Technical Manual for GROMIT

1 March 2000

T J Randle

1.0 Overview

GROMIT (GROwth Model for Individual Trees) is an individual tree model designed to simulate growth over the life of a stand. It has two major components; a canopy assimilation module that is written in FORTRAN, and a growth module that uses the simulation language DARE-P (Lucas, 1974; Wait and Clarke, 1978). The modules are fundamentally process based, although there are some elements of empirical sub-models. The advantage of process based models, is that they can provide predictions of growth where extrapolation is necessary – a failing largely inherent with empirical models.

The model is not structured as a single formulation, but is tailored to specific requirements, including the use of alternative sub-models. 'Add-ons' have been developed for specific purposes. In this description, only brief details of such add-ons are given, but where a function is integral to the model, it is described more fully.

The objective of the canopy assimilation module is to calculate carbon uptake for a given leaf area index (LAI). The well characterised biochemical formulation of photosynthesis developed by Farquhar and co-workers (Farquhar and von Caemmerer, 1982; von Caemmerer et *al.*, 1994) are used, together with a stomatal conductance model after Jarvis (1976). Dates representing bud-burst and end of season (senescence in broadleaf trees) are also modelled. This module has been used for some basic flux simulations, although it does not make any claims to be a full flux model as it includes no representation of canopy CO_2 storage. Its primary objective, within the framework of the growth model, is to define the relationship between LAI and assimilated carbon. The time-steps of calculation are necessarily short (usually hourly), although once basic relationships for a given site have been defined, then this intensive modelling approach may not be necessary.

The growth module uses the relationship derived between LAI and assimilated carbon, and allocates the carbon to compartments within the trees. The compartments consist of foliage, branches, stem, coarse (transport) roots and fine roots. Allocation between compartments follows the pipe model theory of Shinozaki et *al.* (1964). Each tree has a physical X-Y co-ordinate, and the space available to the tree is based on a polygon taking account of the size and location of its neighbours. The growth module uses annual time steps at present, although there is potential to simulate shorter periods.

2.0 Description of assimilation module

2.1 *Basic inputs: Meteorology*

The simulation of carbon balance begins with the input of meteorological data. Typically, hourly data are used with inputs of solar radiation, air temperature, humidity (or wet-bulb temperature), wind-speed and precipitation, together with ambient carbon dioxide concentration. Such detailed datasets are often not available, especially for historical records and future predictions. In these cases, hourly data are derived from daily data using the following routines:

Temperature and Radiation. Where daily values of temperature and radiation are available, sine curves are fitted with peaks at 14:00 hours and 12:00 hours respectively. A methodology has been developed to allow the derivation of hourly radiation estimates from historical data recorded as sunshine duration (see Appendix I).

Relative Humidity. If humidity is not available, it is calculated from wet-bulb and dry-bulb temperatures. Where daily values are given, it is assumed that vapour pressure remains constant throughout the day and relative humidity changes with temperature. For temperatures above freezing, the saturated vapour pressure (Svp) is given by:

$$Svp = 6.1708 \exp^{(17.269\,T_k)/(237.3+T_k)} \quad \textbf{2.1}$$

where, T_k is the temperature in kelvin, and the vapour pressure (Vp) is

$$Vp = Svp_{wet} - 0.66\,(T_{dry} - T_{wet}) \quad \textbf{2.2}$$

with T_{dry} and T_{wet}, the dry-bulb and wet-bulb temperatures.

Relative humidity, *Rh*, is calculated from the vapour pressure and the saturated vapour pressure (at T_{dry}; V_{Pdry}) at the relevant time:

$$Rh = \frac{Vp}{Vp_{dry}} 100 \quad \textbf{2.3}$$

Windspeed and Precipitation. If hourly data are not available, a function must be developed which describes hour to hour variation. This function will be site specific.

Ambient Carbon dioxide Concentration. If measured data are not available a simple function is used, with maximum and minimum concentrations at dawn and two hours after dawn, respectively. The concentration decreases linearly between the maximum and minimum values, remains at the minimum value until two hours prior to dusk, and then increases linearly up to the maximum value at dawn.

2.2 *Basic inputs 2: Canopy structure*

The most appropriate way to envisage how the model considers the structure of the canopy of a tree is as a series of concentric shells (an analogy is a 'Russian doll'). For ease of reference, the term 'zone' is used to represent each shell. Each 'zone' has a number of layers of foliage (definable), and each layer has a proportion of foliage that is either sun-lit or shaded. The physiological characteristics (R_d, V_{max}, J_{max}, g_{smax} etc.) are constant within each 'zone', but may vary between 'zones'. To this end, there are many input and parameters that are required to define the canopy.

2.3 *Light interception*

Previously published formulations of GROMIT have modelled CO_2 assimilation as light interception using the Beer-Lambert Law (Randle and Ludlow, 1998; Ludlow et *al.*, 1990). The model now incorporates a biochemical photosynthesis routine, based on the model of Farquhar and co-workers (see Medlyn et *al.*, 1999).

The canopy is divided into several 'zones' and each 'zone' has a maximum photosynthetic capacity explicitly defined in the parameterisation. Photosynthetically active radiation (PAR) falling on each layer of foliage is attenuated by the canopy leaf area extinction coefficient, such that the total PAR absorbed is given by

$$I_{abs} = I_0(1 - \exp(-K_{ext} LAI)) \qquad \textbf{2.4}$$

where, I_{abs} is absorbed PAR, I_0 the PAR above the canopy, and K_{ext} the light extinction coefficient of the canopy.

GROMIT treats light interception by shaded and sunlit foliage separately (Spitters, 1986b) and integrates these processes with a biochemical CO_2 assimilation model following Meng and Arp (1994). Their approach has been further developed, through assigning each 'zone' specific physiological characteristics, with the total number of zones limited to twelve. Each zone has a defined number of foliage layers (leaf area index, LAI), with each layer of foliage (irrespective of the number of layers in a 'zone') considered in turn, and calculated incident PAR falling on shaded and sunlit leaves used to drive the biochemical model. If a layer spans two 'zones', weighted averages of parameters are input into the biochemical model.

2.3.1 *Partitioning of diffuse and direct light above the canopy*

In order to treat sun-lit and shaded foliage separately, it is necessary to partition incoming radiation into diffuse and direct light.

The amount of cloud cover has a large effect on the proportion of direct and diffuse radiation. All irradiation is diffuse under an overcast sky but 23% is diffuse (with 77% of global irradiation direct) under a clear sky, (Spitters, 1986a). Historical meteorological records have consisted of daily measurements of sunshine duration, which have been used to derive the diffuse and direct components of PAR using functions dependent on zenith angle, atmospheric pressure and potential solar radiation. (Weiss and Norman, 1985). More recently, following the development of electronic sensors and data logging capabilities, PAR or global radiation is measured directly. These data, at a sub-daily timestep are used in many carbon flux and process-based models of forest growth such as GROMIT (Ludlow et *al.*, 1990), MAESTRO (Wang and Jarvis, 1990) and Biomass (McMurtrie et *al*., 1990).

In order to provide these estimates of direct and diffuse radiation input, GROMIT uses the approach of Spitters (1986a). In this approach, the total extra-terrestrial radiation at a plane parallel to the surface of the earth is given by:

$$S_0 = S_c(1 + 0.033\cos(360\ d/365))\cos\theta_z \qquad \textbf{2.5}$$

Where *d* is the day of year, S_c is the solar constant (1370 W/m^2), and θ_z is the azimuth angle of the sun.

A four-part function describes the ratio of diffuse radiation (S_{df}) to total radiation at the earth surface(S_g), as a function of radiation at the earth surface and the extra-terrestrial radiance (S_o) (de Jong, 1980). Both daily and hourly values can be derived (Spitters, 1986a; de Jong, 1980). The relationships are notably constant over a range of climates and latitudes (Collares-Pereira and Rabl, 1979; Erbs et *al.*, 1982) and are appropriate to a wide range of conditions. Since GROMIT usually calculates photosynthesis at an hourly time-step, the most appropriate function is:

$$
\begin{aligned}
S_{df}/S_g &= 1 && \text{for} && S_g/S_0 \le 0.22 \\
S_{df}/S_g &= 1 - 6.4\,(S_g/S_0 - 0.22)^2 && \text{for} && 0.22 < S_g/S_0 \le 0.35 \\
S_{df}/S_g &= 1.47 - 1.66\,(S_g/S_0) && \text{for} && 0.35 < S_g/S_0 \le K \\
S_{df}/S_g &= R && \text{for} && K < S_g/S_0
\end{aligned}
\qquad \textbf{2.6}
$$

where $R = 0.847 - 1.61\cos\theta_z + 1.04\cos^2\theta_z$ and $\mathrm{K} = (1.47 - \mathrm{R})/1.66$.

2.3.2 *Calculation of sunlit and shade light intensities*

Only photosynthetically active radiation (PAR) is considered, and it is assumed that reflection is negligible, although scattering of direct light is taken into account. The separation of PAR into diffuse and direct components is explained in the previous section. Following Neumann et *al.* (1989) and Meng and Arp (1994), PAR on sunlit leaves in the *i*th layer is calculated as:

$$\mathrm{PAR}_{sun}(i) = \mathrm{PAR}_{dir0}(\cos\Psi_{orient}/\sin\theta_z) + \mathrm{PAR}_{shade}(i) \qquad \textbf{2.7}$$

where, PAR_{dirO} is the amount of direct PAR above the canopy, Ψ_{orient} is the orientation angle of the leaf in relation to the sun, and θ_z is the azimuth angle. In most circumstances, PAR_{sun} will be less than the incoming radiation as the surface of the canopy is not a plane surface.

The calculation of PAR incident shaded leaves is more complex, as they receive diffuse light, attenuated direct light and scattered direct light. Since each layer of leaves is treated separately, the average light within the layer is not calculated, although incident light above each layer is a necessary intermediate; for shaded leaves

$$
\begin{aligned}
\mathrm{PAR}_{shade} = {} & \mathrm{PAR}_{diff0}\exp(-\mathrm{K}_{df}\textstyle\sum \mathrm{LAI}(i) - 1) + \\
& \mathrm{PAR}_{dir0}\{\exp[-(1-\sigma_c)^{0.5}\mathrm{K}_{bl}\textstyle\sum \mathrm{LAI}(i) - 1] - \\
& \exp(-\mathrm{K}_{bl}\textstyle\sum \mathrm{LAI}(i) - 1)\}
\end{aligned}
\qquad \textbf{2.8}
$$

where PAR_{diffO} is diffuse PAR above the canopy, K_{df} the canopy extinction coefficient for diffuse light, and σ_c is the scattering coefficient of single leaves. K_{bl} is the black body canopy extinction coefficient (Spitters, 1986b, Meng and Arp, 1994) such that

$$\mathrm{K}_{bl} = \frac{\mathrm{K}_{df}}{1.6(1-\sigma_c)^{0.5}\sin\theta_z} \qquad \textbf{2.9}$$

If light extinction is constant throughout the canopy, then equations (2.7) and (2.8) apply. In circumstances where extinction is not constant, an approximation is made, where for sequential layers of leaves, K_{df} becomes an average of the layers above, and K_{bl} is calculated (equation 2.9) using this value of K_{df}.

2.3.3 *Calculation of sunlit foliage*

In any layer, the foliage is either sunlit or shaded. The proportion of sunlit foliage in each layer is variable, and based on a Markov gap-frequency model, following Neumann et *al*., (1989) and Meng and Arp (1994). A clumped foliage distribution is assumed, with leaf distribution in one layer dependent on the distribution in previous layers. For each layer of foliage, the proportion which is sunlit in layer, *i*, is defined as

$$P_{sun} = \exp\left(\frac{-\Omega_0 G \sum_{n=1}^{i} LAI(n)}{\cos\theta_z} \right) \quad \textbf{2.10}$$

Where G is the leaf orientation function and Ω_0 is the degree of leaf dispersal. For the first layer (top of canopy), i=1, and i=2,3, etc., for subsequent layers.

2.4 *Photosynthetic Assimilation*

The evaluation of incident PAR on shaded and sunlit foliage in each layer enables the calculation of carbon assimilation. The photosynthetic rate is limited by either the regeneration of ribulose 1,5-biphosphate (RuBP), (A_c) or by electron transport (A_j). The formulation follows von Caemmerer et *al.* (1994) and Medlyn et *al.* (1999).

$$A_{net} = \min(A_j, A_c) - R_d \quad \textbf{2.11}$$

Where R_d is the dark respiration. A_c and A_j are given as:

$$A_c = \frac{V_{max}(C_i - \Gamma^*)}{C_i + K_m} \qquad \text{and} \qquad A_j = \frac{J(C_i - \Gamma^*)}{4(C_i + 2\Gamma^*)} \quad \textbf{2.12}$$

K_m is the Michalis-Menton coefficient for the reaction ($K_m = K_c\,(1+O_i / K_o)$), with O_I, the internal oxygen concentration; K_c and K_o temperature dependent Arrhenius (exponential) functions:

$$K_c = 404\exp\left(\frac{59400(T-298)}{(298\ R\ T)} \right) \qquad \text{and} \qquad K_o = 248\exp\left(\frac{36000(T-298)}{(298\ R\ T)} \right) \quad \textbf{2.13}$$

where R is the universal gas constant.

Γ^* is the CO_2 compensation point, a function of temperature (in kelvin):

$$\Gamma^* = 36.9 + 1.88(T-298) + 0.036(T-298)^2 \quad \textbf{2.14}$$

and J is a function of light, light absorption and quantum yield (α) such that:

$$\theta\, J^2 - (I\alpha + J_{max})J + I\alpha\, J_{max} = 0 \quad \textbf{2.15}$$

where internal CO_2 concentration (C_i), is a function of ambient CO_2 concentration (C_a), net assimilation (A_{net}) and stomatal conductance to water vapour (g_s) such that

$$C_i = \frac{C_a - A_{net}}{1.6 g_s} \quad \textbf{2.16}$$

The values V_{max} and R_d are temperature dependent Arrhenius (exponential) functions:

$$\text{Arrhenius:} \qquad \exp\left(\frac{H_a(T - T_{ref})}{T_{ref}\ R\ T} \right) \quad \textbf{2.17}$$

J_{max} may take the form of either an Arrhenius function, or a Lloyd (humped) function:

Lloyd:
$$\frac{\exp\left(\frac{H_a(T-T_{ref})}{T_{ref}\ R\ T}\right)\left(1+\exp\left(\frac{D_s\ T_{ref}-H_d}{R\ T_{ref}}\right)\right)}{\left(1+\exp\left(\frac{D_s\ T-H_d}{R\ T}\right)\right)} \quad \textbf{2.18}$$

The Arrhenius function requires an input parameter of the activation energy of the relevant process, H_a, together with Temperature, T (in kelvin), and the reference temperature for the value, T_{ref}, (also in kelvin). In addition to the parameters of the Arrhenius function, the Lloyd function requires additional parameter values for the de-activation energy (H_d), and an entropy term (D_s).

Calculations are performed layer by layer for both the sunlit and shaded foliage. The product of A_{net} and the proportion of foliage that is either sunlit or shaded gives carbon assimilation in that layer. The summation of successive layers gives the cumulative assimilation for an increasing number of layers of foliage.

2.5 *Stomatal conductance*

Calculation of stomatal conductance is made on a layer by layer basis following Jarvis (1976). Response functions to environmental variables (varying between 0 and 1), are imposed on the maximum value for stomatal conductance (g_{smax}), which is variable between 'zones'.

$$g_s = g_{s\max} f(Q) f(T) f(\psi) f(\varphi) f(C) \quad \textbf{2.19}$$

where $f(x)$ is the response function to light, temperature, humidity, soil-moisture and ambient carbon dioxide concentration.

The light response function is defined as:

$$f(Q) = \frac{S_0(Q+q)}{g_{s\max} + S_0(Q+q)} \quad \textbf{2.20}$$

where S_0 is the slope of the light response function at low light levels, Q is incident PAR and $q=g_{dark}/g_{smax}$, with g_{dark} defined as stomatal conductance in the dark.

The temperature response function is defined as:

$$f(T) = \frac{T-T_{\text{opt}}}{T_{\text{opt}}-T_{\min}}\left(\frac{T_{\max}-T}{T_{\max}-T_{\text{opt}}}\right)^{\left(\frac{T_{\max}-T_{\text{opt}}}{T_{\text{opt}}-T_{\min}}\right)} \quad \textbf{2.21}$$

where T (°C) is temperature, and T_{max}, T_{opt} and, T_{min} are the maximum, optimum and minimum temperatures for stomatal conductance.

The response function to vapour pressure deficit (humidity function) is defined as:

$$f(\psi) = \begin{cases} 0, & V_{pd} > V_2 \\ 1-\dfrac{V_{pd}-V}{V_2-V_1}, & V_2 \geq V_{pd} \geq V_1 \\ 1, & V_1 > V_{pd} \end{cases} \quad \textbf{2.22}$$

where V_1 and V_2 are the values of vapour pressure deficit at which g_{smax} is at a maximum and minimum, respectively, and $V_{pd} = (1-(Rh/100))V$

The response to soil-moisture deficit (S_{md}) is defined as:

$$f(\varphi) = \max(1 - \exp^{S_{m1}(S_{md} - S_{m2})}, 0.0) \quad \textbf{2.23}$$

where S_{m1} is a constant and S_{m2} is the soil moisture deficit at which stomatal closure is complete. The ground is assumed to be frozen (and thus $f(\varphi)=0$) when the air temperature is less then -1^{o}C.

The response of stomata to ambient carbon dioxide concentrations is not well defined in literature. However, an empirical function has been derived for oak (Broadmeadow *et al*., 1999):

$$f(C) = \max\left((1 - C_1(C_a - 350), 0.2\right) \quad \textbf{2.24}$$

where C_a is ambient carbon dioxide concentration, and C_l, is a response function parameter.

2.6 *Water Balance*

GROMIT assumes three water holding zones in the soil. The number of zones can be extended, but in practice three have been sufficient. Each of the zones is defined by a physical depth (which thus gives rise to a volume under the projected area of the crown), and a saturated (holding) capacity. The three zones are defined as:

Rooting zone: This is the only layer from which the tree draws water. Water movement by diffusion from or to storage zone 1 is dependent on the difference in water content (or potential) between the two zones.

Storage zone 1: water may flow by diffusion from or to the rooting zone as well as from and to storage zone 2.

Storage zone 2: water may only flow between this zone and the storage zone 1.

In reality, the flow (diffusion) of water between zones will be continuous. However, for ease of implementation, a time-step (or iterative) approach is used. The time step for evaluation (*eg* 1 hour) is divided into 12 smaller units, termed mini-steps, and calculations of water-balance (transpiration, precipitation and diffusion) are made over these shorter time-steps. This is repeated for each of the remaining mini-steps, thus simulating equilibrium and reducing oscillations.

2.6.1 *Diffusion*

The transfer of water (W_t), from one zone into another, in time, t, (mini-step) is based upon the difference in the water content between the zones($W_{c1} - W_{c2}$) and a diffusion constant, D_c:

$$W_t = t(W_{c1} - W_{c2})D_c \quad \textbf{2.25}$$

2.6.2 *Rainfall*

The proportion of precipitation falling as throughfall depends on the quantity of water intercepted and held within the canopy (leaf-water). If the water holding capacity of a layer is exceeded, then subsequent rainfall is intercepted by the next layer. When all foliage layers in the canopy are at capacity, additional precipitation falling within the time step is defined as throughfall.

The throughfall initially enters the rooting zone. The capacity of this zone depends on the current water content and the maximum holding capacity of the zone. Any additional throughfall enters storage zone 1 and finally storage zone 2. When all the soil water storage zones are full to capacity,

additional precipitation are lost from the system as runoff. Throughfall is assumed to fall evenly over the main time-step, and is added within the mini-steps of water movement.

2.6.3 *Transpiration*

Water demand for transpiration is dependent on the soil moisture content of the rooting zone - if a deficit has developed, then stomatal closure will be initiated (see above). Uptake is also calculated on a mini-step basis.

Transpiration is reduced if foliage water is present, which must be lost through evaporation before transpiration can occur. The function weights transpiration of a layer by the proportion of time that the layer is 'dry'.

$$E_t = \min(L_w, P_e) + \max(0, \tfrac{L_w}{P_e})\ \Phi \qquad \textbf{2.26}$$

Where E_t is evapo-transpiration, L_w, leaf-water, P_e, potential evaporation of a wet surface and Φ, the transpiration from a dry surface. Transpiration is also governed by boundary layer conductance (g_a), which is dependent on humidity, temperature, and wind-speed. Aerodynamic and boundary layer conductances are modelled as in MAESTRO (Wang and Jarvis, 1990; Jarvis et *al*., 1976).

2.7 *Respiration*

Since the assimilation module generally operates at an hourly timestep, calculations of respiration are made within this module. Maintenance respiration of each of the main living tissue compartments (foliage, branch-wood, stem sapwood, transport roots and fine roots) is calculated using equation 2.27 and expressed on an annual basis as a proportion of tissue dry weight (i.e. kg C respired per kg carbon in living tissue).

$$R_t = R_b \exp^{Q_{10}(t - t_b)} \qquad \textbf{2.27}$$

where R_t is the respiration rate at temperature, t, Q_{10} is the respiratory quotient (default 2.0), and R_b is the maintenance respiration rate at reference temperature t_b.

2.8 *Calculation of the Growing season*

For deciduous trees, the growing season is defined as the period during which there is green foliage present on the tree. There is well-documented evidence of growth, elongation, thickening etc of various organs of the tree at various times of the year (e.g. McWilliam, 1972; Mitrukov, 1976; Pietarinen et *al*., 1982). In GROMIT, these phases are grouped together as the 'growing season'. For evergreen species, the definition of growing season is less precise, although there is a period of defined bud-burst in spring, and in many cases, a dormant period during winter.

2.8.1 *Bud-burst*

Several types of models of bud-burst were evaluated, including a simple three parameter thermal time model (Cannell and Smith, 1983), and sequential, alternate and four-phase models which have been reviewed by Kramer (1994). The most suitable approach, given the limited data available for validation, is the synthesis model of Hänninen (1990). This is a four-phase model which has been extended to include the photosensitivity response of Kramer (1994). Unrealistic outputs have been produced for future climate scenarios, although these problems may be a result of poor input data. However, it does indicate that without sufficient parameterisation and validation, extrapolation using the 'modified synthesis' model is unwise. In this case, a modified thermal time model, provided more realistic output, although the model is less sensitive. Either of the models described below can be used, but care should be taken with parameterisation; this is particularly important for the more complex

synthesis model which can easily be over-parameterised, requiring some of the less sensitive parameters to be fixed.

Both models have a state of chilling (S_{chl}) and forcing (S_{frc}):

$$S_{chl} = \sum_{t_1}^{t} R_{chl} \qquad \text{and} \qquad S_{frc} = \sum_{t_2}^{t} R_{frc} \qquad \textbf{2.28}$$

Bud-burst occurs as a function of S_{chl} and S_{frc} which are determined by model specific rates of chilling (R_{chl}) and forcing (R_{frc}). The thermal-time model used in GROMIT predicts bud-burst occurs when S_{frc}>/=S_{chl} and is expressed as:

$$R_{frc} = \begin{Bmatrix} 0, & T \le T_{b1} \\ k(T - T_b), & T > T_{b2} \end{Bmatrix}, \quad k = \begin{Bmatrix} 0, & t < t_1 \\ 1, & t \ge t_2 \end{Bmatrix}, \quad \text{and} \quad R_{chl} = 1 \qquad \textbf{2.29}$$

The parameters t_1 and t_2 represent the date of the onset of rest and quiescence (namely November 1 and January 1), with t, the day of year. The parameters, T_{b1} and T_{b2} are the base temperatures at which chilling or forcing occurs. In the original thermal time model, T_{b1}=T_{b2}=2^{o}C.

The synthesis four-phase model is more complex. The chilling sum, S_{chl}, uses the rate of chilling with an additional modifier, daylength (D_l) and is calculated from November 1.

$$R_{chl} = \partial\, D_l \begin{Bmatrix} 0, & T \le T_{\min} \\ \dfrac{T - T_{\min}}{T_{\text{opt}} - T_{\min}}, & T_{\min} < T \le T_{\text{opt}} \\ \dfrac{T - T_{\max}}{T_{\text{opt}} - T_{\max}}, & T_{\text{opt}} < T \le T_{\max} \\ 0, & T \ge T_{\max} \end{Bmatrix} \qquad \textbf{2.30}$$

Modifiers to the chilling and forcing requirements (Δ_{chl}, Δ_{frc})are also calculated from November 1:

$$\Delta_{chl} = \begin{Bmatrix} 0, & T < T_{low} \\ \dfrac{\Delta_{c\max}}{T_{high} - T_{low}}(T - T_{low}), & T_{low} \le T < T_{high} \\ \Delta_{c\max}, & T \ge T_{high} \end{Bmatrix} \qquad \textbf{2.31}$$

Similarly,

$$\Delta_{frc} = \begin{Bmatrix} 0 & T < T_{\text{low}} \\ \dfrac{\Delta_{f\max}}{T_{\text{high}} - T_{\text{low}}}(T - T_{\text{low}}) & T_{\text{low}} \le T < T_{\text{high}} \\ \Delta_{f\max} & T \ge T_{\text{high}} \end{Bmatrix} \qquad \textbf{2.32}$$

The chilling and forcing modifiers are used to calculate a competence function, $f(C)$:

$$f(C)=\left\{\begin{array}{ll} 0, & R_{chl} < C_{\text{abs}} \\ \dfrac{1-C_{\min}-\Delta_{frc}}{C_{\text{crit}}-\Delta_{chl}-C_{\text{abs}}}(R_{chl}-C_{\text{abs}})+C_{\min}+\Delta_{frc}, & C_{\text{abs}} \le R_{chl} < (C_{\text{crit}}-\Delta_{chl}) \\ 1, & R_{chl} \ge (C_{\text{crit}}-\Delta_{chl}) \end{array}\right\} \quad \textbf{2.33}$$

The rate of forcing is calculated from the competence function:

$$R_{frc}=f(C)\left\{\begin{array}{ll} 0, & T \le 0 \\ \dfrac{a}{1+\exp^{b(T+c)}}, & T > 0 \end{array}\right\} \quad \textbf{2.34}$$

In this model, bud-burst occurs when the state of forcing, (S_{frc}), exceeds a critical threshold,(F_{crit}). For the modified synthesis model, the parameters required are listed in Table 2.1:

Parameter	
$T_{\min}$	Minimum temperature for chilling
T_{opt}	Optimal temperature for chilling
$T_{\max}$	Maximum temperature for chilling
δ	Constant for daylength effect
$\Delta_{c\max}$	Maximum decrease in chilling requirement for full growth competence.
$\Delta_{f\max}$	Maximum increase in growth competence from forcing temperature
T_{low}	Lower temperature value for effect on growth competence
T_{high}	Highest temperature value for effect on growth competence
$C_{\min}$	Minimum growth competence value
C_{crit}	Chilling requirement of rest completion
C_{abs}	Absolute chilling requirement
a	Constant for forcing rate
b	Constant for forcing rate
c	Constant for forcing rate
F_{crit}	Critical value of the state of forcing to achieve bud-burst

Table 2. 1 Parameter nomeneculture for the bud-burst model based on the modified synthesis model of Hänninen (1990), with photosensitivity of Kramer (1994). See equations 2.30–2.34.

2.8.2 *Seasonal Development*

Although the developement of foliage is assumed to be instantaneous on the date of bud-burst, the physiological characteristics are assumed to develop as a function of time. The function *Dv* returns a value between 0.1 and 1.0 dependent on the number of days since bud-burst, with the maximum (1.0) occurring 28 days after bud-burst. The function is used as a scalar for the photosynthetic parameters of J_{max}, V_{max} and R_d, together with the maximum stomatal conductance, g_{smax}. The occurrence of a spring frost retards *Dv* by seven days. Where no instances of frost occur, the function is linear.

$$Dv = \min((0.1 + \frac{0.9}{28}\sum d_i), 1.0) \quad \textbf{2.35}$$

where d_i is the cumulative number of days since bud-burst (reduced by a maximum of 7 if a spring frost occurs).

Values of J_{max} and V_{max} may be determined by an empirical relationship based on nitrogen content of the foliage. There is no change in photosynthetic capacity associated with the withdrawal of nutrients in autumn, although all physiological parameters including those describing respiration can be input at specific time points.

2.8.3 *Determination of the end of the growing season*

For coniferous trees, the end of growing season is less marked, and in reality, limited photosynthesis may occur all year round. However, the amount of assimilation during the 'winter months' is small because of low light intensity and temperature, and short day-length.

For deciduous trees, the end of the growing season is defined by the senescence of foliage. There is a period that precedes this when nutrients are withdrawn from the foliage (leaf yellowing). No attempt in the model is made to simulate this 'nutrient withdrawal'. The errors in the calculation of the overall annual assimilation by this omission are small, as the low-light and temperature result in minimal photosynthetic CO_2 assimilation during this period. Models which attempt to account for the timing of senescence and the translocation of nutrients usually use a thermal chill function, which is sometimes coupled with a photo-period function (Pietarinen et *al.*, 1982; Koski and Sievänen, 1985).

GROMIT defines leaf longevity as a function of carbon balance (between respiration and photosynthesis). The modelling of leaf longevity as a function of carbon gain was proposed by Charbot and Hicks (1982), who expressed it as the difference between photosynthetic rate during the favourable period of the year and maintenance costs during the unfavourable period, together with construction costs, and other costs including defence, transport and storage. This approach was further refined by Kikuzwa (1991, 1995). The assimilation module of GROMIT contains no information on tree structure, and thus whole tree carbon balance cannot be used to assess the longevity of the growing season. An alternative approach has been adopted in which the carbon balance of the outer-most layer of foliage is assessed, and is defined as:

$$\sum_{i=1}^{14} \frac{A_i}{R_i} \geq \lambda \quad \textbf{2.36}$$

Where A_i and are R_i are the daily carbon assimilation totals and respiration costs of the outermost layer of foliage in the canopy, and λ is a threshold value. A 14-day moving average is used to smooth anomalies and prevent the premature prediction of leaf senescence. The end of the growing season is defined as the day when this 14 day moving average falls below λ. Low temperatures over-ride this senescence function, with the occurrence of n_5 days (T>5oC) or n_4 days (T<4oC) also defining the end of the growing season. The threshold value, λ, also responds to frost immediately after budburst.

2.9 *Initialisation*

Most of the input requirements for the assimilation model described above are entered via a single input file. These inputs use the FORTRAN feature of 'namelist'. The 'namelist' feature allows the order of inputs (within any list) to be unimportant. The structure of the various lists groups relevant inputs together; for example, stomatal conductance, soil conditions etc. The input file is in common with the files used for the growth model, although the growth model parameters need not be set.

3.0 Description of the Growth Module

The growth module of GROMIT runs under the simulation language DARE-P (Lucas, 1974, Wait and Clarke, 1978), is written in FORTRAN and should be portable across platforms and machines with only minor system and compiler specific modifications required. The DARE-P system permits the model to be written in a logical order rather than a dependent order (i.e. equations are sorted into the relevant order). The package translates the source model into FORTRAN code, which is then linked with library routines for integration etc. Because of this, functions can be written directly in FORTRAN and linked easily – a feature necessary in some cases where the functions are complex.

The description here provides a combination of the structure of the model within DARE-P and the main assumptions that are made by the model.

3.1 *Individual trees*

As the name of the model implies, GROMIT is an individual tree model. It can simulate up to 144 trees, although usually, fewer are used to reduce computing time. Each tree is given a physical X-Y co-ordinate. The stand of target or core trees are surrounded by a border of other trees around the outside of the plot. The dimensions of the 'border trees' are calculated from the mean characteristics of the 'core' trees. The main purpose of this procedure is to reduce 'edge effects'.

3.2 *DARE-P and GROMIT Preliminaries*

The model code is divided into blocks for the DARE-P system. The blocks are instigated by a '$' in column 2, followed by a keyword letter or letters. The system uses a REPEAT *n* / ENDREPEAT statement pairing. All calculations within the pairing are repeated for *n* trees. Within this pairing, variables are denoted by a '$' attached to the end of the variable name - this is replaced by the tree number when the model is translated into source code. State variables to be integrated are denoted by a prime, (') at the end of the name. There is a limitation on the variable name lengths of six characters, including any number and the prime.

$R is the first block; this is the declaration block, where FORTRAN format is used directly to declare any variables beginning I-N that are real, and any variables A-H or O-Z that are integers.

$M4 Declares the method of integration that can be used by the model. There are several methods of varying precision. The M4 method is a fourth order, variable time-step, Runge-Kutta. (Carnahan et *al*., 1969)

$D1 is the first derivative block; this block contains all the differential equations and forms the bulk of the program.

3.3 *Equations for State variables, intermediate and output variables*

Because of the use of the REPEAT / ENDREPREAT feature, the algebraic description is in terms of a single tree, which is then repeated for each subsequent tree. The state variables are time-dependent and are denoted by use of a prime (').

For any tree, the model has six main compartments indicated by

f foliage
b branches
s stem sapwood

h stem heartwood
t transport or coarse roots (generally considered to be >2mm diameter).
r feeder or fine roots

For these compartments, the state of the tree is described by a number of state variables e.g. W_j, with $j=f,b,s,h,t,r$ for biomass (in kg C).

The effects of competition between trees is calculated from the area available to each tree, and its crown projected area.

Carbon uptake by each tree is calculated from the relationship derived between LAI and assimilation (assimilation module). If the LAI and crown projected area of each tree is known, then the carbon uptake is also known. The carbon is then allocated to the living compartments, based on the pipe-model theory of Shinozaki *et al*. (1964). Currently, a fixed proportion of the carbon (η_r) is allocated to fine roots, whereas allocation to the other compartments is intrinsically calculated (see later section).

3.3.1 *Calculation of Polygons*

Each tree is assumed to occupy a polygon, limited by its neighbours. Calculation of the polygons (area potentially available and projected area) follows the methodology of Nance et *al.* (1988). Initially, all the neighbours of each tree are found, and then boundaries are calculated between each subject tree and its neighbours. Each boundary is perpendicular to the line joining the two trees and lies at a point where the crowns intersect, or where they would intersect if the trees were large enough. All crowns are assumed to be essentially conical, such that the distance, r_n, from tree i to each of its neighbours is given by:

$$r_n = \frac{h_i - h_n + d\cot\alpha_n}{\cot\alpha_i + \cot\alpha_n} \qquad \textbf{3.1}$$

where d is the distance between the two trees, h_i and h_n are the heights and α_i and α_n the crown half-angles of trees i and n. It is assumed that the crown half angles (α) remain constant throughout the life of the tree.

The points at which the boundaries intersect give the corners of the area-available polygon. The projected crown area (projected-area polygon) is calculated from the height of the tree, the half-crown angle and the height of the lowest living foliage (branch) in each direction. Before crowns touch, each tree is assumed to be symmetrical and the projected-area polygon has 12 corners, each r_c meters from the stem, where r_c is given by

$$r_c = (h - h_c)\tan\alpha \qquad \textbf{3.2}$$

h_c is the height of the lowest live foliage at each corner. h_c will usually be zero for open-grown trees or trees in an open stand.

Initially, the projected-area polygon is likely to start much smaller than the projected-area polygon. As trees grow, and h increases, r_c will increase until neighbouring crown touch. At this point, corners of the projected-area polygon will start to fall outside the area-available, which implies that tree crowns are invading each other's space. Although this does occur in real forests, it is assumed that the effect on photosynthesis is negligible because foliage growing inside another crown will be shaded and contribute little to total photosynthesis. Although neighbouring trees may invade each other's space unequally, the errors involved in assuming a symmetrical invasion are likely to be small when compared to total photosynthesis.

The boundary between crowns is considered to be sharp, such that a branch stops growing as soon as it touches a neighbouring crown. This not only simulates the lateral spread of the crown, but can also be used to calculate the height of the lowest living branches in each direction.

3.3.2 *Foliage area*

The leaf area (A_f) of each tree is calculated from the foliage weight, (W_f), and the specific leaf area (σ_f), with appropriate conversions from dry weight to carbon (Y=kg DW kg C^{-1}).

$$A_f = W_f \ \sigma_f \ \mathrm{Y} \qquad \textbf{3.3}$$

The leaf area index, LAI, is calculated from the foliage area of the tree, and the space it occupies (projected area), C_p.

$$LAI = \frac{A_f}{C_p} \qquad \textbf{3.4}$$

The foliage weight, is not static, but dynamic, with mortality and new growth (i.e. integration occurs denoted by the prime, ‘):

$$W_f' = N_f - L_f \qquad \textbf{3.5}$$

where L_f is the foliage lost , based on an annual turnover proportion (γ_f):

$$L_f = \gamma_f \ W_f \qquad \textbf{3.6}$$

and N_f is the new foliage based on the allocation (η_f) and net carbon income, A_{net} (net assimilation = gross assimilation less total respiration of all living tissues of the tree; units: kg C).

$$N_f = \eta_f A_{\mathrm{net}} \qquad \textbf{3.7}$$

3.3.3 *Woody Compartments*

Calculations of the state of the woody tissues, follow the same pattern as for foliage mass, such that:

$$W_j' = [\eta_j \ A_{\mathrm{net}}] - [\gamma_j \ W_j] \qquad \textbf{3.8}$$

with *j* representing notation for branches, stem sapwood, branches, fine and coarse roots.

A similar approach is used to calculate heartwood in the stem, with new heartwood, N_h, equal to the mortality of stem sapwood (i.e. $N_h = \gamma_s \ W_s$). Heartwood may be lost in the same way, with a turnover parameter γ_h, although in practice this is usually zero. Note that in considering branches, branch heartwood and branches that are physically lost to the tree are not distinguished.

3.3.4 *Pipes and the Pipe-model theory*

It is not sufficient to simply know the change in mass of a compartment; the basic premise of the pipe-model is that the amount of new foliage is proportional to the cross-sectional area of the main woody compartments. In general there are two interpretations of the pipe-model theory (Shinozaki et *al.* 1964): One interpretation assumes a constant ratio between active sapwood cross-sectional area and total foliage biomass (Valentine, 1985; Mäkelä, 1986). Supporting evidence from this comes from Nikinmaa (1992) but conflicting evidence comes from Margolis et *al*. (1995). The alternative approach uses the ratio of new foliage to new sapwood (McWilliam, 1972, reviewed by Ludlow and Atkinson, 1996). Again, there is conflicting evidence to this approach (Margolis et *al*., 1995). The approach adopted in GROMIT follows the second interpretation.

The area of new sapwood in the compartments of stem sapwood, branches and coarse roots is given by

$$A_s = \frac{N_s \text{ Y}}{\rho_s \ H_s}, \qquad A_b = \frac{N_b \text{ Y}}{\rho_b \ H_b}, \qquad \text{and} \qquad A_t = \frac{N_t \text{ Y}}{\rho_t \ H_t} \tag{3.9}$$

where, N_j is the new sapwood in stem-wood, branches and transport roots, ρ_j is the respective density of the sapwood in each compartment and H_j, the mean pipe length in each compartment.

The mean pipe length is calculated as:

$$H_s = H - (1 - P_{\text{cd}}) \ C_{\text{d}} \tag{3.10}$$

where H, the is tree height, C_{d} crown depth, and P_{cd} a parameter which represents the proportion of the crown depth at which the mean height of the foliage occurs (above crown base). The pipes within the stem are assumed to extend from crown base to ground level, and form a cone within the crown. In the case of a conical crown, where foliage is distributed evenly over the crown surface, $P_{\text{cd}} = 1/3$. However since foliage is generally sparser in the lower crown and more abundant in the upper crown, this represents a minimum value.

In the case of the pipes in the branches, it is assumed that the mean pipe length is proportional to the crown radius (C_{r}) defined by a parameter, β_b:

$$H_b = C_{\text{r}} \ \beta_b \tag{3.11}$$

If $P_{\text{cd}} = 1/3$, the foliage is evenly distributed over a cone, and the branches are perpendicular to the vertical pipes within the stem, then $\beta_b = 2/3$.

Transport roots are treated in a similar way, with the mean pipe-length proportional to the crown radius, by means of parameter, β_t

3.3.5 *Height, Diameter and Volume*

Height. Height is clearly a state variable, which is dependent on time. It is assumed that new foliage is spread over existing foliage in a uniform way. The increase in height is therefore dependent on the amount of new foliage to be added and the area over which this is spread. The depth of the new layer is defined as (volume occupied by new foliage)/(projected-crown area). Thus:

$$H' = \frac{\nu_f \text{ Y } N_f}{C_{\text{p}}} \tag{3.12}$$

where the volume occupied by new foliage is determined from the weight of new foliage and the parameter, ν_f, which gives the volume (m^3) occupied by 1 kg (DW) of new foliage. In most circumstances, ν_f remains constant, although it is not difficult to make it a functional value, which can change with time; the difficulty is determining the form of the function.

Diameter. Diameter is a state variable, and its rate of change is related to the area of new sapwood that is added. The diameter is calculated at several points, as diameter at various heights helps in determining the volume. The first point at which diameter is considered is at ground level, and it is assumed that there is no butt-swell. New sapwood is added around the existing stem, such that the increment in diameter is dependent on the size of the tree itself:

$$D_0' = \frac{2A_s}{\pi \ D_0} \tag{3.13}$$

Diameters at other heights are calculated in a similar way; until the height is reached, diameter must be zero, above that height, diameter is incremented in the same was as described in equation 3.13. A special case is required when a diameter is attained for the first time. If the critical height falls

within the crown, then account is taken of the taper. For example, at each time-step for diameter at breast height (dbh):

$$D_{\text{bh}}' = \left\{ \begin{array}{ll} 0.0, & H < 1.3 \\ \sqrt{\dfrac{4A_s}{\pi}}, & H \geq 1.3, \quad \text{and} \quad D_{\text{bh}} = 0 \\ \sqrt{\dfrac{2A_s}{\pi\, D_{\text{bh}}}} & H \geq 1.3, \quad \text{and} \quad D_{\text{bh}} \geq 0 \end{array} \right\} \qquad \textbf{3.14}$$

Diameter is calculated at regular intervals up the bole of the tree; namely at ground level, 1.3m, 3.0m, 6.0m, 9.0m etc., likewise the diameter at the crown base (at whatever height that may be) is calculated.

Volumes. Forestry Commission yield tables (Edwards and Christie, 1981) use a cut-off diameter of 7 cm for useful volumes. Each 3 m section of the bole is assumed to be a frustrum in shape, thus account is taken of the different diameters at each end of the section, likewise, the occurrence of taper from the crown base, and the possibility of 'incomplete' section heights. If absolute volume estimates are required, then the masses of stem sapwood and heartwood may be added – giving an overall carbon mass of the stem, which can easily be converted to volume with use of the density parameter, ρ_s.

3.3.6 *Allocation*

If growth is to follow the pipe-model, then there must be a balance of allocation between the living compartments of each tree. Allocation to fine-roots is fixed, whilst allocation to the other compartments is allowed to vary within the convention of the pipe-model. In practice, this means that simultaneous equations are derived in the model, and the program solves these at each time-step. The following derivation does not account for 'growth respiration'. It is assumed that the respiration rates when calculated included this factor – it is not possible to distinguish between the two types of respiration in experimental procedures.

If new sapwood is proportional to new foliage then

$$A_s = k_s\ N_f \qquad \textbf{3.15}$$

where A_s is the area of new sapwood ($m^2\ yr^{-1}$), N_f the dry weight of new foliage (kg C yr^{-1}) and K_s is a constant ($m^2\ kg^{-1}$). K_s is not the ratio of sapwood/foliage that is usually measured in the field (Whitehead, 1978; Waring et *al.*, 1982), which is the total sapwood to total foliage ratio. To ascertain K_s account must be taken of the different mortality rates of sapwood and foliage. Foliage mortality is a proportion (γ_f), a value that is readily measured in the field. A similar assumption applies to the conversion of sapwood to heartwood. If mortality is uniform, then the survival is the reciprocal, i.e. the expected life of foliage is $1/\gamma_f$. If foliage and sapwood production is relatively constant (i.e. stable), then equilibrium may be achieved, thus

$$N_f = W_f\ \gamma_f \qquad \text{and} \qquad A_s = S_a\ \gamma_s \qquad \textbf{3.16}$$

where N_f and W_f are the new foliage and total foliage respectively. A_s and S_a represent the new sapwood and total sapwood area, with γ_f and γ_s the morality rates. If the relationship between N_f and A_s is preserved, from equation 3.16, then

$$\frac{N_f}{A_s} = \frac{W_f\ \gamma_f}{S_a\ \gamma_s} \qquad \textbf{3.17}$$

Thus, the model tends towards an equilibrium ratio, ϕ_s, of total foliage weight to total sapwood area (the value measured in the field and reported in the literature e.g. Whitehead, 1978; Waring *et al*., 1982).

Substituting ϕ_s for W_f / S_a, and re-arranging the previous equation, A_s is expressed as:

$$A_s = \frac{N_f \ \gamma_s}{\phi_s \ \gamma_f} \qquad \textbf{3.18}$$

The additional sapwood can be expressed as volume (pipe length × area), using equation 3.9, although the model requires sapwood weight as an intermediate, which is obtained from equations 3.9 and 3.18, and thus new sapwood (N_s) is expressed as

$$N_s = \frac{N_f \ H_s \ \gamma_s \ \rho_s}{\phi_s \ \gamma_f \ \mathrm{Y}} \qquad \textbf{3.19}$$

similarly for branches,

$$N_b = \frac{N_f \ H_b \ \gamma_b \ \rho_b}{\phi_b \ \gamma_f \ \mathrm{Y}} \qquad \textbf{3.20}$$

and for transport roots

$$N_t = \frac{N_f \ H_t \ \gamma_t \ \rho_t}{\phi_t \ \gamma_f \ \mathrm{Y}} \qquad \textbf{3.21}$$

Equations 3.19-3.21 give the quantity of carbon required in each of the compartments for a given amount of new foliage, and the current size of the tree (pipe length). This is converted to a proportion, η_j, that is the allocation proportion to each compartment. In practice,

$$N_s = \eta_s \ \mathrm{A}_{\mathrm{net}} \qquad \textbf{3.22}$$

where A_{net} is the net assimilation of the tree (kg C).

For sapwood,

$$\eta_s \ \mathrm{A}_{\mathrm{net}} = \frac{N_f \ H_s \ \gamma_s \ \rho_s}{\phi_s \ \gamma_f \ \mathrm{Y}} \qquad \textbf{3.23}$$

and with substitution of $N_f = \eta_f \mathrm{A}_{\mathrm{net}}$, the function becomes

$$\eta_s \ \mathrm{A}_{\mathrm{net}} = \frac{(\eta_f \ \mathrm{A}_{\mathrm{net}}) \ H_s \ \gamma_s \ \rho_s}{\phi_s \ \gamma_f \ \mathrm{Y}} \qquad \textbf{3.24}$$

thus,

$$\eta_s = \frac{\eta_f \ H_s \ \gamma_s \ \rho_s}{\phi_s \ \gamma_f \ \mathrm{Y}} \qquad \textbf{3.25}$$

Similarily, η_b and η_t can be found. Since the allocation coefficients must sum to unity and η_r is constant, substitution results in

$$x_s = \frac{H_s \ \gamma_s \ \rho_s}{\phi \ \gamma_f \ \mathrm{Y}}, \qquad \text{then} \qquad \eta_s = \eta_f \ x_s \qquad \textbf{3.26}$$

and if the same procedure is carried out for the analagous χ_b and χ_t, the following is arrived at

$$1-\eta_r = \eta_f + \eta_f\ x_s + \eta_f\ x_b + \eta_f\ x_t \qquad \textbf{3.27}$$

which leads to the solution of η_f:

$$\eta_f = \frac{1-\eta_r}{1+x_s+x_b+x_t} \qquad \textbf{3.28}$$

3.3.7 *Carbon assimilation and Respiration*

In previous sections A_{net}, the net carbon income has been referred to. The assimilation model described in section 2 develops a function relating gross assimilation of CO_2 to leaf area index. Within the growth module, these values are accessed through a look-up table, with indices of LAI and year. The values returned are expressed on a ground area basis, such that the gross assimilation per tree in carbon is given by

$$A_g = \frac{f_a(\mathrm{Yr}, \mathrm{LAI})\ C_\mathrm{p}\ 12}{44} \qquad \textbf{3.29}$$

where f_a (Yr, LAI) is the look-up function returning gross CO_2 uptake in kg m^2 (ground area) yr^{-1}, in year, 'Yr' and a with leaf area index, LAI. C_p is the projected area of the crown. The atomic weights of carbon and carbon dioxide (12 and 44, respectively) covert the units of A_g to kg C $tree^{-1}$.

Respiration is calculated on a mass per unit mass basis for each of the living tissue compartments, j, by the assimilation module. This value is referenced through a look-up function:

$$R_j = f_r(\mathrm{Yr}, \mathrm{C_{id}})\ W_j\ \kappa_j \qquad \textbf{3.30}$$

with f_r(Yr, C_{id}) the look-up function accessed with the year (Yr) and compartment identity (C_{id}), multiplied by , W_j, the mass (kg C) of the relevant compartment. k_j is a compartment specific scalar. If all tissue is actively respiring the scalar will assume a value of 1.0, but if this is not the case then it will take on a value <1.0. For example, sapwood may live for 12 years, but it is possible that only the last 4 years of sapwood is actively respiring, with the remainder contributing little to sapwood respiration.

Net assimilation is gross assimilation minus the total respiration of the living tissues in all of the compartments:

$$A_\mathrm{net} = A_g - \sum_{j=s,b,t,r} R_j \qquad \textbf{3.31}$$

3.3.8 *Stand Management and mortality*

The mortality (turnover rates) of the various compartments has been discussed in earlier sections and are based on constant proportions (γ_j) of the living tissue in a compartment.

The need for initial X-Y co-ordinates has been discussed earlier, and simulated management refers to these co-ordinates. There is no tree mortality in the model, and the the stand is either thinned or unthinned. In the case of an unthinned stand, the input required is the number of trees per hectare at various ages. This is accessed through a look-up function. In the model, the average spacing per tree is calculated, and the initial X-Y co-ordinates changed to account for an evenly distributed increase in space available. The function uses linear interpolation between years when data is given, thus to avoid continuous mortality/thinning, tree numbers must be held constant for the years between thinnings.

A feature of the simulation package is that it permits 'runs' to be stopped and started again (initialised in the set-up), which therefore allows some user specification. For example, a run may

be set for 20 years, stopped, a function applied, then the run continued for another 20 years. In this way it would be possible to manually select trees that are to be thinned.

3.4 *DARE-P Table function*

Reference has been made to this function during the description of the model. The table function is initialised by use of the $T*n* procedure, where *n* represents the relevant table number. The next line gives the function name, and the number of rows and columns of the table. The header lines (row and column) are not included in the number of rows and columns. Commas are used as separators. For example a call to the function 'assimfun' where assimfun is f_a(Yr, LAI), (equation 3.29), using the values in Table 3. 1, would be **ASSIMFUN(4.0, 5.5)** and would yield**:**

$$4.15 + (4.29 - 4.15) \times 0.5 = 4.22.$$

```
 $T1
Assimfun,  10, 8
      0.0,  1.0,   2.0,   3.0,   4.0,   5.0,   6.0,   7.0
1.0,  0.0,                                              4.22
              1.64   2.76   3.78   4.00   4.13   4.21
              ,      ,      ,      ,      ,      ,
2.0,  0.0,                                              3.84
              1.53   2.62   3.59   3.78   3.85   3.90
              ,      ,      ,      ,      ,      ,
3.0,  0.0,                                              4.14
              1.65   2.77   3.43   4.01   4.14   4.21
              ,      ,      ,      ,      ,      ,
4.0,  0.0,                                              4.37
              1.69   2.85   3.53   3.92   4.15   4.29
              ,      ,      ,      ,      ,      ,
5.0,  0.0,                                              4.22
              1.58   2.75   3.49   3.92   4.06   4.15
              ,      ,      ,      ,      ,      ,
6.0,  0.0,                                              3.82
              1.46   2.58   3.38   3.75   3.85   3.91
              ,      ,      ,      ,      ,      ,
7.0,  0.0,                                              4.15
              1.56   2.68   3.54   3.88   4.01   4.13
              ,      ,      ,      ,      ,      ,
8.0,  0.0,                                              3.74
              1.42   2.54   3.39   3.68   3.79   3.82
              ,      ,      ,      ,      ,      ,
9.0,  0.0,                                              4.20
              1.63   2.72   3.75   4.03   4.12   4.19
              ,      ,      ,      ,      ,      ,
      0.0,                                              4.19
10.0          1.58   2.78   3.54   3.92   4.07   4.15
,             ,      ,      ,      ,      ,      ,
```

Table 3. 1 Example of a table function. In this case, leaf area index increases for 0 to 7 (left to right), for each of 10 years, linear interpolation is used between rows/columns.

3.5 *Initial conditions and parameters*

In this description, some parameters are described as fixed over time (e.g. allocation of carbon to fine roots, allocation of foliage in space, mortality etc.). These values can easily be substituted for functions, which change over the life of the crop, for example, with age or with the state of the trees.

The initial state (conditions) must me given for all of the variables and parameters, otherwise a value of zero is assumed. Thus, in addition to setting all parameters, initial values of height, root collar diameter, foliage weight, stem sapwood weight must be given. Parameters and state values may be initialised in the model (initial conditions section), and any parameters and variables which are not set at this stage will be initialised from the input file, or will be assumed to be zero. There is no REPEAT/ENDREPEAT facility in the 'initial conditions' section, and so any tree-specific values set there must be declared in full.

Variables and parameters, which must be initialised within the model, include the system variables, which set the duration of the simulation (TMAX) and the number of reporting points for outputs (NPOINT). If NPOINT is set to TMAX+1, this gives 'annual' results if the time-step is set to one year.

In the case of the initial conditions, it is unlikely that the values assigned to each tree will be in equilibrium with each other (e.g. foliage weight, sapwood area, diameters etc.). This results in the model attaining functional-balance for the first few years of the simulation, in addition to providing growth simulations.

Setting every tree to have individual values for all variables is potentially a large task; to this end, a normal distribution methodology has been devised. This method is initialised in the input file, and operates from input values of a mean and standard deviation. Initial state values (and parameters if appropriate) for each tree are calculated and assigned at random to each tree. The random assigning is independent of any previous distribution; i.e., a tree with the smallest height is not necessarily the tree with the smallest weight of foliage. The independent nature of such an assigning has obvious advantages and drawbacks; A tree that is smaller than the rest at the outset is likely to have both a smaller height, diameters, less foliage etc. i.e. there is likely to be correlation between these values. Conversely, if trees are initialised at a relatively uniform, but small size (which is recommended), then a random allocation of such characteristics may be more appropriate. In addition, some parameters may be initialised in this way, and again, a random distribution may be appropriate – the parameters having an influence subsequently on the actual growth of the trees (e.g. variation in allocation to roots).

The initial physical X-Y co-ordinates of each tree are set through a further input file.

3.6 *Outputs*

The values of every variable are stored in a binary file, which is created during the execution of the simulation. A 'post processor' program that is executed after the simulation has completed reads this binary file. Selection of the outputs uses a file ('outlst.dat'), which is picked up by the 'post processor'. This 'outlst.dat' file is created when the model is translated into FORTRAN code, and uses the list provided in the output section of the model. The main facilities offered by the output routines are listing and graphing of the variables. However, the graphing is limited to character-based resolution, and so listing is the most commonly used function – this creates a ASCII data file which can be read into most graphical and data analysis software.

Typical listing may be:

```
LIST H01, H02, DBH01, DBH02
```

This would produce an output file of time, height of tree 1, height of tree2, DBH of tree 1, DBH of tree2.

Values of all the initial conditions set through the input file, including the random allocation of normal distributions are listed in an output file, 'initial.conds'.

References

Baldocchi, D.D., Hicks, B.B. and Camara, P., (1987). A canopy stomatal resistance model for gaseous deposition to vegetated surfaces. *Atmospheric Environment*., 21:91-101.

Broadmeadow, M.S.J., Heath, J. and Randle, T.J., (1999). Environmental limitations to O_3 uptake – some key results from young trees growing at elevated CO_2 concentrations. *Water, Air, and Soil Pollution*., 116:299-310.

Cannell, M.G.R. and Smith, R.I., (1983). Thermal time, chill days and prediction of budburst in *Picea sitchensis*. *Journal of applied Ecology*., 20:951-963.

Carnahan, B., Luther, H.A. and Wilkes, J.O., (1969). *Applied numerical methods*. John Wiley and Sons, New York.

Collares-Pereira, M. and Rabl, A., (1979). The average distribution of solar radiation - correlations between diffuse and hemispherical and between daily and hourly insolation values. *Solar Energy.*, 22:155-164.

Chabot,B.F. and Hicks, D.J., (1982). The ecology of leaf life spans. *Annual Review of Ecological Systems.*, 11:233-260.

De Jong, J.B.R.M., (1980). Een karakterisering van de zonnestraling in Nederland. Doctoraalverslag Vakgroep Fysische Aspecten van de Gebouwde Omgeving afd. Bouwkunde en Vakgroep Warmte- en Stromingstechnieken afd. Werktuigbouwkunde, Technische Hogeschool (Techn. Univ.), Eindhoven, Netherlands, 97+67pp.

Edwards, P.N. and Christie, J.M., (1981). Yield models for forest management. *Forestry Commission booklet*, 48. Forestry Commission, Edinburgh.

Erbs, D.G. Kelin, S.A. and Duffie, J.A. (1982). Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy*., 28:293-302.

Farquhar, G.D. and von Caemmerer, S., (1982). Modelling of photosynthetic response to environmental conditions. In, *Physiological Plant Ecology II. Water Relations and Carbon Assimilation*, 12B:550-587; eds, O.L. Lange, C.B. Osmond and H. Ziegler. Springer-Verlag, Berlin.

Hänninen, H., (1990). Modelling bud dormancy release in trees from cool and temperate regions. *Acta Forestalia Fennica*., 213:47pp.

Jarvis, P.G., (1976) The interpretation of leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society of London, Series B*. 273:593-690

Jarvis, P.G., James, G.B. and Landsberg, J.J., (1976). Case Study 6: Coniferous Forest. In, *Vegetation and the Atmosphere* (Volume 2), 170-240; ed, J.L. Montieth. Academic Press, London.

Kikuzwa, K., (1991). A cost-benefit analysis of leaf habit and leaf longevity of trees and their geographical pattern. *American Naturalist*., 138:1250-1263.

Kikuzwa, K., (1995). Leaf phenology as an optimal strategy for carbon gain in plants. *Canadian Journal of Botany*., 73:158-163.

Koski, V. and Sievänen, R., (1985). Timing of growth cessation in relation to the variation of the growing season. In, *Crop Physiology of Forest Trees*, 167-193; eds, P.M.A. Tigerstedt, P. Puttonen and V. Koski. University of Helsinki, University Press.

Kramer, K., 1994. Selecting a model to predict the onset of growth of *Fagus sylvatica*. *Journal of Applied Ecology*. 31:172-181.

Lucas, J.J., (1974). DARE-P, a portable digital simulation. M.S. Thesis (Computer Science), University of Arizona.

Ludlow, A.R. and Atkinson, E., (1996). How will climate change affect the way trees allocate carbon to root and shoot? *Working Paper*, WP16, *for Long-term effects of CO_2 increase and climate change on European forests (LTEEF).* Commission of the European Communities, DG XII, Brussels.

Ludlow, A.R., Randle, T.J. and Grace, J.C., (1990). Developing a processed-based growth model for Sitka spruce. In, *Process modeling of forest growth responses to environmental stress*, 249-262; eds, R. Dixon, R. Meldahl, G. Ruark and W. Warren. Timber Press, Portland, Oregon, USA.

McMurtrie, R.E., Rook, D.A. and Kelliher, F.M., (1990). Modelling the yield of *Pinus radiata* on a site limited by water and nitrogen. *Forest Ecology and Management*., 30:381-413.

McWilliam, A., (1972). Some effects of the environment on the growth and development of *Picea sitchensis*. PhD thesis, University of Aberdeen.

Mäkelä, A., (1986). Implications of the pipe-model theory on dry matter partitioning and height growth in trees. *Journal of Theoretical Biology.*, 123:103-120.

Margolis, H., Oren, R., Whitehead, D. and Kaufmann, M.R., (1995). Leaf area dynamics of conifer forests. In, Ecophysiology of coniferous forests, 181-223., eds, W.K. Smith and T.M. Hinkley, Academic Press, London.

Medlyn, B.E., Broadmeadow, M.S.J., Randle, T.J., Matteucci, G., and Dufrêne, E., (1999). Model Comparison. In, *Predicted Impacts of Rising Carbon Dioxide and Temperature on Forests in Europe at Stand Scale, 97-105*; Ecocraft final report ENV4-CT95-007 DG. XII, Brussels.

Meng, F.R. and Arp, P.A., (1994). Modelling photosynthetic responses of a spruce canopy to SO_2 exposure. *Forest Ecology and Management*., 67:69-85.

Mitrukov, A.E., 1976. Seasonal growth of shoots, needles and radial increment of the stem, in stands of the Pinetum cladinosum of S. Karelia. *Lesovedenie*., 3:44-49.

Nance, W.L., Grissom, J.E. and Smith, W.R., (1988). A new competition index based on weighted and constrained are potentially available. In, *Forest Growth Modelling and Prediction*., eds, A.R. Ek, S.R. Shifley and T.E. Burke; 134-142. USDA Forest Service North Central Forest Experiment Station.

Neumann, H.H., Hartog, G.D. and Shaw, R.H., (1989). Leaf area measurements based on hemispheric photographs and leaf-litter collection in a deciduous forest during autumn leaf-fall. *Agricultural and Forest Meteorology*., 45:325-335.

Nikinmaa, E., (1992). Analyses of the growth of Scots pine: matching structure with function. *Acta Forestalia Fennica*, 235:68pp.

Pietarinen, I., Kanninen, M., Hari, P. and Kellomaki, S., (1982). A simulation model for daily growth of shoots, needles, and stem diameter in Scots pine trees. Forest Science., 28:573-581.

Randle, T.J. and Ludlow, A.R., (1998). Growth costs to plantations: modelling the cumulative effect of defoliation by *Elatobium abietinum*. In, *The Green Spruce Aphid in Western Europe: Ecology, Status, Impacts and Prospects for Management*, 32-40; eds, K. Day, G. Halldorsson, S. Harding and N. Straw. Forestry Commission Technical Paper 24, Forestry Commission, Edinburgh.

Shinozaki, K., Yoda, K., Hozumi, K. and Kira, T., (1964). A quantitative analysis of plant form – the pipe model theory. I. Basic analysis. *Japanese Journal of Ecology*., 14:97-105.

Spitters, C.J.T., (1986a). Separating the diffuse and direct component of global radiation and its implications for modelling canopy photosynthesis. Part I. Components of incoming radiation. *Agricultural and Forest Meteorology*., 38:217-229.

Spitters, C.J.T., (1986b). Separating the diffuse and direct component of global radiation and its implications for modelling canopy photosynthesis. Part II. Calculation of canopy photosynthesis. *Agricultural and Forest Meteorology*., 38:231-242.

Valentine, H., (1985). Tree Growth models: derivations employing the pipe-model theory. *Journal of theoretical biology*, 117:579-585.

von Caemmerer, S., Evans, J.R., Hudson, G.S., and Andrews, T.J., (1994). The kinetics of ribulose-1,5-biphosphate carboxylase/oxygenase in vivo inferred from measurements of photosynthesis in leaves of transgenic tobacco. *Planta*., 195:88-97.

Wait, J.V. and Clarke, D., (1978). DARE P Users' manual. (Version 4.2). Department of Electrical Engineering, University of Arizona.

Wang, Y-P. and Jarvis, P.G., (1990) Description and validation of an array model – MAESTRO. *Agricultural and Forest Meteorology*., 51:257-280.

Waring, R.H., Schroeder, P.E. and Oren, R., (1982). Application of the pipe model theory to predict canopy leaf area. *Canadian Journal of Forest Research*, 14:556-560.

Weiss, A. and Norman, J.M., (1985). Partitioning solar radiation into direct and diffuse, visible and near-infrared components. *Agricultural and Forest Meteorology*.,34:205-213.

Whitehead, D., (1978). The estimation of foliage area from sapwood basal area in Scots pine. *Forestry*, 51:35-47.