FUNCTIONALITY CONTAINED IN THE NEW ZEALAND FARM FORESTRY ASSOCIATION RADIATA PINE CALCULATOR VERSION 2

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FOREST AND FARM PLANTATION MANAGEMENT COOPERATIVE

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EXECUTIVE SUMMARY

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Version 2 of the radiata pine calculator, which has been jointly developed with the New Zealand Farm Forestry Association, and released for testing in July 2004, utilises some 71 algebraic functions or groups of functions that are embedded directly in it. This report describes the functions used, their sources, and provides ancillary background, including Visual Basic for Applications (VBA) code, permitting their implementation within the calculator. The functions described are as incorporated in the calculator as at July 2004. In all cases NZ-wide functions have been incorporated, with one exception. The Central North Island Pumice Plateau Weibull (diameter distribution) function no 19 has been incorporated as an interim measure.

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INTRODUCTION

In version 1 of the NZ Farm Forestry Association calculator, some functionality was embedded in the calculator, however most of the calculations were estimated from regressions fitted to a database of STANDPAK output. In version 2, all functionality is embedded directly in the calculator.

Most of the 71 functions or groups of functions the calculator utilises are generally available to Cooperative members and researchers though the published literature or Cooperative reports, although some reside in rather obscure places, and collating them together can be time consuming. This report is designed to provide ready access to the functions to facilitate future maintenance of the radiata pine calculator version 2. It is also expected access to the functions in a single report may provide obvious benefits to Cooperative members for application in their day-to-day work.

Table 1. Summary of functions used in the Farm Forestry Calculator Version 2

Topic	Function Numbers	When developed	Developed by	Reference
Stand Growth	1-8	2004	Forest Research/FFPM	Kimberley (pending)
Tree-level volume/taper	9-20	1999	Forest Research/FFPM	FFPM Coop report no 66
Stand level volume	21	2004	Forest Research/SFF/ NZ FFA	Hansen et al. NZ J For Science (submitted).
Height/age	22-24	2004	Forest Research/FFPM	Budianto (pending)
Diameter distribution	25-31	1990	Forest Research/SGMC	Lawrence, 1990
Diameter over stubs	32-34	1986	Forest Research/FFPM	FRI Bulletin 12
Pruned Log Index	35-38	1989	Jim Park, Interface Forest & Mill Ltd	Park, 1989. NZ J For Science 19(1) 41-53
Branches	39-42	1990	Forest Research/FFPM	FFPM Coop report 1
Wood density	43	1997	Forest Research	Kimberley and McConchie (1997)
Canopy closure	44	2000	Forest Research/FFPM	McElwee and Knowles, NZ J For Science 30(3) 422-435, FFPM Coop report 62, FFPM Coop Proceedings, May 2000
Crown height, crown length	45-46	1998	Forest Research/FFPM	FFPM Coop proceedings, May 1998 pp9-24
Understorey grazing	47-53	1986	Forest Research/AgResearch	FRI Bulletin 139
Livestock performance	54	1986	AgResearch	FRI Bulletin 139
Root biomass	55	1990	Landcare Research	Watson and O'Loughlin N.Z. Journal of Forestry Science 20(1): 97-110.
Root biomass decay	56-57	1979	Landcare Research	O'Loughlin and Watson NZ J For Science 9: 284-293.
Labour content of silvicultural operations	58-71	1975	NZ Forest Service, Kaingaroa Forest, Work Study Section.	Unpublished

Stand Growth - The 300-Index Growth Model

The 300-index model was initially developed as an index for comparing site productivity using extensive growth and field trial data for radiata pine available in New Zealand. The 300 Index is a volume productivity index, and is defined as the mean annual volume increment, in m^3/ha/yr, at an age of 30 years, assuming a final stocking of 300 stems/ha, timely pruning to 6m, and thinning to final crop at completion of pruning.

By placing the 300 Index and stand age together with an estimate of height (derived from site index and a ht/age curve), and basal area, (derived from the 300 index and a stand-level volume function) the 300 Index can be turned into a simple growth model. The growth model can be calibrated for any given site using the two site productivity indices of *SI* (mean top height at age 20 years) and the 300-index.

The initial form of the 300 Index as a growth model was installed in the Calculator version 1, however its role was to calibrate the stand, and it was not included directly in the yield calculations. In the calculator version 2, the 300 Index as a growth model is fully embedded, and is used to grow the stands directly.

The equations for this model are, in brief, as follows. To predict *DBH* at a given age *T* and stocking *N* in an unthinned and unpruned stand, the following equations are used:

$$T_z = r_1 \exp(r_2 SI) \tag{1}$$

$$a = a_1(1 + DI) \tag{2}$$

$$b = b_1 + b_2(SI - 28) + b_3 DI + b_4(SI - 28)DI \tag{3}$$

$$D_{200} = a\left(\frac{1 - \exp(b(T - T_z))}{1 - \exp(b(30 - T_z))}\right)^c \tag{4}$$

$$q = q_1\left(1 + q_2(SI - 28)\right)Sign(N - 200)\left(\left|\log(N) - \log(200)\right|\right)^{q_3} \tag{5}$$

$$p = p_1 + p_2 N + p_3 DI \tag{6}$$

$$DBH = D_{200} - q\log\left(1 + \exp(s(D_{200} - p))\right) \tag{7}$$

The coefficients as estimated are: r_1 = 8.6877, r_2 = -0.0539, a_1 = 56.523, b_1 = -0.09045, q_1 = 2.6416, p_1 = 28.1224, c = 1.4821, b_2 = -0.00212, p_3 = 15.7581, p_2 = -0.00455, b_3 = -0.1325, s = 0.1702, b_4 = -0.0084, q_2 = 0.0209, q_3 = 0.8234. And '| |' denotes absolute value and *Sign* is the signum function, i.e.

$$y(x) = \begin{cases} -1, & x < 0 \\ 0, & x = 0 \\ 1, & x > 0 \end{cases} \tag{8}$$

These equations use *SI*, and *DI* to calibrate the model to a particular site. *DI* is a diameter index, which is derived from the *SI* and 300-index. This is accomplished by an iterative procedure in which the above equations are used to estimate volume at age 30 for a '300-index' stand, i.e. a final stocking of 300 stems/ha, timely pruning to 6m, and thinning to final crop at completion of pruning. The procedure finds the value of *DI*, which achieves a volume MAI equal to the 300-index.

The method of modelling thinning is based on a time-shift approach. Firstly, the *DBH* after thinning is predicted from *DBH* before thinning using the thinning function. An iterative procedure is then used to predict age corresponding to the *DBH* and stocking after thinning for an unthinned stand. The thinning age shift T_s, defined as the difference between this predicted age and the actual age, is then calculated. The model gradually increases T_s by a maximum of 0.5 years in the period following thinning, and it then remains constant until the end of the rotation or the next thinning. Predictions of *DBH* are obtained using the above unthinned model equations, but using T-T_s in place of T. Any subsequent thinning is treated in the same way with each thinning increasing the age shift, T_s.

Pruning effects are also modelled using a time-shift approach in which 'effective' age is gradually adjusted downwards from the 'actual' age by a pruning age-shift term T_p which is a function (not described in detail here) of pruned height, crown length and stocking. T_p continues to increase until several years after the final pruning, beyond which it remains constant until the end of the rotation.

To estimate the 300-index from a stand measurement, an iterative procedure is used, which finds the 300-index that achieves the measured BA (or DBH or Volume) at the given age for the specified stocking and pruning history.

Tree-level Taper and Volume Function

The tree-level taper function works off the equations in Gordon and Budianto (1999), which uses a 3-point taper function form, which utilises DBH, ht, and an estimate of the diameter under bark at 6 m (D_6). The D_6 is predicted from tree DBH and form quotient ($D_6 = DBH \cdot FQ$), the latter is predicted from stand parameters using the following regression

$$FQ = \beta_0 + \beta_1 e^{-\beta_2 sd} + \beta_3 e^{-\left(\frac{H}{mth}\right)^2} + \beta_4 H_p \qquad (9)$$

Where H is tree height (m), H_p is pruned height (m), *mth* is stand mean top height (m), and *sd* is stand density, which is calculated as

$$sd = \frac{mdbh^2}{\sqrt{\frac{100}{mth\sqrt{n}}}} \qquad (10)$$

Where *mdbh* is stand quadratic mean diameter at breast height (cm), n is stocking (stems per hectare), and *mth* is stand mean top height (m). The coefficients of equation (9) are β_0 = 0.945, β_1 = -0.387, β_2 = 0.000686, β_3 = -0.267, and β_4 = 0.00357.

Once D_6 is estimated, the diameter over bark (dob) at height L is calculated using the following equation

$$dob = \sqrt{DBH^2\left(\beta_1 z^{\gamma_1} + \beta_2 z^{\gamma_2} + \beta_3 z^{\gamma_3}\right)} \qquad (11)$$

Where

$$z = \frac{L}{H} \qquad (12)$$

$$z_b = 1 - \frac{1.4}{H} \qquad (13)$$

$$z_u = 1 - \frac{6}{H} \qquad (14)$$

$$\beta_1 = \frac{1 - \left(\frac{z_b^{\gamma_2}}{z_u^{\gamma_2}}\right)\left(\frac{D_6^2}{DBH^2} - \beta_3 z_u^{\gamma_3}\right) - \beta_3 z_b^{\gamma_3}}{z_b^{\gamma_1} - \frac{z_b^{\gamma_2} z_u^{\gamma_1}}{z_u^{\gamma_2}}} \quad (15)$$

$$\beta_2 = \frac{\frac{D_6^2}{DBH^2} - \beta_1 z_u^{\gamma_1} - \beta_3 z_u^{\gamma_3}}{z_u^{\gamma_2}} \quad (16)$$

$$\beta_3 = \beta_{30} + \beta_{31} \frac{DBH - D_6}{6 - 1.4} \quad (17)$$

$$\gamma_1 = \gamma_{10} + \gamma_{11} \frac{D_6}{H - 6} \quad (18)$$

$$\gamma_3 = \gamma_{31} H \frac{D_6}{DBH} \quad (19)$$

Where the coefficients are: β_{30} = 0.7768, β_{31} = -0.1347, γ_{10} = 1.018, γ_{11} = 0.2967, γ_2 = 12.68, γ_{31} = 1.047. The diameter under bark is then estimated using the following relationship:

$$dub = \sqrt{dob\left(\alpha_0 + \alpha_{01} H + \alpha_{10} z \exp\left(\frac{-\alpha_{12} H}{2}\right) + \alpha_2 z \exp(\alpha_{31} H)\right)} \quad (20)$$

Where the coefficients are: $\alpha 0$ = 0.4242, α_{01} = -0.002822, α_{10} = 0.6067, α_{12} = 0.06129, α_2 = -0.207, and α_{31} = 0.3208.

The volume function essentially integrates the above equation, and works with the algorithm given in Appendix D in Gordon and Budianto (1999), which is not repeated here.

Stand-level Volume Function

A New-Zealand-wide dataset available to Forest Research was collated (Carolyn Andersen pers.comm.) and the individual tree volumes were estimated for a range of stands using the above three-point single-tree taper/volume function. Using time-specific and plot-specific dbh/height regressions the height was estimated for all trees in the plots, including those measured for height. Based on the measured DBH and the estimated heights the individual tree volumes were estimated for all trees in the plots using the single-tree taper/volume function of Gordon and Budianto (1999). The stem diameter at 6 m for individual trees, which is a requirement of the individual tree volume function, was all estimated from diameter at breast height and the plot-level parameters following the approach outlined in Gordon and Budianto (1999), I.e. An actual diameter at 6m was not used. Finally, total plot volume was calculated as the sum of the individual tree volumes. The estimated stand-level volume was then regressed against stand mean parameters using:

V = exp((log(*BA*) - *a* - *b* log(*MTH*) - *d* log(*N*) -*e* log(*N*)^2 - *f* log(*MTH*)^2 - *g* log(*MTH*) log(*N*)) / (*h* log(*N*) + *c*)) (21)

Where *V* is stand volume (m^3/ha), *BA* is basal area (m^2/ha), *MTH* is mean top height (m), and *N* is stocking (stems/ha). The coefficients were estimated as *a* = 2.5880, *b* = -2.1434, *c* = 1.3972, *d* = -0.4376, *e* = 0.0509, *f* = 0.1070, *g* = 0.1238, and *h* = -0.0814.

A paper describing this work has been submitted to the NZ Journal of Forestry Science for publication (Hansen *et al.* 2004).

Height/Age Function

The height/age function is based on a model made by Budianto (Cooperative report and paper in prep). The model is of the form:

$$MTH = 0.25 + \left(MTH_{20} - 0.25\right)\left(\frac{1-\exp\left(-T\exp(a)\right)}{1-\exp\left(-20\exp(a)\right)}\right)^{b} \quad (22)$$

Where *MTH* is mean top height, MTH_{40}, and the coefficients *a* and *b* are given as

$$a = \exp\left(e_0 + e_1 L + e_2 A\right) \quad (23)$$

and

$$b = \frac{1}{e_3 + e_4 SI} \quad (24)$$

Where *L* is latitude (degrees south), *A* is altitude (m), and *SI* is site index (MTH at age 20), and the coefficients are e_0= -1.335, e_1 = -0.03581, e_2 = -0.0006306, e_3 = 0.499, and e_4 = 0.005059.

Log Cutting Overview

The total standing volume is distributed to log grades through simulated log cutting of model trees. To simulate the distribution of tree and branch sizes the cutting simulation is iterated for model trees in each diameter class (2 cm steps) across the diameter distribution, and for each BIX class (steps of $\sigma/2$) within each diameter class (σ is the standard deviation). The result from each simulation is multiplied by the probability of finding a tree in that particular diameter and BIX class. Once the volume is distributed to log grades across both distributions, a user-input percentage of each grade is downgraded to the poorest grade (usually pulp), and the total merchantable volume across grades is automatically adjusted to fit the user-input conversion percentage.

Modelling Diameter Distributions

The probability of each diameter class is modelled using the probability density function of the three-parameter Weibull distribution:

$$W_{pdf}(x) = 1 - e^{-\alpha(x-\gamma)^{\beta}} \quad (25)$$

The coefficients (α, β, and γ) are estimated iteratively from stand minimum DBH ($DBH_{\min}$), maximum DBH ($DBH_{\max}$) and the DBH variation (Var_{DBH}) following the approach of Goulding and Shirley (1979). The VBA implementation is as follows:

```
Function Wparms(minDBH, maxDBH, DBH, SPH)
  Dim Out(0, 2)
  Pi = 3.14159265359873
If DBH > 0 Then
   DBHvar = Wvar(minDBH, maxDBH) 'Estimate DBHvar
   BA1 = DBH ^ 2 * Pi / 40000
   BA2 = minDBH ^ 2 * Pi / 40000
   hat = DBHvar / ((BA1 - BA2) ^ 2)
   counter = 0
   betad = 0.5
   betau = 15
   While Abs(betau - betad) > 0.00001 And counter < 200
      beta = 0.5 * (betad + betau) 'guess halfway between up and down, i.e. binary search
      g1 = Exp(Excel.WorksheetFunction.GammaLn(1 + 2 / beta))
      g2 = Exp(Excel.WorksheetFunction.GammaLn(1 + 1 / beta))
      diff = (1 / (SPH ^ (-1 / beta) - 1) ^ 2) * (g1 / g2 ^ 2 - 1) - hat
      If diff < 0 Then
         betau = beta
      Else
         betad = beta
      End If
      counter = counter + 1
   Wend
```

```
        If Abs(betau - betad) < 0.00001 Then 'make sure the search has converged
            beta = 0.5 * (betau + betad)
            k = Abs((BA1 - BA2) / (1 - 1 / SPH ^ (1 / beta))) / g2
            Out(0, 0) = 1 / k ^ beta 'Estimate alpha parameter
            Out(0, 1) = beta 'Estimate beta parameter
            Out(0, 2) = BA1 - k * g2 'Estimate gamma parameter
        End If
    End If
    Wparms = Out 'Return parameters
    End Function
```

The minimum DBH is estimated from Table 19 empiric regression CNI Pumice Plateau (Lawrence, 1990) using

$$DBH_{\min} = a + bDBH + cT + dBA \qquad (26)$$

Where *DBH* is the quadratic mean diameter at breast height (cm), *T* is stand age (years), *BA* is stand basal area (m^2/ha), and the coefficients are: *a* = -0.545, *b* = 1.03064, *c* = -0.4172, and *d* = -0.13705.

The maximum DBH is estimated from Table 19 empiric regression in Lawrence (1990) using

$$DBH_{\max} = a + bDBH + cT + dBA \qquad (27)$$

Where *DBH* is the quadratic mean diameter (cm) at breast height, *T* is stand age (years), *BA* is stand basal area (m^2/ha), and the coefficients are: *a* = 1.135, *b* =0.8301, *c* =0.649, and *d* =0.13085.

The DBH variation (Var_{DBH}) is estimated from minimum DBH (DBH_{min}) and maximum DBH (DBH_{max}) as:

$$Var_{DBH} = a + b\left(\frac{c}{4}\left(DBH_{\max}^2 - DBH_{\min}^2\right)\right)^2 \qquad (28)$$

The height (H_i) (m) of a tree in *i*'th diameter class is estimated from its diameter (DBH_i) (cm) using a general Peterson height/DBH curve of the form:

$$H_i = 1.4 + \left(a + \frac{b}{DBH_i}\right)^{-2.5} \qquad (29)$$

Where the coefficients *a* and *b* are determined from empiric (undocumented) regressions as:

$$a = \frac{\alpha DBH + \beta BA + \gamma \ln(T)}{MTH} \qquad (30)$$

$$b = DBH\left(\exp\left(\frac{\ln(MTH - 1.4)}{-2.5}\right) - a\right) \qquad (31)$$

Where *DBH* is stand mean DBH (cm), *BA* is stand basal area (m*2*/ha), *T* is stand age (years), *MTH* is stand mean top height (m), and the coefficients are: α = 0.05003, β = 0.039241, and γ = 1.2555.

Model for Diameter-Over-Stubs (DOS)

The diameter-over-stubs (*DOS*) is estimated using the original approach of Knowles *et al.* (1987), which was later verified and redeveloped by Knowles and McElwee (1999).

$$DOS = a + bDA_{DOS} + cBr_{\max} + dBr_{\max}^2 + eH_{DOS} + fH_{DOS}^2 \qquad (32)$$

Where DA_{DOS} is the diameter at the DOS height (H_{DOS}) (cm), Br_{max} is the maximum branch in the DOS whorl (mm), and the coefficients are *a* = 0.6787, *b* = 0.8597, *c* = 0.1439, *d* = -0.0007354, *e* = 0.4777, and *f* = -0.03793.

The size of the maximum branch ($Br_{\max}$) in the DOS whorl is estimated as

$$Br_{\max} = a(H - H_{DOS})\left(\frac{DBH}{H-1.4}\right)^2 + b\sqrt{H_{DOS}} \quad (33)$$

Where H is tree height (m), H_{DOS} is the DOS height(m) (the height from the ground to the largest whorl), DBH is diameter at breast height (cm), and the coefficients are a = 0.7011 and b = 12.122.

The diameter at the DOS whorl (DA_{DOS}) (cm) is calculated from tree height (H)(m) and DOS height (H_{DOS})(m) using

$$DA_{DOS} = DBH\frac{H - H_{DOS}}{H-1.4} \quad (34)$$

Model for Pruned Log Index (PLI)

Pruned log index is estimated using the approach of Park (1989), i.e.

$$PLI = \left(\sqrt{\frac{D_{13} - D_c}{10}}\right)\left(\frac{D_{13}}{D_c}\right)V_R^{1.6} \quad (35)$$

Where D_{13} is the diameter (mm) of the log 1.3 m from the large end, D_c is the diameter of the defect core (mm), and V_R is the ratio between the common volume and the log volume, where common volume is the volume of the log not intercepted by the defect core. The coefficients were estimated from a matrix of output generated from an Excel implementation of the PLI calculator (Park 2004)

D_{13} is estimated from the small-end diameter (SED) (mm), the length of the log (L) (m) and the taper (Δt) (mm/m) as

$$D_{13} = SED + (L - 1.3)\Delta t \quad (36)$$

D_c is estimated from sweep (SW) (mm/m) and diameter-over-stubs (DOS) in mm, as

$$D_c = a + bSW + DOS \quad (37)$$

Where the coefficients are a = 46.375, and b = 1.841.

V_R is calculated as a multiple linear regression using log length (L) (mm), small-end-diameter (SED) (mm), sweep (SW) (mm/m) and taper (Δt) (mm/m) using the following equation:

$$V_R = aL + bSED + cSW + d\Delta t + e \quad (38)$$

With coefficients a = -0.008, b = 0.00019, c = -0.0093, d = -0.00354, and e = 0.8694.

Model for Branch Index (BIX)

The branch index models (Kimberley and Knowles 1993) are centred on BIX for the second log (BIX_2)

$$BIX_2 = a + b\ln\left(1 + \exp\left(\frac{c}{b} + \frac{d}{b}DBH_{20} + \frac{e}{b}H_{thin} + \frac{f}{b}SI + \frac{g}{b}GF\right)\right) \quad (39)$$

Where DBH_{20} is the DBH at age 20 (cm), H_{thin} is the mean top height (m) at first thinning, SI is site index (mean top height (m) at age 20), and GF is the GF rating, nominally set at 14. The coefficients are a = 3, b = 3.52, c = 0.985, d = 0.356, e = -0.321, f = -0.354, and g = -0.212

The BIX of the first log (BIX_1) (cm) is then calculated from BIX_2 as

$$BIX_1 = BIX_2\left(a - b^{cSPH}\right) \quad (40)$$

Where SPH is the stocking (stems/ha) and the coefficients are a = 1.61, b = 0.947, and c = 0.01.

The BIX for the n'th log is calculated from height at thinning (H_{thin}) (m) and final crop stocking (SPH) (stems/ha) as

$$BIX_n = BIX_2\left(a + bH_{thin} + cSPH + dH_{thin}SPH\right) \qquad (41)$$

Where the coefficients are a = *0.622*, b = *0.0361*, c = 0.0000953, and d = - 0.0000769.

BIX Class Distribution

The branch index for the n'th log of a model tree in the i'th diameter class is assumed normal distributed with a mean of $BIX_{i,n}$ as given in the equations above, and a standard deviation of σ = 0.6. The effects of this distribution on the log cutting are simulated through cutting model trees in 10 different BIX classes with boundaries from -2σ to 2σ, in steps of $\sigma/2$. The probability and mean value for each class is determined from the normal distribution, and the mean for each diameter class.

Model for Maximum Branch (Br_{max})

Maximum branch diameter in the log (as against BIX) is used to determine the log grade. The size of the maximum branch for the n'th log of the i'th model tree ($Br_{i,n,\max}$) is modelled from the BIX (BIX_n) of the mean tree, and the difference between the DBH (cm) of the model tree (DBH_i) and the mean tree ($\overline{DBH}$), i.e.

$$Br_{i,n,\max} = a + bBIX_n + c(DBH_i - \overline{DBH}) \qquad (42)$$

Where the coefficients are a = 0.133, b = 1.111, and c = 0.05.

Model for Wood Density

The mean density of the wood (ρ) (g/cm^3) at harvest time (T) (years) is estimated from outerwood measurements at an earlier time (T_{meas}) (years) The function is from Kimberley and McConchie (1997) and is of the form:

$$\rho = a + b\left(\rho_{BH,OW} + c\left(d^{T_{meas}} - d^{T}\right)\right) + eT + fT\left(\rho_{BH,OW} + c\left(d^{T_{meas}} - d^{T}\right)\right) \qquad (43)$$

Where $\rho_{BH,OW}$ is the breast height outerwood density (g/cm^3) measured at time T_{meas}. The coefficients are a = 202.3, b = 0.415, c = 298, d = 0.923, e = 3.12, and f = 0.0081.

Understorey Grazing

The pasture production within the plantation is calculated by reducing the livestock carrying capacity prior to afforestation by an amount proportional to the crown closure of the stand. This amount is then reduced again by the amount of slash produced from silvicultural operations. No grazing is assumed in the first three years.

The canopy closure (CC) (%) model uses the model form described by Knowles et al (1997), McElwee (1999) and McElwee and Knowles (2000), but refitted (specifically for the calculator) using the original data plus an extra set from a more recent validation study by Dean (2000). The model is of the form

$$CC = a\left(1 - \exp\left(-bBA\left(1 - c\left(\frac{H_{GC}}{MTH} - 0.4\right)\right)\right)\right)^{\frac{1}{d}} \qquad (44)$$

Where BA is stand basal area (m^2/ha), H_{GC} is the height to the green crown (m), MTH is stand mean top height (m), and the coefficients are a = 85.8279, b = 0.05967, c = 1.5027, and d = 0.6989.

The height of the green crown (H_{GC}) is modelled from mean height (H) (m) and crown length (CL) (m) as

$$H_{GC} = H - CL \tag{45}$$

Crown length (CL) (m) of unpruned stems is modelled using the approach of Turner (1998), i.e.

$$CL = \min\left(k(MTH - 0.1), a + \frac{b}{SPH}\right) \tag{46}$$

Where SPH is the stocking (stems/ha) and MTH is the mean top height (m), with coefficients k = 0.71, a = 13.48, and b = 598.63. The crown length of a pruned tree is then given by whichever is the shortest, the unpruned crown length or the total height minus pruned height

The reduction in pasture production due to slash has two sources, pruning and thinning, based on Paton (1986). The proportionate reduction is calculated as the proportion of ground area covered by slash at any one time. The area (m^2) of slash from pruning one tree (SA_P) is estimated as

$$SA_P = a + bDOS\ln(L+1) \tag{47}$$

Where DOS is diameter over stubs (cm) and L is the length (m) of stem pruned (originally referred to as effective length), with coefficients a = -0.252 and b = 0.465. This value is converted to ground area coverage (GC_P) (%) by

$$GC_P = Ovl\frac{SPH_P SA_P}{10000}100 \tag{48}$$

Where SPH_P is the number of stems pruned (stems/ha), and Ovl = 0.80 is the amount of slash not overlapping.

The ground coverage from thinning slash involves two elements: crown and stem. The contribution from one stem (SA_{TS}) (m^2) is calculated as

$$SA_{TS} = \frac{D_1 + D_2}{2}H_{GC} \tag{49}$$

Where D_1 is the diameter (cm) at the base of the stem (cm), D_2 is the diameter (cm) at the height of the green crown (H_{GC}). The slash contribution from one crown (SA_{TC}) (m^2) is calculated as

$$SA_{TC} = CW\frac{CL}{2} \tag{50}$$

Where CW is the width of the crown (m) and CL is the crown length (m). The crown width is estimated using an empiric regression for all New Zealand (the mean for the values given for North Island and South Island in Paton (1986)).

$$CW = a + bDBH \tag{51}$$

Where DBH is diameter at breast height (cm), and the coefficients are a = 0.567 and b = 0.1445.

The ground coverage by thinning slash is then multiplied by the number of stems thinned per hectare (SPH_T), reduced to 80% due to overlap, and expressed as percentage of land area covered;

$$GC_T = \frac{(SA_{TS} + SA_{TC})SPH_T}{10000}100 \tag{52}$$

The accumulation and decay of the slash (and its ground coverage) is modelled on a yearly basis as

$$GC_{S,T} = GC_{S,T-1}(1+r)^{-1} + \Delta GC_T + \Delta GC_P \tag{53}$$

Where T is time (years), GC_{T-1} is ground coverage (%) at time T-1 (years), r=*0.5* is the decay rate, ΔGC_T and ΔGC_P is the increment in ground coverage (%) caused by thinning and pruning operations in the period from time T-1 to time T.

Livestock performance under trees is poorer for a given intake of dry matter than on open pasture, so carrying capacities are adjusted downward according to the equation given in Percival et. al. 1988.

Adjusted carrying capacity (ACC%)=(0.75*CC%)+(0.0025*cc%^{2}) (54)

Root Biomass

Root biomass is a useful surrogate for estimating the effect of a stand of trees on slope stability, and predicted from stand stocking and mean DBH using the following function provided by Watson and O'Loughlin, (1990):

$$\text{RootBiomass} = \text{SPH}\ ((10\ \hat{}\ (2.24 \log_{10}(\text{DBH}) - 1.16\ ))\ /\ 1000) \quad (55)$$

Where RootBiomass is the root biomass in tons/hectare, SPH is the stocking in stems/ha, and DBH is the stand quadratic mean DBH.

Root Decay

Root decay following logging is based on O'Loughlin and Watson (1979):

$$S_{t2} = S_{t1} e^{-bt2} \quad (56)$$

Where S_{t1} is root tensile strength (MPa) at clear-felling*t2* is the time since clear-felling (months), and the coefficient *b* is 0.056

Compared to other tree species, *Pinus radiata* has a relatively high root weight for a given tree DBH, but the roots have relatively low tensile strength and a rapid decay rate. If it is assumed that over any given period, loss in root strength and loss in root weight will have an equivalent effect on soil stability, the magnitude of the root effect after clearfelling can be estimated from the following equation :

$$D_{t2} = M_{t1}(S_{t2}/S_{t1}) \quad (57)$$

where: D = weight of decaying tree roots (t/ha), a value equivalent to root tensile strength in terms of its effect on soil erosion, M = weight of all tree roots prior to the onset of root decay (t/ha), S = tensile strength of roots (MPa), *t1*= time at beginning of period (yr), *t2* = time at end of period (yr).

These equations can be used to estimate changes in total tree root weight over the course of one or more rotations, including the effects of pruning and thinning.

Work Study Standards

Waste Thinning

These estimates are based on regressions fitted to the work study standards as per Kaingaroa Forest Work Study Section (1975).

Waste thinning fell time (*FT*) (minutes per tree)

$$FT = 0.0587 + 0.0011DBH + 0.0005DBH^2 \quad (58)$$

Where *DBH* is the stand mean diameter at breast height (cm)

Waste thinning hang-up time (*HAT*) (minutes per tree)

$$HAT = 0.4 \quad (59)$$

Waste thinning clear-away time (*CAT*) (minutes per tree)

$$CAT = 0.006(H-1) \quad (60)$$

Where H is hindrance (on a scale from 1 to 4).

Walk-and-select time (*WST*) (minutes per tree)

$$WST = 0.0303H + 0.0332 - \frac{8.112}{SPH} + \frac{34.26H}{SPH} \quad (61)$$

Where SPH is the stand stocking before thinning (stems per ha) and H is hindrance (on a scale from 1 to 4).

Slope allowance (*SA*) (multiplier)

$$SA = 1 + 0.0139S - 0.001S^2 = 0.00004S^3 \quad (62)$$

Where S is the slope in degrees.

Total allowance (*TA*) (multiplier)

$$\begin{aligned} S \le 20, H \le 2 &: TA = 1.643 \\ S > 20, H \le 2 &: TA = 1.653 \\ S \le 20, H > 2 &: TA = 1.653 \\ S > 20, H > 2 &: TA = 1.663 \end{aligned} \quad (63)$$

Where S is slope in degrees, and H is hindrance (on a scale from 1 to 4).

Total time per tree (*TTPT*)

$$TTPT = SA \cdot TA \cdot (FT + HAT + CAT + WST) \quad (64)$$

Pruning Time

Based on regressions fitted to the work study standards as per Kaingaroa Forest Work Study Section (1975).

Prune time (*PT*)

$$\begin{aligned} H_p \le 2.2 &: \quad PT = 0.383 + 0.0466DBH + 0.0859H \\ 2.2 < H_p \le 4.0 &: \quad PT = 0.1820 + 0.0559DBH - 138.3/SPH + 14.50\,DBH/SPH \\ H_p > 4.0 &: \quad PT = 0.69 + 0.05(DBH - 14) \end{aligned} \quad (65)$$

Where H_p is pruning height (m), DBH is stand mean diameter at breast height (cm), SPH is stocking (stems per ha).

Ladder handling (*LH*)

$$\begin{aligned} H_p \le 2.2 &: \quad LH = 0 \\ 2.2 < H_p \le 4.0 &: \quad LH = 0.135 + 0.071H \\ H_p > 4.0 &: \quad LH = 0.221 + 0.00675S + 0.053H \end{aligned} \quad (66)$$

Where H_p is pruning height (m), H is hindrance (on a scale from 1 to 4), and S is slope in degrees.

Walk-and-select time (WST)

$$H_p \leq 2.2 \quad : \quad WST = 0.243 - 0.00017SPH + 0.1118H$$

$$2.2 < H_p \leq 4.0 \quad : \quad WST = 0.2346 + \frac{35.02}{SPH} - 0.1988H + 0.0692H^2 \qquad (67)$$

$$H_p > 4.0 \quad : \quad WST = 0.1448 + \frac{11{,}89}{SPH} + 0.0292H + 8.56\frac{H}{SPH}$$

Where H_p is pruning height (m), *DBH* is stand mean diameter at breast height (cm), *SPH* is stocking (stems per ha), and *H* is hindrance (on a scale from 1 to 4).

Total allowance (*TA*) (multiplier) for low pruning (H_p<=2.2 m) is *TA* = 1.335.
Total allowance (*TA*) (multiplier) for medium pruning is:

$$\begin{aligned} S \leq 20, H \leq 2 &: TA = 1.353 \\ S > 20, H \leq 2 &: TA = 1.363 \\ S \leq 20, H > 2 &: TA = 1.363 \\ S > 20, H > 2 &: TA = 1.373 \end{aligned} \qquad (68)$$

Where *S* is slope in degrees, and *H* is hindrance (on a scale from 1 to 4).

Total allowance (*TA*) (multiplier) for high pruning (H_p > 4.0 m)

$$\begin{aligned} S \leq 20, H \leq 2 &: TA = 1.359 \\ S > 20, H \leq 2 &: TA = 1.369 \\ S \leq 20, H > 2 &: TA = 1.369 \\ S > 20, H > 2 &: TA = 1.379 \end{aligned} \qquad (69)$$

Where *S* is slope in degrees, and *H* is hindrance (on a scale from 1 to 4).

Slope allowance (*SA*) (multiplier) for all pruning types are:

$$SA = 1 + 0.0139S - 0.001S^2 = 0.00004S^3 \qquad (70)$$

Where *S* is the slope in degrees.

Total time per tree (*TTPT*)

$$TTPT = SA \cdot TA \cdot (PT + LH + WST) \qquad (71)$$

Where all parameters are defined in the above.

CONCLUSIONS

From the above, it is clear that considerable functionality exists to readily enable modelling of stand level growth and quality of radiata pine at the national level in New Zealand. Where obvious gaps have presented themselves, for example to predict stand level volume at the national level, we have been able to fit a new function from existing NZ-wide data (Hansen *et al.* 2004). Several NZ-wide functions have been incorporated which have not previously been employed in decision support systems, or have been updated so they can be utilised at the national level. These include the three-point taper/volume function (Gordon and Budianto, 1999), canopy closure (McElwee, 1999; Dean, 2000), understorey pasture production (Knowles *et al.* 1997), height/age curves (Van der Colff, in prep), and 300 Index (Kimberley, in prep).

One obvious gap is that no NZ-wide diameter distribution function is available. As an interim measure, we have incorporated the Weibull model 19 Central North Island Pumice Plateau (Lawrence, 1990). It is recommended that a new national diameter distribution function be derived and incorporated in the calculator.

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