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A National Model of *Pinus Radiata* Growth in New Zealand

The 300 Index Growth Model

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EXECUTIVE SUMMARY

The 300 Index Growth Model, an empirical stand-level model for predicting yield in *Pinus radiata* plantations, was developed for the Plantation Management Cooperative during the early 2000's. The 300 Index Model is unique in using site productivity indices to calibrate it to sites of varying productivity. This enables the model to perform well on both fertile and impoverished sites. The model also accommodates the effects of pruning and thinning on growth.

Strictly speaking, the 300 Index Model is a model for predicting basal area growth, but it is used in conjunction with other models for predicting height growth and mortality. The complete modelling system is described in this document. All the components in this system were developed using the extensive database of permanent measurement plots available at Scion.

The model has been found to perform well on most sites throughout New Zealand. It has shown some tendency to over-predict yield projections from early measurements on coastal sand sites, and on some very dry sites, although in both cases, performance of the model is acceptable from mid-rotation age. However, these site types make up only a small proportion of the national estate. On all other sites, including fertile ex-pasture sites, and traditional forest sites, the model shows little bias at any age or stocking. It has also been shown to perform well in *Pinus radiata* sands in New South Wales.

This report briefly describes the development of the components making up the modelling system, and the data used to develop them. The performance and validation of the model is then discussed. A detailed description of the functions and processes of each component is then presented along with an explanation of the linkages between them.

INTRODUCTION

The 300 Index Growth Model [1], a model for predicting basal area (BA) growth in *Pinus radiata*, was developed in the early 2000's for the Plantation Management Cooperative. Development of a new stand-level BA growth model was timely because of the large quantity of additional data that had become available since the last major generation of stand-level models developed in the 1980's [2, 3, 4]. Most previous *Pinus radiata* growth models were intended for use within a restricted region within New Zealand. However, the 300 Index model is intended to be used throughout New Zealand.

The 300 Index model is unique in using site productivity indices to calibrate it to sites of varying productivity. Traditionally, *Site Index* (SI), a measure of height growth, was used to measure site productivity. Height has the advantage of being only weakly influenced by stocking or stem density, making it easy to predict SI from stands of different stockings. Unfortunately, height growth productivity is only weakly related to diameter growth productivity, meaning that SI is of only limited use in predicting stem volume growth. The *300 Index*, a new measure of productivity based on stem volume growth has therefore been developed [1]. Both the SI and 300 Index are used for site calibration in the 300 Index Growth Model.

Site Index is defined for *Pinus radiata* in New Zealand as mean top height (MTH) at age 20 years [5], and is measured in metres.

The definition of the 300 Index is more complex, as stem volume is influenced by stocking, thinning and pruning. The index is defined as the total standing stem volume mean annual increment (MAI) at age 30 years, excluding the volume of any mortality or thinnings, for the following reference regime:

- All crop trees pruned to six metres using pruning lifts performed in a timely fashion
- Thinned to final stocking at the completion of the final pruning lift (before about 11 m height)
- A final crop stocking of 300 stems/ha at 30 years of age

The units used to measure the 300 Index are m^3/ha/yr.

As will be demonstrated later, both SI and the 300 Index can be estimated for a stand using measurements of tree diameters and heights obtained from measurement plots.

Unlike most previous *Pinus radiata* growth models, the 300 Index Model is a silvicultural growth model which accommodates the effects of pruning and thinning on growth. Both these operations are accounted for using an age-shift technique. As will be shown in the detailed description of the model which follows, BA is modelled as a function of an adjusted age. This adjusted age equals the actual age minus pruning and thinning age lag effects. For example, during pruning, a pruning age lag calculated on the basis of crown length and pruned height is used to reduce the age increment supplied to the BA model at each growth step, causing a temporary slowing in BA growth.

This report briefly describes the development of the 300 Index model and the data used to derive it. The performance and validation of the model is then discussed. Finally, a detailed description of the model is given. Strictly speaking, the 300 Index Model is a model for predicting BA only, but it is used in conjunction with various other components including models for predicting height growth and mortality, and a volume function for estimating stem volume from MTH and BA. This report describes all these components and the linkages between them.

DEVELOPMENT OF THE 300 INDEX MODEL

All the components of the 300 Index Model were developed using historical growth measurement data stored in a database of permanent sample plots (PSPs) maintained by Scion [(6)]. Some plots were obtained from replicated research trials, while others were growth monitoring plots located throughout the plantation estate within New Zealand. All measurements were subjected to rigorous screening procedures to eliminate errors or unrepresentative data. The PSP database contains error checking functions, but further manual checking of summarised data was also applied before data were accepted for model development. Different data quality requirements were needed for each component in the system, meaning that somewhat different data sets were used for each.

The development of the BA model is described briefly [(1)]. A total of 775 growth and stocking-trial plots were used to develop the model. Site Index ranged from 12 to 40 m and averaged 28 m. An important component was data from 20 final-crop stocking trials established throughout New Zealand by the then FRI in the 1970s and 1980s [(7)]. These stocking trials mostly contain two or more replications of final stockings of 50, 100, 200, 400 and 600 stems/ha, and measurements to, or close to, age 25 years. They are situated throughout New Zealand with SI ranging from 16 m to nearly 40 m. An additional 353 growth plots were also used. Further field trials were used specifically to establish thinning and pruning effects. To ensure that the model performed best for commonly used regimes the maximum final crop stocking was restricted to 800 stems per ha. Only 11% of the plots had measurements older than 30 years and only 3% older than 35 years, and the model can therefore only be expected to perform well within these stocking and age limits.

Plots were carefully screened for data quality. The most important requirement was that all plots had complete histories of initial stocking, pruning and thinning operations. Those that showed extreme levels of mortality representing catastrophic events were also excluded.

Development of the height model was funded by the New Zealand Foundation for Research, Science and Technology. A description of the model is currently being prepared for publication [(8)]. A total of 2,900 sample plots containing 23,800 measurements, aged between 3 and 61 years old, were used to develop this model.

The mortality function was developed in conjunction with the BA model using mortality measurements from 2,300 PSPs. A number of plots that showed extreme levels of mortality representing catastrophic events were excluded. Plots were all in stands established after 1960, and plots with stockings greater than 3,000 stems/ha were excluded. Mortality was calculated for each growth increment, and only increments of at least one year were included in the analysis.

The function used to estimate volume losses due to mortality was developed from 3,400 growth PSPs. The function for predicting BA following thinning was fitted using records of 986 waste thinning events from the same data set.

To predict stem volumes, the BA and MTH models are used in conjunction with existing stand-level volume functions [(9)].

VALIDATION OF THE 300 INDEX MODEL

Using the 300 Index and Site Index to calibrate model predictions to individual sites enables the model to perform well on both fertile and impoverished sites. Examples of predictions from the model are given in Fig. 1, which shows actual and predicted BA at three stockings for a fertile ex-pasture site with a 300 Index of 32 m^3/ha/yr, and a very poor site with an index of only 12 m^3/ha/yr. For each site, the predictions were obtained using a single 300 Index estimated from the initial BA measurement for the 200 stems/ha stocking, and this single index provided good predictions across the range of stockings and ages at both sites.

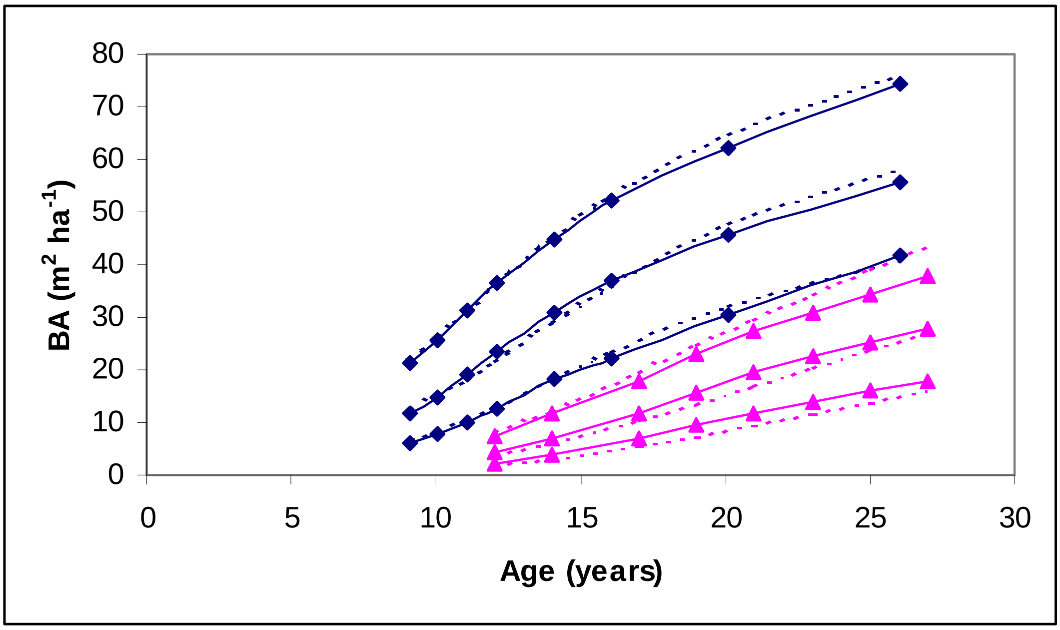

Fig. 1: Actual (solid lines) and predicted (dashed lines) BA for a high productivity ex-farm site at Tikitere (blue), and a low productivity site in Balmoral Forest (pink). At each site, stockings of 100, 200, and 400 stems/ha are given by the lower, middle and upper lines respectively.

The model has been tested on data from a wide range of sites nationally [(1)], and generally performs well. One way of testing the model is to use it to estimate the 300 Index for different sites over a range of stockings and ages. If the model is performing well, estimates of the 300 Index should remain constant over time for measurements taken from the same plot, and should not vary with stocking in plots from the same site. In Fig. 2, the 300 Index is plotted against stocking for data from stocking trials at six sites of varying productivity, and it can be seen that it remains stable across stockings. It can be concluded that the model therefore accounts well for the effect of stocking on volume. Other validations using large numbers of PSPs have also found little trend in the 300 Index with stocking.

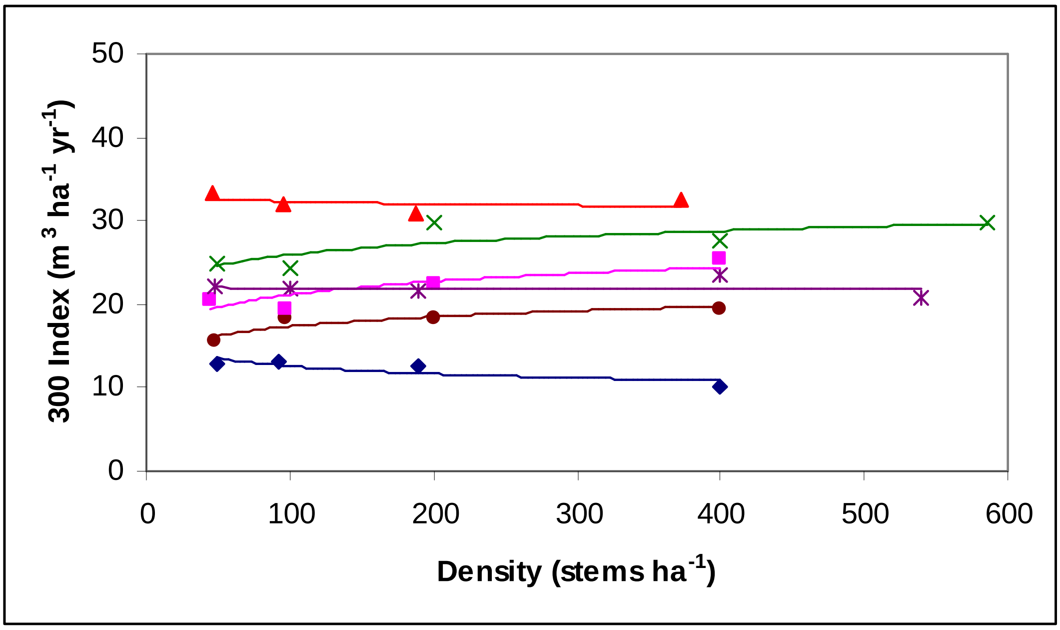

Fig. 2: The 300 Index calculated at age 25 years for a range of stockings at six sites.

To determine whether the index remains stable over time, an extensive validation was carried out using PSP data from the following four geo-climatic zones: Central North Island (CNI) forest sites; New Zealand-wide fertile ex-farm sites; dry east coast sites from both North and South Islands; and coastal sand sites from the west coast of the North Island. The results are summarised in Table 1 and Fig. 3, and show that the index remained very stable over time for the dry sites, showed a slight increasing trend for the CNI forest sites, and a slight decreasing trend for the ex-farm sites. Overall it was concluded that the model accounts adequately for the development of volume over time on these three site types.

However, there was a pronounced downward drift in the index for coastal sand forests, with the index averaging 24 m^3/ha/yr for age 5-10 year growth data, reducing to 17 m^3/ha/yr for age 25 data. The drift was particularly pronounced for coastal forests north of Auckland, and is probably caused by a deterioration in the nitrogen status of these forests following suppression of previously established nitrogen-fixing lupins by the growing pine trees. In all cases however, predicting the 300 Index from stand age 15 years or older was reliable. A similar downward drift was noticed for several of the driest sites such as Eyrewell Forest in Canterbury, although on most dry sites the index was stable. Care must be taken when using the model on sites showing a downward drift in the index, as projecting growth forward from early measurements on these sites will result in over-estimation of yield.

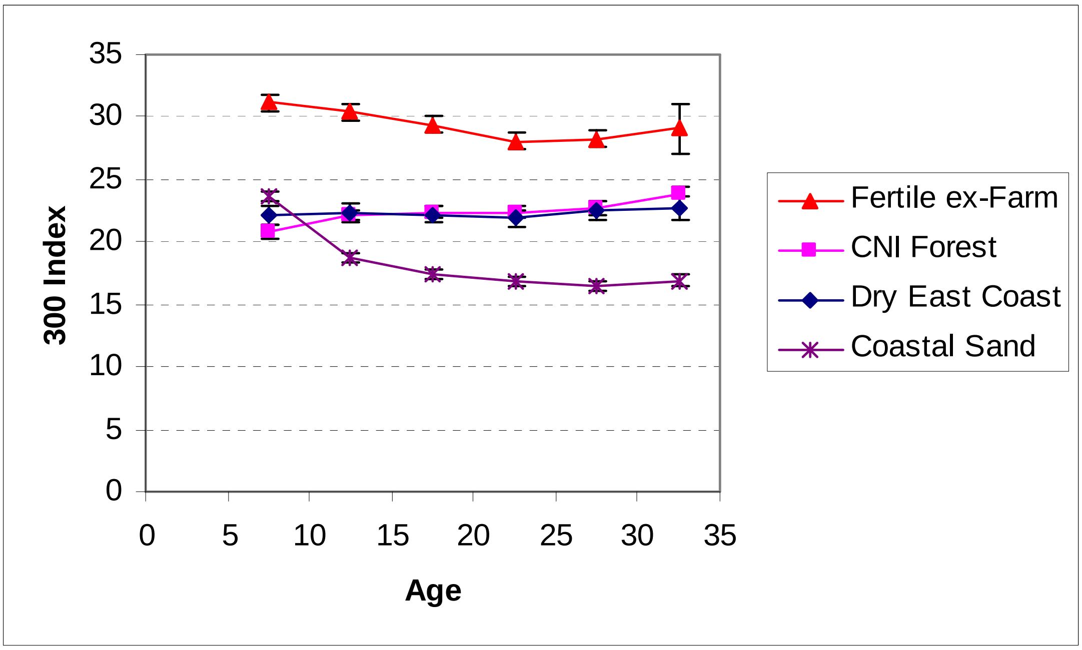

Fig. 3: Mean 300 Index calculated from PSP measurements taken over time for four contrasting site types. Error bars show 95% confidence intervals.

Table 1. Mean 300 Index and mean drift in the index over time in four site types.

Site type	Number of plots	Number of measurements	Mean 300 Index	Mean Drift (%/yr)
East Coast Dry	439	4005	22.8	0.04
Fertile ex-Farm	337	4712	31.7	-0.60
Coastal Sand	733	6543	18.6	-1.59
C. N. I. Forest	756	8155	22.4	0.29

Finally, the 300 Index Model has been validated against 12 thinning trials containing 31 PSPs in radiata pine plantations in New South Wales, Australia. The average measurement span in these trials was 10 years. Each trial contained several treatments involving various timings of thinning, and often included an unthinned control treatment. For each plot, SI and 300 Index were predicted from the initial measurement, and using these indices, the model was used to predict BA at the final measurement. The model showed very little error, performing well across all stockings and thinning treatments. The mean prediction error (actual – predicted BA) for the final measurement was less than 0.4 m^2/ha for the thinned plots. The model also performed well in the unthinned plots having an average prediction error of only -2 m^2/ha, even though these plots were considered to lie outside the normal range of the model, having an average stocking of over 1000 stems/ha.

DESCRIPTION OF THE 300 INDEX MODEL

Programme Structure

A version of the 300 Index model is currently implemented in Microsoft Excel VBA (Excel 2002). It consists of a small controlling subroutine which reads the input variables, calls the subroutine GROWTH which contains the growth model, and then outputs the results in the required format for use by C-Change. The subroutine GROWTH models the development of a stand from establishment at age zero to felling age. It calls numerous other subroutines and functions which are all described in the following sections.

Generally when a stand is pruned, there will be several levels of pruning intensity or pruned 'elements'. For example, some trees may be left unpruned, while others may receive only one pruning lift. Typically the final crop element in a pruned stand receives two or three pruning lifts. Lesser pruned elements may be thinned out at some point or may be left as 'followers' until clearfelling. In the Excel version of the 300 Index Model, these differently pruned elements are modelled separately. However, the version described in this document assumes that all trees in the stand are pruned to the same intensity. In its current form, C_Change cannot accommodate more than one pruned element, and it is therefore unnecessary for the 300 Index Model to have this facility. In this implementation, when a stand has more than one pruned element, growth is assumed to be identical to a single element stand having the same average pruned height.

Standard Functions

A number of standard functions are used in the following sections:

- Ln(x) - the natural log function
- Exp(x) – the exponential function
- Sgn(x) – the sign function (equals 1 if x is positive, -1 if x is negative)
- Abs(x) – the absolute value of x
- Min(x1,x2) – smallest of x1 and x2
- Max(x1,x2) – largest of x1 and x2
- Sqrt(x) – the square root of x

Input Variables

The following input variables are required to run the subroutine GROWTH:

Stocking History

The initial stocking at age zero must be specified. At each thinning, the age and the stocking following the thinning must be specified. There can also be one or more intervening age/stocking pairs. The stocking history is stored in a 2-dimensional array SHIST. The first column of SHIST contains the age, the second column contains stockings other than those connected with a thinning, and the third column contains stocking after thinning. The number of stocking entries is recorded in the variable NSHIST and could be as low as 1 or as high as 20. SHIST should be declared with 3 columns and NSHIST rows.

Table 2 gives an example of a typical stocking history. In this example the stand was planted at 850 stem/ha, and thinned at age 7 to 550 stems/ha, and again at age 12 years to 250 stems/ha. There were two intervening assessments of stocking at ages 8 and 12.5 years.

Table 2. Example of the stocking history array SHIST.

Age	N1	N2
0	850	
7		550
8	530	
12		250
12.5	250	

A number of data checking procedures should be applied to this array. The first column must always have a value, and there must be one entry in either column 2 or 3. The ages in the first column must always increase down the column. The 1st row must contain zero in the 1st column and the stocking at planting in the 2nd column. Due to the requirements of C-Change, all thinnings (when there is a value in the 3rd column) must occur at whole-number ages. Other stocking assessments (when there is a value in the 2nd column) can occur at fractional ages. Working from left to right and downwards through columns 2 and 3, values in the 2nd column must be equal to or less than the preceding value, while values in the 3rd column must be less than the preceding value. Stockings could generally range between 1 and 10,000 stems/ha.

Pruning History

At each pruning lift, the age and mean pruned height must be specified. This information is stored in the 2-dimensional array LIFT which contains the age of the lift in the 1st column, and the pruned height in the 2nd column. The mean pruned height must be based on all trees including any unpruned stems (for which the pruned height equals zero). A new lift should be recorded whenever any trees in the plot are pruned. A new 'lift' can also occur during a thinning operation when the mean pruned height can increase even though there has been no physical pruning (e.g. if unpruned trees are thinned out). In both cases, a new row of values should be entered in the array LIFT. The number of rows in LIFT is recorded in the variable NLIFTS, and could be as low as 0 or as high as 20. LIFT should be declared with 2 columns and NLIFT rows. A typical example of LIFT is shown in Table 3.

Table 3. Example of the pruning history array LIFT.

Age	Prune Height
5	1.8
6	3.8
7	3.9
8	5.7

The following error checking procedures should be applied to LIFT. There must be an entry in both columns of each row. The ages in column 1 must increase down the array and must be whole numbers. The pruned heights in column 2 must also increase down the array. Pruned heights will generally range between 0.1 m and 12 m.

Clearfell Age

The age of clear-felling in years is recorded in the variable FELLAGE.

Site Index and 300 Index

The subroutine GROWTH requires the productivity indices Site Index (SI) and 300 Index (I300). As shown later, these are generally derived using an iterative procedure from a plot measurement of stocking, DBH and MTH. In some cases, for example when a plot is too young to provide useful data, or for some other reason plot data cannot be obtained, SI and I300 will have to be specified directly by the user. The controlling subroutine can cater for both these situations. The typical range for SI is between 5 and 41 while for I300, the range is from 1 to 45.

GROWTH Subroutine

The subroutine GROWTH predicts the status of the stand through time from establishment to clearfelling. The stand is grown in steps of STEPLENGTH = 0.01 years. C-Change requires annual predictions at integer ages and the VBA version of the programme outputs stand parameters to a worksheet when the age is a whole number. Equivalently, these values could be stored in arrays ready for passing to C-Change. C-Change also requires that the status of the stand is stored before and after a pruning or thinning operation, meaning that there should be two lines of data stored in the arrays at each pruning and/or thinning age. An outline flowchart of the subroutine is shown in Fig. 4.

The following stand parameters are predicted at each growth step. These are declared as global variables as they are accessed by several subroutines and functions.

- Age in years (AGE)
- The adjusted age in years (ADJAGE)
- Stocking in stems/ha (N)
- Mean top height in metres (MTH)
- Mean height in metres (MEANHT)
- Pruned height in metres (PRUNEHT)
- Crown length in metres (CRLENGTH)
- Diameter at breast height (DBH) - this is calculated as a quadratic mean (the square root of the mean of DBH^2)
- Basal area in m^2/ha (BA)
- Stem volume in m^3/ha (VOL)
- Stem volume lost to mortality within a growth year in m^3/ha/yr (MORTVOL)
- Thinning age lag in years (TOTALTHINLAG)
- The total prune age lag in years (TOTALPRLAG)
- The current prune age lag in years (PRUNELAG)
- The thinning selection age lag in years (SELECTIONLAG)

Bisection Method Function

The bisection method is a simple means of finding when a function equals zero [10]. It is used by several modules within the 300 Index Model. In the following code, func is the function, xlower and xupper are the upper and lower bracketing values between which the root is known to occur, and n is the number of bisections that will be applied.

```
Function Bisection(func, x1, x2, n)
    xA = xlower
    FA = func(xA)
    xB = xupper
    FB = func(xB)
    For j = 1 To n
        xC = (xA + xB) / 2
        FC = func(xC)
        If FA * FC < 0 Then
            xB = xC
            FB = FC
        Else
            xA = xC
            FA = FC
        End If
    Next j
    Bisection = xC
End Function
```

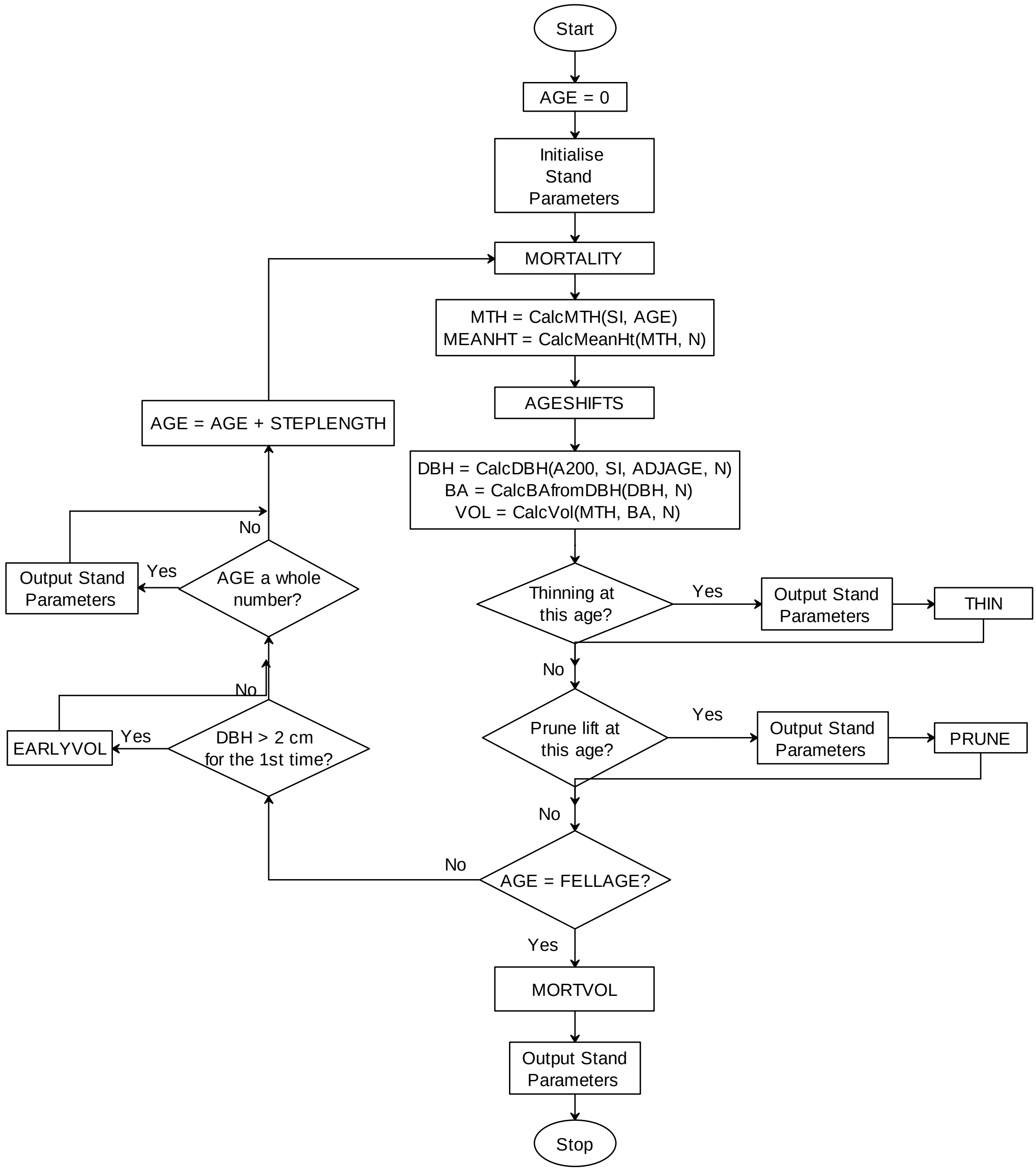

Fig. 4. Outline flowchart of the subroutine GROWTH.

Stand Parameter Initialisation

At the beginning of each run, the stand parameters are initialised as follows:

```
N = Initial Stocking
AGE = 0
DBH = 0
VOL = 0
BA = 0
MTH = 0.25
MEANHT = 0.25
PRUNEHT = 0
PRUNELAG = 0
TOTALPRLAG = 0
TOTALTHINLAG = 0
SELECTIONLAG = 0
```

The following three procedures are also carried out at the start of the run.

1. The height model coefficients, ha and hb, are calculated from SI and, if available, latitude and altitude:

```
If latitude and altitude are both specified then
    ha = Exp(h5 + h6 * latitude + h7 * altitude)
    hb = 1 / (h8 + h9 * SI)
Else
    ha = Exp(h1 + h2 * SI)
    hb = 1 / (h3 + h4 * SI)
End If
```

   The height model coefficients are:
   h1 = -2.475, h2 = -0.01406, h3 = 0.33417, h4 = 0.0104,
   h5 = -1.335, h6 = -0.03581, h7 = -0.0006306,
   h8 = 0.499, h9 = 0.005059

2. The age when height reaches 1.4 m (defined as breast height) is calculated:

```
AGEZERO = -Ln(-(1-Exp(-ha*20))*((1.4-0.25)/(SI-0.25))^(1/hb)+1)/ha
```

3. A200 is the predicted DBH at 200 stems/ha and age 30 for the specified SI and I300 assuming no pruning or thinning. It is calculated from SI and I300 as follows:

```
BA300_30 = CalcBAfromVol(CalcMTH(SI, 30), I300 * 30, 300)
DBH300_30 = CalcDBHfromBA(BA300_30, 300)

Function A200Func(x)
    A200Func(x) = DBH300_30 - calcDBH (x, SI, 28.7, 300)
End Function

A200 = Bisection(A200Func, 10, 150, 15)
```

Mortality Subroutine

This predicts the stocking N at each growth step.

Firstly, the percentage mortality M is calculated as follows.

If the growth step falls between ages T1 and T2 with known stockings N1 and N2 respectively, and with no intervening thinning operations, then:

```
M = 100*Ln(N1/N2)/(T2-T1)
```

Otherwise:

```
If DBH = 0 Then
    M = 0
Else
    x = Exp(m1+m2*I300/SI+m3*(ln(N)+m4*Ln(DBH)))
    M = (m5+(1-m5)*x/(1+x))*100
End If
```

Stocking N is then calculated from stocking at the previous step prevN using:

```
prevN = N
N = prevN / Exp(M * StepLength / 100)
```

The parameter m5 represents attritional mortality in a low-stocked stand, expressed as an annual proportion (the default value is 0.00246 equivalent to annual mortality of 0.246%). In some versions of the 300 Index, this parameter can be altered by the user but in the MFE implementation the default value should be used. The remaining parameters in the mortality function control the greater mortality that occurs in highly-stocked stands in response to competition.

The mortality model coefficients are:
m1 = -44.691, m2 = -4.611, m3 = 3.901, m4 = 1.3533,
m5 = 0.00246

Height Functions

These functions are used to predict MTH and mean height in a stand of known Site Index SI, age, and stocking N:

```
Function CalcMTH(SI, AGE)
    CalcMTH = 0.25 + (SI - 0.25) * ((1 - Exp(-ha * AGE)) /
        (1 - Exp(-ha * 20))) ^ hb
End Function

Function CalcMeanHt(MTH, N)
    CalcMeanht = MTH * (1 – mh1 * (1 - Exp(mh2 * (N - 100))))
End Function
```

The mean height function coefficients are: mh1 = 0.07, mh2 = -0.00399

AgeShifts Subroutine

At each growth step, the adjusted age is calculated. The adjustments to age take account of pruning, thinning and selection effects. Prior to any thinning or pruning operations, the adjusted age equals the actual age. The following steps are carried out in this subroutine:

Pruning age lag:

```
If PRUNEHT > 0 Then PRUNELAG = min(TOTALPRLAG,
        PRUNELAG+0.3*STEPLENGTH)
```

For each previous thinning, the following steps are performed to calculate the thinning age lag attributable to the thinning:

```
TimeSinceThin = AGE - ageThin
ThinLag = InitialLag + Min(InitialLag, th1) * th2 *
        (1 - Exp(th3 * TimeSinceThin))

TOTALTHINLAG = sum of ThinLag over all thinnings
```

The coefficients used in this function are:
Th1 = 0.5, th2 = 0.5, th3 = -0.47

The new adjusted age is then calculated by subtracting the pruning, thinning and selection age lags from the current age:

```
ADJAGE = AGE – PRUNELAG – TOTALTHINLAG – SELECTIONLAG
```

DBH Function

This function predicts DBH at each step from A200, SI, ADJAGE and stocking N:

```
Function CalcDBH(A200, SI, ADJAGE, N)
        site_effect = A200 / d1 - 1
        stk = min(N, 2000)
        a = d1 * (1 + site_effect)
        b = min(-0.05, (d2 + d6 * (SI - 28) + d9 * site_effect
                + d11 * (SI - 28) * site_effect))
        If ADJAGE < AGEZERO Then
                CalcDBH = 0
        Else
                D200 = a * ((1 - Exp(b * (ADJAGE - AGEZERO))) /
                        (1 - Exp(b * (30 – agezero)))) ^ d5
                q = d3 * (1 + d12 * (SI - 28)) * Sgn(stk - 200) *
        (Abs(Ln(stk) – Ln(200))) ^ d13
                p = d4 + d8 * stk + d7 * site_effect
                CalcDBH = D200 - q * Log(1 + Exp(d10 * (D200 - p)))
        End If
        If CalcDBH < 0 Then CalcDBH = 0
End Function
```

The coefficients used in this function are:
d1 = 56.523, d2 = -0.09045, d3 = 2.6416, d4 = 28.1224,
d5 = 1.4821, d6 = -0.00212, d7 = 15.7581, d8 = -0.00455,
d9 = -0.1325, d10 = 0.1702, d11 = -0.0084, d12 = 0.0209,
d13 = 0.8234

Functions for Converting Between Stand Parameters

CalcVol Function

The volume function predicts total stem volume of the stand, VOL, from basal area BA and mean top height MTH. The function given below is an interim version of a new stand-level volume function being developed for MfE. The final version will be described in a forthcoming report.

```
Function CalcVol(MTH, BA)
    If MTH <= 1.6 Then
        CalcVol = 0
    Else
        CalcVol = MTH * BA * (v1 * (MTH - 1.4) ^ v2 + v3)
    End If
End Function
```

The coefficients used in this and the following functions are:
v1 = 0.989, v2 = -1.2752, v3 = 0.3191

CalcBAfromVol Function

It is sometimes necessary to predict BA from Volume and MTH, and an inverse form of the volume function will do this:

```
Function CalcBAfromVol(VOL, MTH)
    If VOL <= 0 Or MTH <= 1.6 Then
        calcBAfromVol = 0
    Else
        calcBAfromVol = VOL / (MTH * (v1 * (MTH - 1.4)^v2 + v3
    End If
End Function
```

CalcDBHfromBA Function

This function calculates DBH from BA and stocking:

```
Function CalcDBHfromBA(BA, N)
    CalcDBHfromBA = Sqrt(1.273 * BA / N) * 100
End Function
```

CalcBAfromDBH Function

This function calculates BA from DBH and stocking:

```
Function CalcBAfromDBH(DBH, N)
    CalcBAfromDBH = N / 1.273 * (DBH / 100) ^ 2
End Function
```

Thin Subroutine

At each thinning, the model firstly predicts the basal area, BA, immediately following thinning from basal area before thinning, prevBA, stocking before thinning, prevN, and stocking after thinning, N, using:

```
prevBA = BA
prevDBH = DBH
prevN = N
N = stocking after thinning
BA = prevBA * (N / prevN) ^ tr
```

The coefficient used in this function is: tr = 0.784

The initial increase in age lag that occurs because of competition due to the higher stocking prior to the thinning initialLag, and the reduction in age lag due to the selection of larger trees at thinning selectionLag, are then calculated:

```
INITIALLAG = ADJAGE – CalcAge(PrevDBH, A200, N, SI)
TOTALTHINLAG = TOTALTHINLAG + INITIALLAG
SELECTIONLAG = AGE – PRUNELAG – TOTALTHINLAG –
        CalcAge(DBH, A200, N, SI)
```

The new adjusted age is then calculated by subtracting the pruning, thinning and selection age lags from the current age:

```
ADJAGE = AGE – PRUNELAG – TOTALTHINLAG – SELECTIONLAG
```

CalcAge Function

This function calculates age from DBH, A200, Stocking & SI using the Bisection Method:

```
Function AgeFunc(x)
        AgeFunc(x) = DBH - calcDBH(A200, SI, x, N)
End Function

Function CalcAge(DBH, A200, N, SI)
        CalcAge = Bisection(AgeFunc, 0.001, 150, 15)
End Function
```

Prune Subroutine

The total age lag due to pruning TOTALPRUNELAG is updated when there is a new pruning lift to height PRUNEHT and the previous pruned height is prevPRUNEHT.

```
prevPRUNEHT = PRUNEHT
PRUNEHT = new pruned height
CRLENGTH = MEANHT - PRUNEHT
TOTALPRLAG = TOTALPRLAG + pr1 * (prevPRUNEHT ^ pr2 –
        PRUNEHT ^ pr2) * Exp(-pr3 * CRLENGTH)
```

The coefficients used in this function are:
pr1 = 0.0934, pr2 = 1.98, pr3 = 0.2119.

EarlyVol Subroutine

When tree height is less than breast height (1.4 m), DBH and BA are undefined and the growth model sets them to zero. When this occurs, the volume function incorrectly calculates the stem volume to be zero. This usually only occurs during the first 2 or 3 years growth in a stand but for C-Change to operate smoothly, realistic volumes are required for these years.

The following subroutine accomplishes this. It is called when the predicted DBH first exceeds 2 cm, and recalculates volumes for the previous annual growth steps. This subroutine operates by assuming that early volumes of individual trees increase at a rate proportional to age to the power of 2.7, an assumption that is borne out by early growth data. The subroutine requires annual predicted values of Age, Volume, DBH, and Stocking to be stored in the arrays AGEArray, VOLArray, DBHArray, and NArray, with array indices for the current year being J.

```
Subroutine EarlyVol()
    InitialTreeVol = 0.0000064
    K = (VOLArray(J)/NArray(J)-InitialTreeVol)/(AGEArray(J)^2.7)
    For I = J - 1 To 1 Step -1
        VOLArray(I) =
            (InitialTreeVol+K*AGEArray(I)^2.7)*NArray(I)
    Next I
End Sub
```

Stem Volume Mortality Model

For each year of annual growth period, the stem volume lost to mortality is predicted from stem volume at the beginning V1 and end V2 of the year, and stocking at the beginning N1 and end N2 of the year using:

MORTVOL = (V1 + V2) × ((N1/N2)^vm – 1)

The coefficient used in this function is: vm = 0.541

Note that when there is a thinning at the end of the period, N2 and V2 are taken prior to thinning. When there is a thinning at the start of the period, V1 and N1 are taken after the thinning.

Unlike other stand parameters which are modelled in 0.01 year growth steps, this parameter is calculated annually. It is therefore derived from the stand parameter arrays as the final step in the GROWTH subroutine.

Predicting SI from a Plot Measurement

The following statements predict Site Index, defined as MTH at age 20 years, from a plot measurement of MTH, H, at age T years, using the bisection method:

```
Function SIFunc (SI)
        SIFunc(SI) = H – calcMTH(SI, T)
End Function

If T = 20 Then
        SI = H
Else
        SI = Bisection(SIFunc, 5, 60, 15)
End If
```

Predicting the 300 Index from a Plot Measurement

The following statements predict the 300 Index, I300, from a plot measurement of quadratic mean DBH, D, and stocking at age T years, along with stocking and pruning history which must be stored in the arrays SHIST and LIFT as described above. The plot stocking measurement must also be stored in the array SHIST. The procedure calls the subroutine GROWTH repeatedly and compares the predicted DBH at age T with the measured value, using the bisection method to find the value of I300 which results in a predicted DBH equal to D. Prior to running this routine, the SI must be predicted as explained in the previous section.

```
Function I300Func(I300)
        FELLAGE = T
        Call GROWTH
        I300Func = D – DBH
End Function

I300 = bisection(I300Func, 2, 60, 14)
```

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