'height-age-site index function for Caribbean Pine
'per Alder et al , 2003 model
Dim m As Double, k As Double, a As Double
m = 0.48465 - 0.01784 * si
k = 0.0606
a = si / (1 - Exp(-k * 10)) ^ (1 / (1 - m))
Hdom = a * (1 - Exp(-k * age)) ^ (1 / (1 - m))
End Function

Function GetSI(Hd As Double, t As Double) As Double
'iterative solution for Pinus caribaea site index
Dim s1 As Double, s0 As Double, n As Integer
s1 = 20               'initial guess
'loop until convergence
Do While Abs(s0 - s1) > 0.001
   s0 = s1
   s1 = Hd * ((1 - Exp(-0.606)) / (1 - Exp(-0.0606 * t))) ^ _
    (1 / (0.01784 * s0 + 0.5153))
   n = n + 1
   If n > 1000 Then GetSI = -1: Exit Do 'stop if indefinite cycling
Loop
GetSI = s1
End Function

Function V5obha(Hd As Double, nha As Double) As Double
'yield (stand volume) function for Caribbean Pine
'for volume to 5 cm top, overbark, per ha
'per Alder et al , 2003 model, not used in this model except for comparison
Dim S As Double, vt As Double
S = Sqr(10000 / nha)    'mean tree spacing
vt = (0.493 * Log(S) + 0.282) * 0.000712 * Hd ^ 2.1673
V5obha = vt * nha
End Function

Function V10ubha(v5ob As Double, dg As Double) As Double
'gives volume underbark to 10cm top for Caribbean Pine given
'overbark volume to 5 cm top and mean diameter
'per Alder et al , 2003 model, not used in this model except for comparison
V10ubha = 0.23232 * dg ^ 0.30142 * v5ob ^ 1.02238
End Function

Function SelfThin(nha As Double, Hd As Double, Optional f As Double = 1#) As Double
'self thinning rule for Caribbean Pine
Dim Nlim As Double
Nlim = 232093 * Hd ^ -1.6055 * f
If Nlim < nha Then
   SelfThin = Nlim      'stocking reduced to self thinning line
ElseIf nha > 0 Then
   SelfThin = nha       'stocking unchanged
Else
   SelfThin = 0         'may arise if thinning >standing stock
End If
End Function

Function dg(n As Double, v As Double) As Double
'estimates mean basal area diameter (Dg) from total volume (V)
'and trees/ha (N)
'per Alder et al , 2003 model, not used in this model except for comparison
dg = 42.17384797 * v ^ 0.31065768 * n ^ -0.342456151
End Function
```

Module MainProgram

This has the entry point for the model, procedure Run_Model, which organises and controls the simulation, and some subsidiary functions which cannot be run independently. Run_Model can be executed from the Excel Alt-F8 key as well as the **`Update`** button, but will only operate correctly if the active sheet heading, rows 1-8 is formatted exactly as per Figure 11.

```
Option Explicit

Const vertext = "Global Woods Uganda Carib Pine Model ver 1.2"  'title and version control
'Coding by Denis Alder (denis@validinternational.org) September 2017

'model parameters
Dim run_mode As Integer 'mode for setting initial conditions
Dim si As Double    'site index
Dim yr0 As Integer      'starting year of simulation
Dim yrf As Integer      'final year of simulation
Dim hd0 As Double      'initial dominant height
Dim nha0 As Double     'initial stocking
Dim diam0(1 To 5) As Double 'initial diameter vector

Dim thin_mode As Integer    'mode for deciding to thin
Dim thinTH As Double        'thinning threshold, either BA (M2/ha) or SDI%
Dim thinPct As Double       'percentage of trees to thin
Dim mvMinD(1 To 2) As Double    'minimum diameters for merchantable volume
Dim mvMinL(1 To 2) As Double    'minimum log length
Const StumpHt = 0.2  'assumed stump height for merchantable volume
Public Running As Boolean      'set true while model is running

Sub Run_Model()
'runs the model using data on the current sheet
Dim yr As Integer       'year loop index
Dim r As Integer        'output row index
Dim j As Integer        'general purpose loop index
Dim k As Integer        'a column index
Dim qp As Double        'quantile value
Dim dg As Double        'quadratic mean diam
Dim age As Double       'stand age.
Dim Hd As Double        'dominant height
Dim nha As Double       'current stocking
Dim vob As Double       'overbark total volume
Dim vim(1 To 2) As Double  'inside bark merchantable volume
Dim stvub As Double     'stump volume ub
Dim m As Integer        'merchantable volume index
Dim hm As Double        'merchantable height point for a tree/cohort
Dim hq As Double        'height for a diameter quantile
Dim dq As Double        'diameter quantile
Dim thinr As Double     'thinning ratio
Dim nthin As Variant    'no. of stems thinned, by diameter classes
Dim dthin As Variant    'quadratic mean diameters of thinning classes
Dim maiv(0 To 2) As Double  'MAI Volume for Vob, Vub class 1 and 2
'warns that sheet will be overwritten, or stops if sheet doesn't look right
model_setup             'read and check model parameters (aborts if an error)
Running = True: [A5] = ""
r = 8   'output table starts in row 8
' age loop - outputs start at year 2 as year 1 figures not realistic
For yr = yr0 To yrf
    '------ Worksheet columns A-C : age, dominant height, stocking ----
    'age
    Cells(r, 1) = yr
    age = yr
    'dominant height
    If yr > yr0 Then Hd = Hdom(si, age) Else Hd = hd0
    Cells(r, 2) = Hd
    'stocking
```

```
    If yr = yr0 Then
        nha = nha0
    Else
        'adjust stock for thinnings and self-thinning (Reineke Line)
        nha = Cells(r - 1, 3) - Cells(r - 1, 19) 'previous years stock less no. thinned (col N)
        nha = SelfThin(nha, Hd)                  'self-thinning may occur at high stocking
    End If
    'if stocking is less than 1 tree, exit simulation
    If Int(nha) <= 0 Then
        Range(Cells(r, 1), Cells(r, 10)).ClearContents
        Exit For
    End If
    Cells(r, 3) = nha
    '------ Worksheet columns F-J : diameter distribution ----
    'diameter distribution
    dg = 0
    For k = 1 To 5
        qp = Cells(7, k + 5)     'Percent of cum. diameter distribution
        'if post-thinning diameters, use them, otherwise last year
        If Cells(r, k + 5) > 0 And r > 8 Then
            dq = Cells(r, k + 5)
        Else
            dq = Cells(r - 1, k + 5)
        End If
        If yr = yr0 Then
            If run_mode <> 3 Then
                'for first row, use direct calculation of diameter
                Cells(r, k + 5) = qDiam(Hd, qp, nha)
            Else
                'except in mode 3, where diameter distribution is given
                Cells(r, k + 5) = diam0(k)
            End If
        Else
            'add increment to previous diameter
            Cells(r, k + 5) = dq + qDiamInc(si, age, qp, nha)
        End If
        dg = dg + Cells(r, k + 5) ^ 2
    Next k
    '------ Worksheet columns D-E : Mean basal area diameter, basal area -----
    'Dg - quadratic mean diameter
    dg = Sqr(dg / 5)
    Cells(r, 4) = dg
    'basal area
    Cells(r, 5) = dg ^ 2 * 0.00007854 * nha
    '------ Worksheet columns K-M : Standing volumes, total and merchantable -----
    'standing volumes
    vob = 0: vim(1) = 0: vim(2) = 0
    'accumulate volume for each quantile diameter
    For k = 1 To 5
        'tree height corresponding to quantile diameter
        dq = Cells(r, k + 5)
        hq = treeHeight(Hd, dg, dq)
        vob = vob + vobTaper(hq, dq)
        stvub = vibTaper(Hd, dq, StumpHt)
        'merchantable heights
        For m = 1 To 2
            If hq > mvMinL(m) And dq > mvMinD(m) Then
                hm = hmTaper(Hd, dq, mvMinD(m), 1)  'height to merch. diam ub point
                'if there is a minimum length constraint, see if tree is OK
                If (hm - StumpHt) >= mvMinL(m) Then
                    'add merchantable volume (less stump volume)
                    vim(m) = vim(m) + vibTaper(Hd, dq, hm) - stvub
                End If
             End If
        Next m
    Next k
    'adjust for stocking per quantile (1/5 of total stocking)
    Cells(r, 11) = vob * nha / 5     'overbark volume in col. K
    Cells(r, 12) = vim(1) * nha / 5 'underbark class 1 volume in col. L
    Cells(r, 13) = vim(2) * nha / 5 'underbark class 1 volume in col. M
    '------ Worksheet columns N-R : Thinnings, rule, stems and volumes -----
    'write Stand Density Index
    Cells(r, 17) = getSDI(nha, dg)
```

```
        'if check thinning mode and threshold, if applicable
        thinr = 0   'reset from previous cycle
        Select Case thin_mode
        Case 1: 'control by basal area (column 5)
            If Cells(r, 5) >= thinTH Then thinr = thinPct
        Case 2:  'control by SDI (column 17)
            If Cells(r, 17) >= thinTH Then thinr = thinPct
        Case 3:  'custom thinning specification
            thinr = Cells(r, 18)
        Case Else
            thinr = 0
        End Select
        'do thinning if required
        If thinr > 0 Then
            Cells(r, 18) = thinr        'write out thinning ratio
            Cells(r, 19) = nha * thinr 'no of trees thinned
            doThinning r, thinr, dthin, nthin
            'calculate and output thinning volumes
            vob = 0: vim(1) = 0: vim(2) = 0
            'accumulate volume for thinned diameter class
            For k = LBound(dthin) To UBound(dthin)
                'tree height corresponding to quantile diameter
                dq = dthin(k)
                hq = treeHeight(Hd, dg, dq)
                vob = vob + vobTaper(hq, dq) * nthin(k)
                stvub = vibTaper(Hd, dq, StumpHt)
                'merchantable heights
                For m = 1 To 2
                    If hq > mvMinL(m) And dq > mvMinD(m) Then
                        'merchantable height
                        hm = hmTaper(Hd, dq, mvMinD(m), 1)
                        'check log at least minimum specified length
                        If (hm - StumpHt) >= mvMinL(m) Then
                            'add merchantable volume (less stump volume)
                            vim(m) = vim(m) + (vibTaper(Hd, dq, hm) - stvub) * nthin(k)
                        End If
                     End If
                Next m
            Next k
            'output thinned volumes
            Cells(r, 20) = vob     'overbark volume in col. P
            Cells(r, 21) = vim(1)  'underbark class 1 volume in col. Q
            Cells(r, 22) = vim(2)  'underbark class 1 volume in col. R
        End If
        '-------- Worksheet columns S-U :  Mean Annual Volume Increment ---------
        'total standing volumes + previous thinned volumes
        For k = 0 To 2
            maiv(k) = Cells(r, k + 11)
            For j = 8 To r - 1
                maiv(k) = maiv(k) + Cells(j, k + 20)
            Next j
        Next k
        'convert to MAI : divide by age and output
        For k = 0 To 2
            maiv(k) = maiv(k) / age
            Cells(r, k + 14) = maiv(k)
        Next k
        r = r + 1
    Next yr
    [A5] = ""
    Running = False
    End Sub

    Private Sub model_setup()
    'check parameter settings on the model sheet and gives warning message if wrong or missing
    'returns TRUE of all parameters seem OK, FALSE otherwise
    'also sets internal variables with parameter values
    Dim msg As String, crlf As String  'used form check messages, with newline separator
    Dim i As Integer                   'loop index
    Dim v As Double                    'a numeric value
    Dim ch As Variant                  'any character
    Dim psr As Double                  'planting survival rate
    Dim erm As String, ern As Integer   'runtime error message and number
    On Error GoTo ErrorHandler
```

```
crlf = Chr(13) + Chr(10)
'initial conditions mode
ch = Left([A3], 1)
If ch >= "1" And ch <= "3" Then
    run_mode = CInt(Left([A3], 1))
Else
    msg = msg + "Initial conditions option [A3] should be in range 1-3." + crlf
End If
'site index
si = CDbl([G3])
If si < 14 Or si > 26 Then msg = msg + "Site index [G3] should be in range 14-26." + crlf
'initial stocking
nha0 = CDbl([I3])
If nha0 < 100 Or nha0 > 3000 Then msg = msg + "Initial stocking [I3] should be in range
100-3000 stems/ha." + crlf
'survival
psr = CDbl([K3])
If psr < 0.1 Or psr > 1 Then msg = msg + "Survival after planting [K3] should be in range
10% - 100%." + crlf
'last year of simulation
yrf = CInt([K4])
'thinning calculation method
Select Case Left([U2], 1)
    Case "B": thin_mode = 1 'basal area control
    Case "S": thin_mode = 2 'stand density index
    Case "C": thin_mode = 3 'custom selection
    Case Else: thin_mode = 0 'no thinning
End Select
'minimum thinning interval, only required in thin_mode>1
If thin_mode > 0 And thin_mode < 3 Then
    thinTH = CDbl([U3])
    If thinTH <= 0 Then msg = msg + _
        "Thinning threshold [U3] must be more than zero" + crlf
    thinPct = CDbl([U4])
    If thinPct <= 0.2 And thinPct >= 0.67 Then _
        msg = msg + "Percent of trees to be thinned [U4] should be between 20-66%" + crlf
ElseIf thin_mode = 3 Then
    For i = 8 To 36
        If Cells(i, 18) < 0 Or Cells(i, 18) > 1 Then _
            msg = msg + "Thinning ratio [R" + CStr(i) + _
            "] must be between 0-100%" + crlf
    Next i
End If
'class definitions for merchantable volume
For i = 1 To 2
    mvMinD(i) = CDbl(Cells(3, 15 + i))
    mvMinL(i) = CDbl(Cells(4, 15 + i))
    If mvMinD(i) < 0 Or mvMinD(i) > 100 Then msg = msg + "Minimum top diameter for class "
+ CStr(i) + " [" + Chr(82 + i) + "3] should be in range 0-100 cm" + crlf
    If mvMinL(i) < 0 Or mvMinL(i) > 40 Then msg = msg + "Minimum log length for class " +
CStr(i) + " [" + Chr(82 + i) + "4]  should be in range 0-40 m" + crlf
Next i
'initial conditions for age, nha, hdom, diameter distribution
Select Case run_mode
Case 1  'start from age 2 - standard startup
    yr0 = 2                 'initial age
    hd0 = Hdom(si, 2#)      'initial hdom
    nha0 = nha0 * psr        'initial stocking
    For i = 1 To 5          'initial diameter quintiles
        v = 0.1 + (i - 1) * 0.2
        diam0(i) = qDiam(hd0, v, nha0)
    Next i
Case 2  'use initial age, hdom, nha supplied, generate initial diam vector
    yr0 = CInt([A8])
    hd0 = CDbl([B8])
    'estimate site index, check in reasonable range
    si = GetSI(hd0, CDbl(yr0))
    If si < 10 Or si > 30 Then msg = msg + "Please check initial height-age values [A8:B8]
are correct." + crlf
    [G3] = si
    nha0 = CDbl([C8])
    'set initial diameter quintiles
    For i = 1 To 5          'initial diameter quintiles
        v = 0.1 + (i - 1) * 0.2
```

```
        diam0(i) = qDiam(hd0, v, nha0)
    Next i
Case 3  'use initial age, hdom, nha and diameter quintiles supplied
    yr0 = CInt([A8])
    hd0 = CDbl([B8])
    'estimate site index, check in reasonable range
    si = GetSI(hd0, CDbl(yr0))
    If si < 10 Or si > 30 Then msg = msg + "Please check initial height-age values [A8:B8]
are correct." + crlf
    [G3] = si
    nha0 = CDbl([C8])
    'set read and check diameter quintiles
    For i = 1 To 5            'initial diameter quintiles
        diam0(i) = Cells(8, i + 5)
        If i > 1 Then
            If diam0(i) <= diam0(i - 1) Then msg = msg + "Please check diameter values
[F8:J8] are correct." + crlf
        End If
    Next i
End Select
'check if any messages
If msg > "" Then
    MsgBox msg, vbOK + vbCritical, vertext
    GoTo AbortRun
End If
'check user wants to overwrite the current sheet
If MsgBox("The current sheet rows 8-36 will be updated with model outputs. Proceed?",
vbOKCancel + vbQuestion, vertext) _
            = vbCancel Then GoTo AbortRun
'clear output area (thinning not cleared if set manually, mode 1)
'clear table preparatory to output
[A8:Q100].ClearContents
[S8:V100].ClearContents
If thin_mode <> 3 Then [R8:R100].ClearContents 'column R reset except for custom thinning
'set lines and background colour for table
tableStyle 8, 8 + yrf - yr0, yr0
Exit Sub
ErrorHandler:
    'handles run-time errors, most likely incompatible data types
    erm = err.Description
    ern = err.Number
    On Error GoTo 0
    If MsgBox("Error " + CStr(ern) + ": " + erm + crlf + "Do you want to retry/debug?", _
            vbYesNo + vbDefaultButton2 + vbCritical, vertext) = vbNo Then
    End If
    Resume
AbortRun:
    'exit point after error messages or selecting an abort option
    [A5] = ""
    Running = False     'flag for worksheet onchange handler
    End
End Sub

Private Sub doThinning(r As Integer, thinr As Double, tdiam As Variant, tnha As Variant)
'Does a thinning of intensity <thinr> % to be removed
'Results are calculated and written to table on row r
Dim tbias As Double         'bias effect on diameter distribution
Dim qDiam(0 To 6) As Double 'Pre-thinning quintile diameters
Dim qpre(0 To 6) As Double  'Pre-thinning quintile probabilities
Dim qpost(1 To 6) As Double 'Post-thinning quintile probabilities
Dim nha(1 To 2, 0 To 6) As Double   'stocking pre and post thinning by quintiles
Dim x(1 To 5) As Double, y(1 To 5) As Double 'used to estimate weibull parameters
Dim alpha As Double, beta As Double 'weibull parameters
Dim k As Integer
'set bias effect due to thinning (none if N/ha <100)
'Uses equation (4.4.6) from Alder, 1978, p.41
If Cells(r, 3) > 100 And thinr < 0.8 Then      'if N/ha > 100, or ratio<80%
    tbias = (1 / (1 - thinr))    'use Alder, 1978 method
Else
    tbias = 1                    'otherwise, no bias
End If
'read quintile probabilities and diameters from workbook
For k = 1 To 5
    qpre(k) = (k - 1) * 0.2 + 0.1   'probabilities 0.1, 0.3, 0.5, 0.7, 0.9
```

```
        qDiam(k) = Cells(r, k + 5)  'current diameter values
        qpost(k) = qpre(k) ^ tbias
    Next k
    'add 0 and 100% estimates for largest and smallest diams
    qpre(0) = 0: qpre(6) = 1
    qDiam(0) = qDiam(1) * 2 - qDiam(2) 'estimated smallest diam
    qDiam(6) = qDiam(5) * 2 - qDiam(4) 'estimated largest diam
    'stocking by quintiles pre- and post- thinning
    nha(1, 6) = Cells(r, 3)             'pre-thin stocking
    nha(2, 6) = nha(1, 6) * (1 - thinr) 'post-thin stocking
    'pre and post thin stocking by quintile diameter limits
    For k = 1 To 5
        nha(1, k) = nha(1, 6) * qpre(k)
        nha(2, k) = nha(2, 6) * qpost(k)
    Next k
    'get thinning frequencies and quadratic mean diams by classes
    ReDim tdiam(1 To 6) As Double
    ReDim tnha(1 To 6) As Double
    For k = 1 To 6
        tdiam(k) = Sqr((qDiam(k - 1) ^ 2 + qDiam(k) ^ 2) / 2)
        tnha(k) = (nha(1, k) - nha(1, k - 1)) - (nha(2, k) - nha(2, k - 1))
    Next k
    'post thinning residual diameter distribution
    If tbias > 1 Then
        'use Weibull function to interpolate post-thinning diameter quintiles
        For k = 1 To 5
            y(k) = Log(-Log(1 - qpost(k)))
            x(k) = Log(qDiam(k) - qDiam(0))
        Next k
        beta = WorksheetFunction.Slope(y, x)
        alpha = Exp(-WorksheetFunction.Intercept(y, x) / beta)
        'calculate post-thinning standing diameters and write to row below current one
        For k = 1 To 5
            Cells(r + 1, k + 5) = qDiam(0) + alpha * (-Log(1 - qpre(k))) ^ (1 / beta)
        Next k
    Else
        'distribution is unchanged at low stocking
        For k = 1 To 5
            Cells(r + 1, k + 5) = qDiam(k)
        Next k
    End If
    End Sub

    Private Sub tableStyle(r1 As Integer, r2 As Integer, yr0 As Integer)
    'does colour fill and lines for the main table
    Dim rng As Range
    Dim cols As Variant
    Dim c As Variant, y As Integer, r As Integer
    cols = Array(5, 10, 13, 16, 19)
    Set rng = Range(Cells(r1, 1), Cells(r1 + 100, 22))
    'clear existing borders within table space
    With rng
        .Borders(xlEdgeLeft).LineStyle = xlNone
        .Borders(xlEdgeRight).LineStyle = xlNone
        .Borders(xlEdgeBottom).LineStyle = xlNone
        .Borders(xlInsideHorizontal).LineStyle = xlNone
        .Borders(xlInsideVertical).LineStyle = xlNone
        .Interior.Color = xlNone
    End With
    'set table pale green
    Set rng = Range(Cells(r1, 1), Cells(r2, 22))
    rng.Interior.Color = RGB(226, 239, 218)
    'set vertical lines
    For Each c In cols
        Set rng = Range(Cells(r1, c), Cells(r2, c))
        With rng.Borders(xlEdgeRight)
                .LineStyle = xlContinuous
                .Weight = xlHairline
        End With
    Next c
    'set horizontal lines
    For y = yr0 To yr0 + (r2 - r1)
        If y Mod 5 = 0 Then 'lines every 5th year
            r = y - yr0 + r1 - 1
```

```
        Set rng = Range(Cells(r, 1), Cells(r, 22))
        With rng.Borders(xlEdgeBottom)
                .LineStyle = xlContinuous
                .Weight = xlHairline
        End With
    End If
Next y
'thick top and bottom borders to table
Set rng = Range(Cells(r1, 1), Cells(r1, 22))
With rng.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .Weight = xlThick
End With
Set rng = Range(Cells(r2, 1), Cells(r2, 22))
With rng.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .Weight = xlThick
End With
'create white areas
Range(Cells(r1, 1), Cells(r1, 3)).Interior.Color = xlNone
Range(Cells(r1, 6), Cells(r1, 10)).Interior.Color = xlNone
Range(Cells(r1, 18), Cells(r2, 18)).Interior.Color = xlNone
End Sub
```

Module TaperFunctions

This module contains functions for the Ata Marie (2105) taper equations. These can be used if required as worksheet functions.

```
'------- Uganda Caribbean Pine Taper functions from Ata Marie June 2015 study -------
-
'coding by Denis Alder (denis@validinternational.org) - September 2017

Function vobTaper(ht As Double, dbh As Double, Optional hm As Double = -1) As Double
    'Ata Marie Taper function - whole tree volume overbark
    'ht - Total height, dbh - Tree dbh (cm), hm - merchantable height (m)
    Dim b1 As Double, b2 As Double, g1 As Double, g2 As Double  ' beta, gamma
coefficients
    Dim tL As Double, vtot As Double 'length from tip, volume of whole tree
    If hm = -1 Then hm = ht
    tL = ht - hm
    'whole tree volume
    b2 = 6.28018
    g1 = 4.42443
    g2 = 1.52747
    b1 = (1 - (b2 / (dbh * ht) ^ 0.3) * (1 - 1.3 / ht) ^ g2) / ((1 - 1.3 / ht) ^ (g1
/ ht ^ 0.2))
    vtot = 3.14159246 * dbh ^ 2 / 40000 * ((b1 / (ht ^ (g1 / ht ^ 0.2) * (g1 / ht ^
0.2 + 1))) * (ht ^ (g1 / ht ^ 0.2 + 1)) + b2 * ht ^ (g2 + 1) / ((dbh * ht) ^ 0.3 * ht
^ g2 * (g2 + 1)))
    If tL <= 0 Then
        'volume of whole tree
        vobTaper = vtot
    Else
        b2 = 6.28018
        g1 = 4.42443
        g2 = 1.52747
        b1 = (1 - (b2 / (dbh * ht) ^ 0.3) * (1 - 1.3 / ht) ^ g2) / ((1 - 1.3 / ht) ^
(g1 / ht ^ 0.2))
        vobTaper = vtot - 3.14159246 * dbh ^ 2 / 40000 * ((b1 / (ht ^ (g1 / ht ^ 0.2)
* (g1 / ht ^ 0.2 + 1))) * (tL ^ (g1 / ht ^ 0.2 + 1)) + b2 * tL ^ (g2 + 1) / ((dbh *
ht) ^ 0.3 * ht ^ g2 * (g2 + 1)))
    End If
End Function

Function vibTaper(ht As Double, dbh As Double, Optional hm As Double = -1) As Double
    'Ata Marie Taper function  whole tree volume inside bark
    'ht - Total height, dbh - Tree dbh (cm), hm - merchantable height (m)
    Dim a0 As Double, a1 As Double, a2 As Double    ' alpha coefficients
```

```
    Dim b1 As Double, b2 As Double, g1 As Double, g2 As Double  ' beta, gamma coefficients
    Dim t1 As Double, t2 As Double  'intermediate terms repeated in main equation
    Dim tL As Double, vtot As Double 'length from tip, volume of whole tree
    If hm = -1 Then hm = ht
    tL = ht - hm
    b2 = 6.28018
    g1 = 4.42443
    g2 = 1.52747
    a0 = 0.682537
    a1 = 0.524777
    a2 = -0.487183
    t1 = g1 / ht ^ 0.2
    t2 = (dbh * ht) ^ 0.3
    b1 = (1 - b2 / t2 * (1 - 1.3 / ht) ^ g2) / ((1 - 1.3 / ht) ^ (g1 / ht ^ 0.2))
    vtot = 3.14159246 * dbh ^ 2 / 40000 * _
            (a0 * b1 / (ht ^ (t1 + 0) * (t1 + 1)) * ht ^ (t1 + 1) _
            + a1 * b1 / (ht ^ (t1 + 1) * (t1 + 2)) * ht ^ (t1 + 2) _
            + a2 * b1 / (ht ^ (t1 + 2) * (t1 + 3)) * ht ^ (t1 + 3) _
            + a0 * b2 / (t2 * ht ^ (g2 + 0) * (g2 + 1)) * ht ^ (g2 + 1) _
            + a1 * b2 / (t2 * ht ^ (g2 + 1) * (g2 + 2)) * ht ^ (g2 + 2) _
            + a2 * b2 / (t2 * ht ^ (g2 + 2) * (g2 + 3)) * ht ^ (g2 + 3))
    If tL <= 0 Then
        vibTaper = vtot
    Else
        vibTaper = vtot - 3.14159246 * dbh ^ 2 / 40000 * _
            (a0 * b1 / (ht ^ (t1 + 0) * (t1 + 1)) * tL ^ (t1 + 1) _
            + a1 * b1 / (ht ^ (t1 + 1) * (t1 + 2)) * tL ^ (t1 + 2) _
            + a2 * b1 / (ht ^ (t1 + 2) * (t1 + 3)) * tL ^ (t1 + 3) _
            + a0 * b2 / (t2 * ht ^ (g2 + 0) * (g2 + 1)) * tL ^ (g2 + 1) _
            + a1 * b2 / (t2 * ht ^ (g2 + 1) * (g2 + 2)) * tL ^ (g2 + 2) _
            + a2 * b2 / (t2 * ht ^ (g2 + 2) * (g2 + 3)) * tL ^ (g2 + 3))
    End If
End Function

Function dobTaper(ht As Double, dbh As Double, hm As Double) As Double
   ' gives Diam overbark hm metres above ground for tree of ht m height and dbh cm
   ' diameter. See page 11 (sect 3.2, eqn. 3) of Ata Marie 2015 report
   Dim ltip As Double       'length from tip to hm point
   Dim b1 As Double, b2 As Double, g1 As Double, g2 As Double 'coefficients
   If hm < 0 Or hm > ht Then dobTaper = 0: Exit Function
   ltip = ht - hm
   b2 = 6.28018
   g1 = 4.42443
   g2 = 1.52747
   b1 = (1 - (b2 / (dbh * ht) ^ 0.3) * (1 - 1.3 / ht) ^ g2) / ((1 - 1.3 / ht) ^ (g1 / ht ^ 0.2))
   dobTaper = Sqr(dbh ^ 2 * (b1 * (ltip / ht) ^ (g1 / ht ^ 0.2) + (b2 / (dbh * ht) ^ 0.3) * (ltip / ht) ^ g2))
End Function

Function dibTaper(ht As Double, dbh As Double, hm As Double) As Double
   ' gives Diam inside bark hm metres above ground for tree of ht m height
   ' and dbh cm diameter.  See p.9 of Ata Marie 2015 report.
   Dim ltip As Double       'length from tip to hm point
   Dim dob As Double        'overbark diameter at point hm on tree
   Dim lth As Double        'length (from tip) to height ratio
   If hm < 0 Or hm > ht Then dibTaper = 0: Exit Function
   ltip = ht - hm           'length from tip
   lth = ltip / ht          'ratio of length from tip to total height
   dob = dobTaper(ht, dbh, hm)  'overbark diameter
   dibTaper = Sqr(dob ^ 2 * (0.682537 + 0.524777 * lth - 0.487183 * lth ^ 2)) 'underbark diameter
End Function

Function hmTaper(ht As Double, dbh As Double, dm As Double, _
      Optional ub As Boolean = False) As Double
   'For tree of height ht m, dbh cm, solves for height of merchantable diam dm
   'if ub set TRUE, uses underbark diam, otherwise uses overbark.
   'uses bisection method to solve dobTaper or dobTaper equations.
   'converges to 0.01 m height, fails if iterations <it> exceed 100
   Dim hm As Double, h0 As Double, h1 As Double 'height median, lower and upper estimates
   Dim d0 As Double, d1 As Double     ' diameters at h0, h1 heights
```

```
    Dim d2 As Double ' median of d0 and d1
    Dim it As Integer
    'start intitally with h0 and h1 as base and tip of tree
    h0 = 0: h1 = ht: hm = (h1 - h0) / 2
    Do While it < 100 And Abs(h1 - h0) > 0.01    'termination conditions
       'diameters of end points
       If ub Then
          'inside bark diameters (ub = TRUE)
          d0 = dibTaper(ht, dbh, h0)
          d1 = dibTaper(ht, dbh, h1)
       Else
          'overbark diameters (default)
          d0 = dobTaper(ht, dbh, h0)
          d1 = dobTaper(ht, dbh, h1)
       End If
       d2 = (d0 + d1) / 2
       If d2 > dm Then
          h0 = hm
       Else
          h1 = hm
       End If
       hm = (h1 + h0) / 2
       it = it + 1
    Loop
    hmTaper = Round(hm, 2)  'result only accurate to 2 dp
 End Function
```