Supplementary Material

University of Virginia Forest Model Enhanced – User's Manual

The University of Virginia Forest Model Enhanced (UVAFME), written in Fortran(90), is an update and extension of the individual-based gap model FAREAST (Yan & Shugart 2005) into an object-oriented flexible structure, allowing easier model modifications and enhancements. UVAFME is an individual-based gap model that simulates the annual establishment, growth, and death of individual trees on independent patches (i.e. plots) of a landscape. An average of several hundred of these patches simulates the average biomass and species composition of a forested landscape through time. Climate is based on inputs of mean monthly precipitation and temperature, derived from the historical data record (see Section A). Soil moisture and soil nutrients are simulated based on a coupled, three-layer soil submodule using inputs on site and soil characteristics (Section B).

Individual tree growth for each year is calculated through optimal diameter increment growth, modified by available resources and species- and tree size-specific tolerances to temperature and light, moisture, and nutrient availability. Individual trees can thus compete with one other for above- and belowground resources. Light availability throughout the canopy is calculated using the Beer-Lambert Law and is dependent on the vertical distribution of LAI within the plot (Section C). Tree growth response to temperature is based on an asymptotic relationship between growth rate and annual growing degree-days. Drought response is based on an index that represents the proportion of the growing season that experiences soil moisture limitation. The final annual increment growth for each tree is determined by multiplying the smallest (i.e. most limiting) growth-limiting factor by the optimal increment growth (Section D).

Establishment of seedlings and saplings is based on species-specific resource and environmental tolerances (Section F).

UVAFME also simulates the responses to fire and windthrow disturbance, based on inputs of disturbance return interval and mean intensity (Section E.1). The occurrence of both disturbances is probabilistic, based on the site's disturbance-specific return interval. When fire occurs on a plot, the intensity of the fire as well as species- and size-specific tolerances determine which trees die from fire-related cambial damage. Windthrow is stand-replacing in UVAFME, and as such kills all trees on the plot when it occurs. When high intensity fires or windthrow occurs, there is a five-year delay on seedling and sapling establishment. Trees can also die due to age- or stress-related factors (Section E.2). Trees that die, as well as leaf litter and coarse woody debris are transferred to the soil layers.

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A. Climate

A.1. Temperature and Precipitation

Climate in UVAFME is simulated through distributions of monthly temperature and precipitation. The mean minimum and maximum monthly temperatures (in °C), as well as the standard deviations for these values, for a specific site (averaged from at least 30 years of historical climate data) are used to create the range of possible temperatures for the site in question. Mean monthly precipitation (mm) and the standard deviation of this value for each site (also from 30 years of historical data) are also used. These distributions of climate data are used to generate daily values of maximum temperature (t_{max}), minimum temperature (t_{min}), and precipitation (p) throughout the simulation. Initially, the monthly values of t_{max} and t_{min} are modified with the following equation:

$$t_m = \bar{t}_m + \bar{t}_{std}\, t_f \qquad (A.1)$$

where t_m is the monthly temperature minimum or maximum for a particular simulated month, $\bar{t}_m$ is the input average (minimum or maximum) temperature for that month, $\bar{t}_{std}$ is the input standard deviation, and t_f is a normally distributed random number (mean of 0.0 and a standard deviation of 1.0) between -1.0 and 1.0.

These monthly values are generated anew for each year of the simulation. These values can also be generated separately for each plot, depending on whether or not the user wants climate to be fixed for all plots within a site. Daily values of t_{min} and t_{max} for each year are then created through the following equation:

$$t_d = t_m + \left(\frac{t_{m+1} - t_m}{j_{m+1} - j_m}\right)(j_d - j_m) \qquad (A.2)$$

where t_d is the minimum or maximum temperature for that day, j_m is the Julian Day corresponding to the middle of that particular month, and j_d is the Julian Day corresponding to that day. The daily average temperature is then generated with the following equation (see Figure A.1 for an example):

$$t_{av_d} = \frac{t_{max_d} + t_{min_d}}{2} \quad (A.3)$$

where t_{av_d} is the daily temperature for that day, t_{max_d} is the maximum temperature for that day, and t_{min_d} is the minimum temperature for that day. In this way, for each daily time step in the simulation, a daily minimum, maximum, and average temperature are generated.

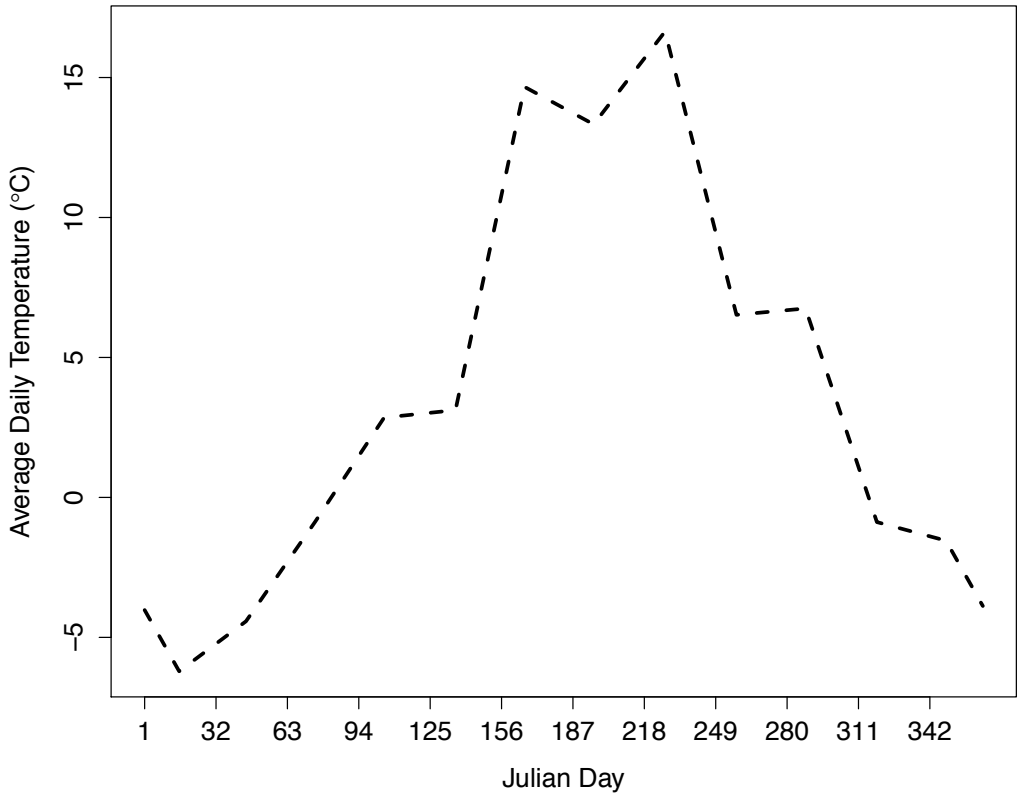

Figure A.1. Example calculation of daily average temperature (°C) for a year for a site in the Colorado Rocky Mountains.

To generate daily precipitation values, the initial monthly values of precipitation are first modified with the following equation:

$$p_m = \max(\bar{p}_m + \bar{p}_{std} p_f, 0.0) \quad \text{(A.4)}$$

where p_m is the average precipitation for a particular month (cm), $\bar{p}_m$ is the input average precipitation for that month (cm), $\bar{p}_{std}$ is the input standard deviation of that precipitation measurement, and p_f is a normally distributed random number (mean of 0.0 and standard deviation of 1.0) between -0.5 and 0.5. These monthly values are generated anew for each year of the simulation, as with the temperature values. These values can also be generated separately for each plot as with the temperature values. Daily values of precipitation for year are then generated through the following equations.

First the number of rain days for each month is generated:

$$r_m = \min(25.0, \frac{p_m}{4.0} + 1.0) \quad \text{(A.5)}$$

where r_m is the amount of rain days for that month (days). In this way, the amount of rainfall per month determines the distribution of rain for that month (Fig. A.2).

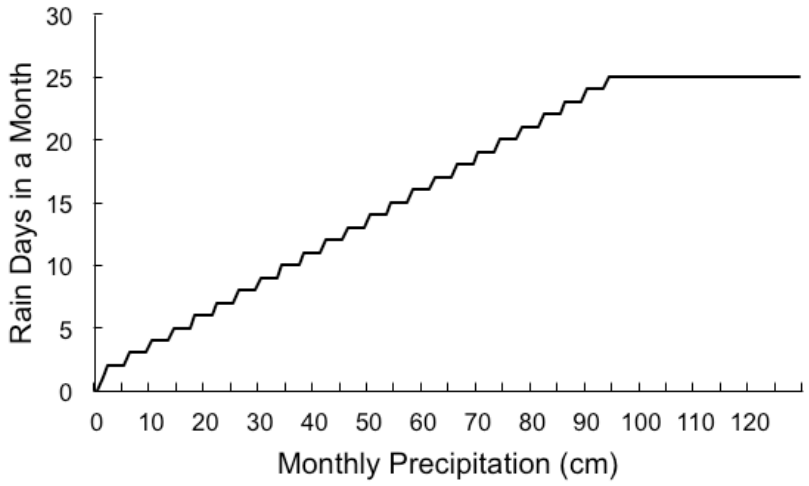

Figure A.2. Number of rain days for a month based on monthly precipitation (cm) for that month.

Then, daily precipitation values are generated through the following:

Starting from the first of each month, for each day in each month, if the number of rain days is greater than 0, (i.e. $r_m > 0$) then a uniformly distributed random number between 0.0 and 1.0 is generated (u_r). If this number is less than or equal to the percent of days in the month on which it rains (i.e. $u_r \leq \frac{r_m}{d_m}$, where r_m is the number of rain days for a particular month, and d_m is the number of days in that month), then the amount of rainfall for that day (p_d, cm) is equal to $\frac{p_m}{r_m}$. If the random number is greater than $\frac{r_m}{d_m}$, then the amount of rainfall for that day is 0.0.

The number of rain days is then subtracted by 1, and the model moves to the next day. This continues until there are no more rain days left in the month, at which point all subsequent days in the month receive no rainfall. In this way, monthly precipitation values are distributed throughout the month to generate daily precipitation values.

A.2. Extraterrestrial Radiation

Daily extraterrestrial radiation, extraterrestrial noon radiation, and day length for each day at a site are calculated based on latitude of the site and day of the year. Extraterrestrial radiation is later used to calculate potential evapotranspiration.

First, the relative distance from the Earth to the Sun for that particular day is calculated:

$$d_r = 1.0 + 0.033 \cos(0.017214 j_d) \quad \text{(A.6)}$$

where d_r is the relative distance from the Earth to the Sun, and j_d is the Julian Day of the year.

Next, the solar declination (δ_d, in radians) for that day is calculated:

$$\delta_d = 0.409 \sin(0.017214\, j_d - 1.39) \quad \text{(A.7)}$$

Finally, sunset hour angle (Ω_d, in radians) for that day is calculated through the following:

$$\omega_d = -\tan(\varphi) \tan(\delta_d) \quad \text{(A.8)}$$

where φ is latitude of the site, in radians. If ω_d is greater than or equal to 1.0, $\Omega_d = 0.0$. If ω_d is less than or equal to -1.0, $\Omega_d = \pi$. Otherwise:

$$\Omega_d = \cos^{-1}(\omega_d) \quad (A.9)$$

Extraterrestrial radiation for that day (R_d, in MJ m^{-2} d^{-1}) is then calculated (see Figure A.3 for an example):

$$R_d = 37.58603 \cos(\varphi) \cos(\delta_d)(\sin(\Omega_d) - \Omega_d \cos(\Omega_d)) \quad (A.10)$$

Day length for that day (l_d, in hrs) is calculated as (see Figure A.4 for an example):

$$l_d = 7.639437\Omega_d \quad (A.11)$$

Extraterrestrial noon radiation for that day (R_{d_n}, in MJ m^{-2} min^{-1}) is calculated as:

$$R_{d_n} = 0.082 d_r \cos(\varphi - \delta_d) \quad (A.12)$$

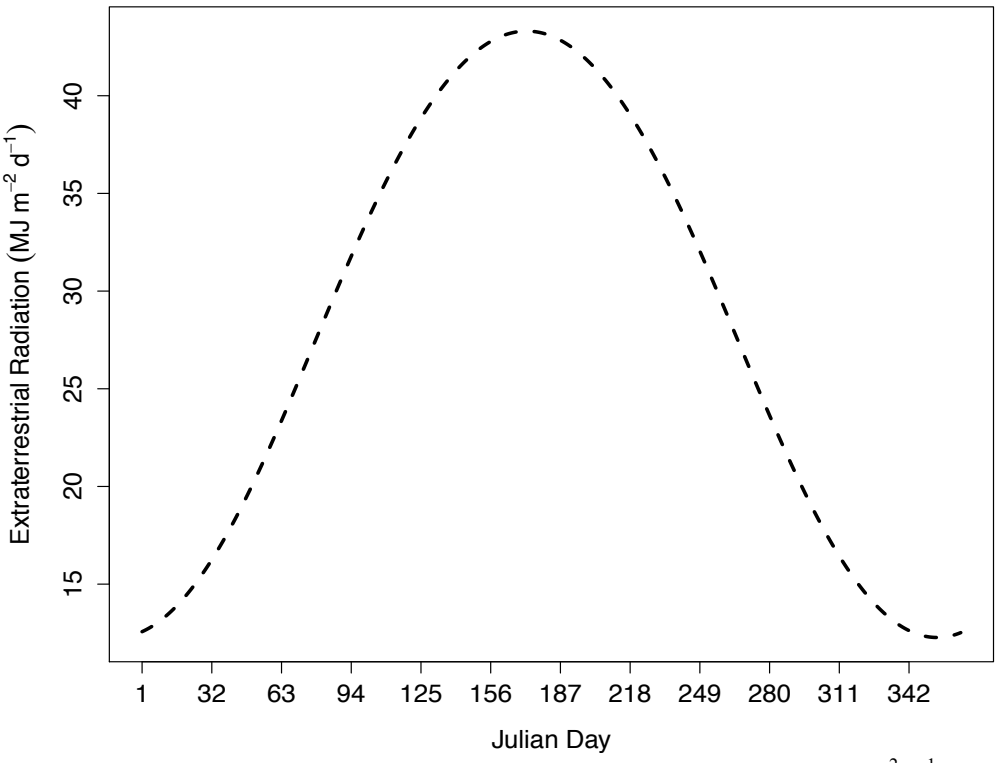

Figure A.3. Example calculation for daily extraterrestrial radiation (MJ m^{-2} d^{-1}) for the year for a site at a latitude of 40°N.

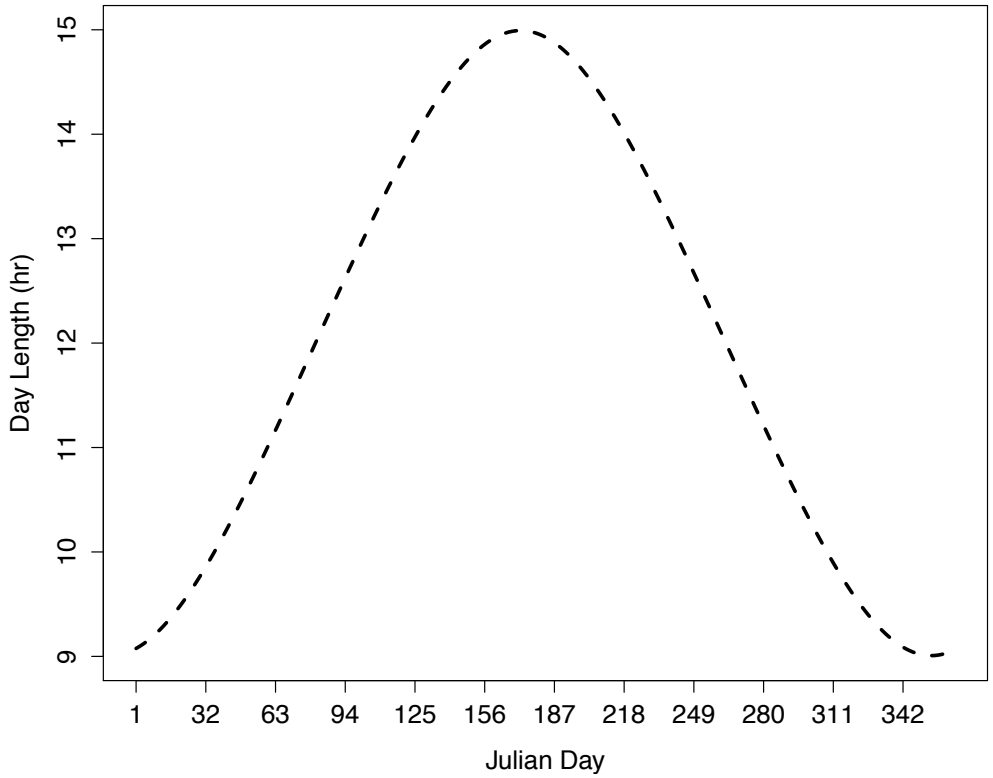

Figure A.4. Example calculation for day length (hr) for the year for a site at a latitude of 40°N.

A.3. Potential Evaporation

Daily potential evaporation is calculated using Hargreaves Evaporation Formulation, with inputs of daily minimum (t_{min_d}, °C), maximum (t_{max_d}, °C), and average temperatures (t_{av_d}, °C), and daily extraterrestrial radiation (R_d, MJ m^{-2} day^{-1}). If the average temperature for that day is less than or equal to 0.0 (i.e. $t_{av_d} \leq 0.0$), then potential evaporation (PET, cm) for that day is 0.0. Otherwise (see Figure A.5 for an example):

$$PET = 9.3876\times10^{-5}\sqrt{\left(t_{max_d} - t_{min_d}\right)}\left(t_{av_d} + 17.8\right)R_d \qquad (A.13)$$

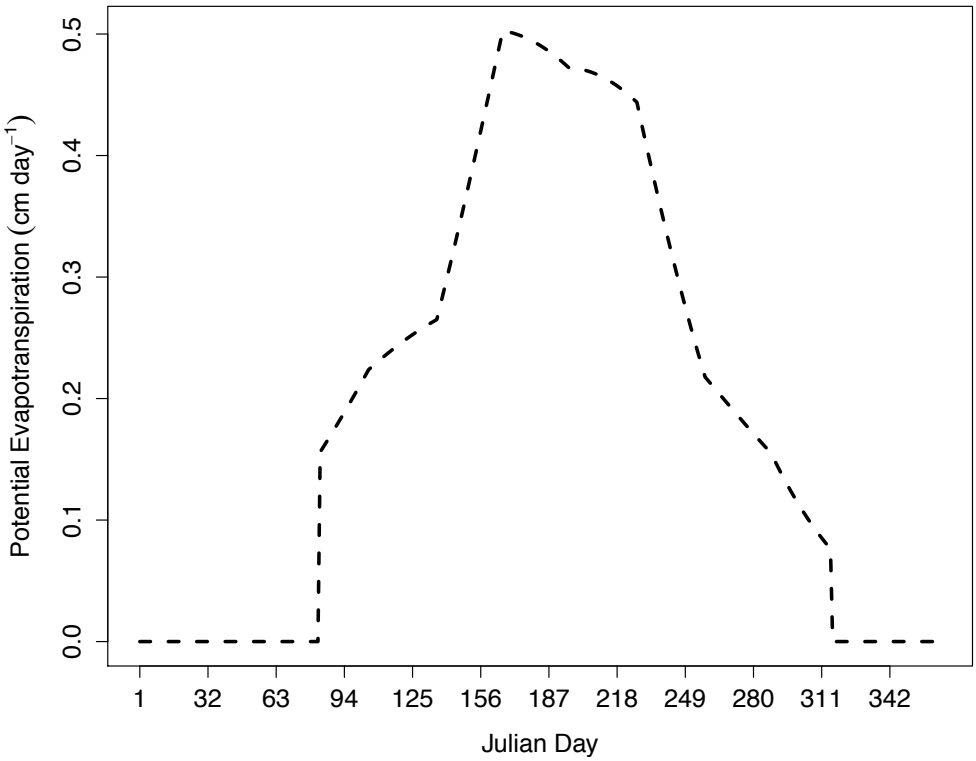

Figure A.5. Example calculation of potential evaporation (cm day^{-1}) for the year for a site in the Colorado Rocky Mountains.

A.4. Climate Change

Linear climate change can be prescribed in UVAFME. This is achieved by modifying the initial values of average minimum and maximum temperatures and precipitation for a particular site. The minimum and maximum temperatures for a site are modified through the following equations:

First the amount of temperature change per year is calculated from input values of total temperature change and duration of change:

$$t' = \frac{t_c}{y_c+1} \quad (A.14)$$

where t' is the amount of temperature change per year once climate change starts (in °C yr^{-1}), t_c is the total amount of temperature change prescribed (in °C), and y_c is the duration of climate

change (in years). When climate change starts in the model, the initial minimum and maximum temperature values are modified each year for the duration of climate change with the following equation:

$$\bar{t}_m = \bar{t}_m + t' \quad \text{(A.15)}$$

where t_m is the average (minimum or maximum) temperature for a particular month and a particular site. This continues for the duration of climate change, at which point the total change in temperature (t_c) will have occurred, and temperature stabilizes at the new value of $\bar{t}_m + t_c$. Average precipitation for a site can be modified through the following:

Again, the amount of precipitation change per year is calculated from input values of total precipitation change (in % yr^{-1}) and duration of change:

$$p' = \frac{p_c}{y_c+1} \quad \text{(A.16)}$$

where p' is the amount of precipitation change per year once climate change starts (in %), p_c is the total amount of temperature change prescribed (in %), and y_c is the duration of climate change (in years). When climate change starts, the initial monthly precipitation values are modified each year for the duration of climate change:

$$\bar{p}_m = \bar{p}_m + \bar{p}_m p' \quad \text{(A.17)}$$

where p_m is the monthly precipitation for a particular month and site (cm). This continues for the duration of climate change, at which point the total change in precipitation (p_c) will have occurred, and precipitation stabilizes at the new value of $\bar{p}_m + \bar{p}_m p_c$.

Climate change can also be generated using a GCM file as an input file. In this way, non-linear changes in temperature and precipitation can be prescribed.

A.5. Altitudinal Change

Often it is beneficial to run the model at the same site, but at a different elevation (such as in studies in complex terrain). Both temperature and precipitation change as altitude/elevation changes. These changes can be generated in UVAFME using input values of the original site elevation, the new elevation (altitude), and temperature and precipitation lapse rates. As with climate change, these changes are made to the initial average minimum and maximum monthly temperatures and precipitation for a particular site. Temperature is modified using the following equation:

$$\bar{t}_m = \bar{t}_m - 0.01(a - e)\, t_l \qquad (A.18)$$

where $\bar{t}_m$ is the average (minimum or maximum) temperature for a particular month, a is the new altitude at which the model is to be run (in meters), e is the original elevation at which the input climate data was generated (in meters), and t_l is temperature lapse rate for the site (in °C km^{-1}). Precipitation is modified using the following equation:

$$\bar{p}_m = \max\left(\bar{p}_m + 0.001 p_l(a - e), 0.0\right) \qquad (A.19)$$

where $\bar{p}_m$ is the average precipitation for a particular month and p_l is the precipitation lapse rate for the site (in cm km^{-1}).

B. Soil Processes

B.1. Soil water

Soil water balance in UVAFME is modeled as a simple bucket model with a daily time step. Outputs are aggregated over the year to influence yearly tree growth. Using this simple model allows for relatively little inputs: slope (in degrees), canopy LAI (in m m^{-1}), A_O layer dry matter content (tonnes ha^{-1}), field capacity of the soil (cm), wilting point of the soil (cm), base soil depth (cm), potential evapotranspiration (cm day^{-1}), and precipitation (cm). These inputs are

received from site input variables and from the Climate module. Variables that are derived and used in the soil water model are A_O layer water content (cm), A layer water content (cm), and base layer water content (cm). Output variables for this model include daily actual evapotranspiration (cm), and daily runoff (cm).

Precipitation (input from the Climate module) is received at the surface. This precipitation is then divided into canopy evapotranspiration, canopy interception, runoff, ground water storage, and evaporation from the soil surface.

B.1.1 If potential evaporation (PET, cm) is less than or equal to 0.0

If PET is less than or equal to 0.0 cm for that day, then precipitation is first partitioned into throughfall and canopy interception:

$$I = \min\left(\max\left((LAI_{wmax} - LAI_{w0}), 0.0\right), p\right) \quad (B.1)$$

where I is the canopy interception (cm), p is precipitation (cm), and LAI_{wmax} is the maximum canopy water content possible, defined as $0.15LAI$, where LAI is the leaf area index (m m^{-1}) of the plot. This maximum value means that each leaf or needle can contain at most a 0.15 cm film of water. Throughfall (T, cm) is then calculated as:

$$T = \max(\mathrm{p} - \mathrm{I}, 0.0) \quad (B.2)$$

The canopy water content is then updated:

$$LAI_w = \mathrm{LAI_{w0}} + I \quad (B.3)$$

where LAI_w is the updated canopy water content (cm). If the snow accumulation and snowmelt routine is being used, the model checks if the throughfall is accumulated in the snowpack. If the air temperature is less than 5°C (i.e. $t_{av_d} < 5.0$) then the throughfall is assumed to be snow and is accumulated in the snowpack ($S_P = S_P + T$). Daily thaw of the snowpack is calculated using a

simple degree-day model, using air temperature. If the air temperature is above the base temperature (t_b, generally 0°C):

$$M = \min\left(0.01 c_m \left(t_{av_d} - t_b\right), S_P\right) \quad \text{(B.4)}$$

where M is the thaw (cm) and f_m is the melt factor, based on site conditions. If the air temperature is below the base temperature, no thawing occurs. If thaw occurs, the snowpack depth is updated as $S_P = S_P - M$, and the thaw is set to the new throughfall value for further soil water modeling.

Next, throughfall (either from the canopy throughfall or indirectly through snowmelt) is partitioned into ground water storage and runoff. Slope runoff is first calculated as:

$$R_S = \left(\frac{\theta}{90.0}\right)^2 T \quad \text{(B.5)}$$

where R_S is the amount of runoff due to slope factors (cm), and θ is the slope of the site (in degrees). The water available for groundwater (GW_{avail}, cm) is then calculated as:

$$GW_{avail} = T - R_S \quad \text{(B.6)}$$

Next, the groundwater in the organic soil layer is updated and infiltration into the A layer is calculated:

$$AO_w = \min\left(AO_{w0} + GW_{avail}, AO_{wmax}\right) \quad \text{(B.7)}$$

$$OtoA = \max\left(GWavail - AO_w + AO_{w0}, 0.0\right) \quad \text{(B.8)}$$

where AO_w is the updated organic layer soil moisture storage (cm), AO_{w0} is the current organic layer soil moisture storage (cm), $OtoA$ is groundwater infiltration from the organic into the A layer (cm), and AO_{wmax} is the maximum possible organic later soil moisture, defined as the organic layer carbon content times 0.25 (i.e., $0.25AO_{C0}$). Next, groundwater in the A layer is updated and infiltration into the base layer is calculated:

$$SA_w = \min\left(SA_{w0} + OtoA, SA_{fc}\right) \quad \text{(B.9)}$$

$$AtoB = \max\left(OtoA - SA_w + SA_{w0}, 0.0\right) \quad \text{(B.10)}$$

where SA_w is the updated A layer soil moisture (cm), SA_{w0} is the current organic layer soil moisture (cm), SA_{fc} is the field capacity of the A layer (cm), and $AtoB$ is the groundwater infiltration from the A layer into the B layer (cm). The base soil layer water storage is then updated as:

$$B_w = \min\left(SB_{w0} + AtoB, SB_{wmax}\right) \quad \text{(B.11)}$$

where SB_w is the updated base soil moisture (cm), SB_{w0} is the current base soil moisture (cm), and SB_{wmax} is the maximum base soil layer moisture (cm), defined as the base soil depth times 0.6 (i.e., $0.6Z_{SB}$). Finally, groundwater runoff is calculated as whatever groundwater is left over after groundwater storage:

$$R_G = \max\left(AtoB - SB_w + SB_{w0}, 0.0\right) \quad \text{(B.12)}$$

where R_G is the groundwater runoff (cm). Total runoff is then calculated as $R = R_S + R_G$. After these calculations have been completed, the canopy water content, organic layer soil moisture, A layer soil moisture, and base layer soil moisture are updated (i.e. $LAI_{w0} = LAI_w$, $AO_{w0} = AO_w$, $SA_{w0} = SA_w$, and $SB_{w0} = SB_w$).

B.1.2 If PET is greater than 0.0

If potential evapotranspiration is greater than 0.0 cm, evapotranspiration is also considered in the simulation. First, canopy interception, throughfall, snow accumulation and snow melt, and slope runoff are calculated as above. The amount of water available for groundwater infiltration after losses to canopy interception, runoff, and potential evapotranspiration is then calculated:

$$GW_{avail} = T - R_s - PET \quad \text{(B.13)}$$

If available groundwater infiltration is greater than 0.0:

If this available soil moisture (GW_{avail}) is greater than 0.0 cm, then the water will be allocated to different soil layers in descending order (soil organic layer, soil A layer, and base soil layer) as above. As there is greater available water than atmospheric demand, actual evapotranspiration (cm) is equal to potential evapotranspiration ($AET = PET$). Groundwater runoff and total runoff are then calculated as above, and the canopy water content and soil water content of all layers are updated as above.

The figure below (Fig. B.1) shows a schematic of the situation just described. Precipitation is received at the canopy level and some of that is lost to interception. Throughfall is calculated as the amount of precipitation left over after losses to canopy interception. Then some of that water is lost to slope runoff and evapotranspiration (as there is more precipitation than PET, AET = PET), and the rest of the water infiltrates into the soil layers. Any water left over is also lost to runoff.

If available groundwater infiltration is below 0.0:

If precipitation has been depleted, or if GW_{avail} is less than or equal to 0.0, evaporatranspiration will extract water from the following layers, in order: the canopy, the organic layer, the A layer, and then the base soil layer. GW_{avail} should be negative in this scenario, and represents the atmospheric demand that needs to be extracted from the soil layer. As such, the atmospheric demand on the soil and canopy (GW_{demand}) is set equal to GW_{avail}. Next, canopy evapotranspiration is calculated as:

$$E_{LAI} = \min\left(-GW_{demand}, \max(LAI_w - LAI_{wmin}, 0.0)\right) \quad \text{(B.14)}$$

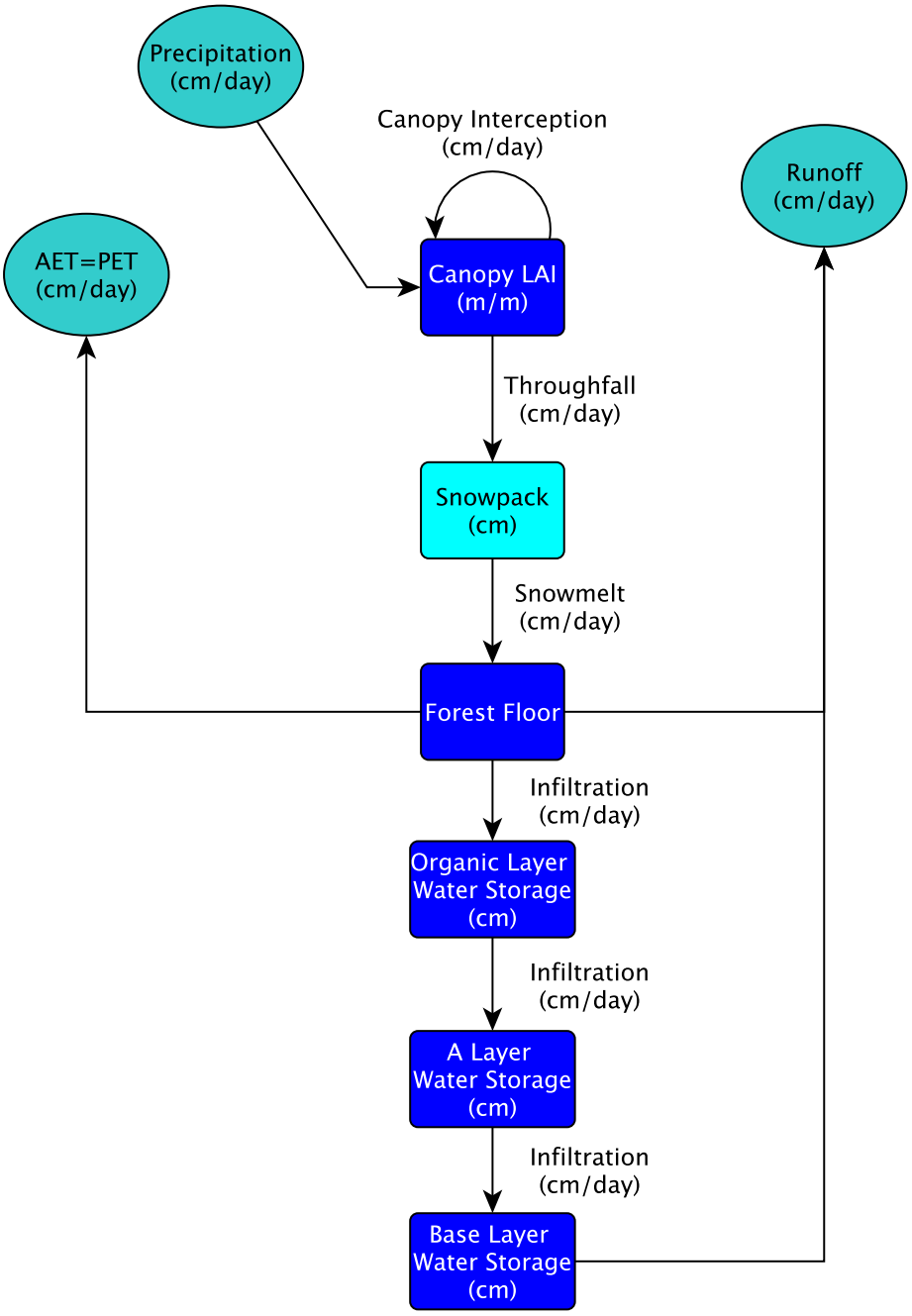

Figure B.1. Schematic of water flow in the soil moisture routine of UVAFME when there is adequate soil moisture and precipitation to meet evaporative demand.

where E_{LAI} is the canopy evapotranspiration (cm day^{-1}), LAI_w is the canopy water content (cm), and LAI_{wmin} is the minimum possible canopy water content, defined as $0.01LAI$. The canopy water content is then reduced:

$$LAI_w = LAI_w - E_{LAI} \quad (B.15)$$

Next, actual evapotranspiration is updated as:

$$AET = AET + E_{LAI} \quad (B.16)$$

The atmospheric demand on the organic layer (AO_{demand}, cm) is then calculated as:

$$AO_{demand} = \min\left(GW_{demand} + E_{LAI}, 0.0\right) \quad (B.17)$$

This water is then extracted from the AO layer and AET is updated:

$$E_{AO} = \min(-AO_{demand}, max(AO_{w0} - AO_{wmin}, 0.0)) \quad (B.18)$$

$$AET = AET + E_{AO} \quad (B.19)$$

where E_{AO} is the evaporation from the organic layer (cm day^{-1}), AO_{w0} is the current organic layer soil moisture (cm), and AO_{wmin} is the minimum possible soil moisture for the organic layer, calculated as the organic layer carbon content times 0.025 (i.e. $0.025AO_{C0}$). The evaporated water is extracted from the organic layer:

$$AO_{w0} = AO_{w0} - E_{AO} \quad (B.20)$$

The atmospheric demand on the A layer (A_{demand}, cm) is then calculated:

$$A_{demand} = \min\left(AO_{demand} + E_{AO}, 0.0\right) \quad (B.21)$$

The amount to be extracted from the soil A layer is then calculated as:

$$E_{SA} = \min\left(-A_{demand}, \max\left(SA_{w0} - SA_{wp}, 0.0\right)\right) \quad (B.22)$$

where E_{SA} is evaporation from the A layer (cm day^{-1}), SA_{w0} is the current A layer soil moisture (cm), and SA_{wp} is the wilting point of the A layer (cm). Actual evapotranspiration is updated again:

$$AET = AET + E_{SA} \quad (B.23)$$

Then the A layer soil moisture is updated:

$$SA_{w0} = SA_{w0} - E_{SA} \quad (B.24)$$

The atmospheric demand on the base layer (B_{demand}, cm) is calculated:

$$B_{demand} = \min\left(A_{demand} + E_{SA}, 0.0\right) \quad (B.25)$$

The amount of water extracted from the base soil layer is then calculated as:

$$E_{SB} = \min\left(-B_{demand}, \max(SB_{w0} - SB_{wmin}, 0.0)\right) \quad (B.26)$$

where E_{SB} is the evaporation from the base soil layer (cm day^{-1}), SB_{w0} is the current base soil layer water content (cm), and SB_{wmin} is the minimum possible base soil layer water content (cm), defined as the base soil height times 0.1 (i.e. $0.1Z_{SB}$). Finally, the base layer soil moisture and AET are updated:

$$SB_{w0} = SB_{w0} - E_{SB} \quad (B.27)$$

$$AET = AET + E_{SB} \quad (B.28)$$

As there is no left over soil moisture in the soil column for groundwater runoff, total plot runoff is calculated as just runoff due to slope:

$$R = R_s \quad (B.29)$$

Below is a schematic of the situation described above (Fig. B.2). Precipitation is received at the canopy level and some of that is lost to interception. Throughfall is calculated as the amount of precipitation left over after losses to canopy interception. Then some of that water is lost to slope runoff and evapotranspiration. At this point, PET is greater than the available moisture, and water is extracted from each soil layer until PET is diminished or the soil layers are depleted to their minimum moisture levels or until atmospheric demand is satisfied.

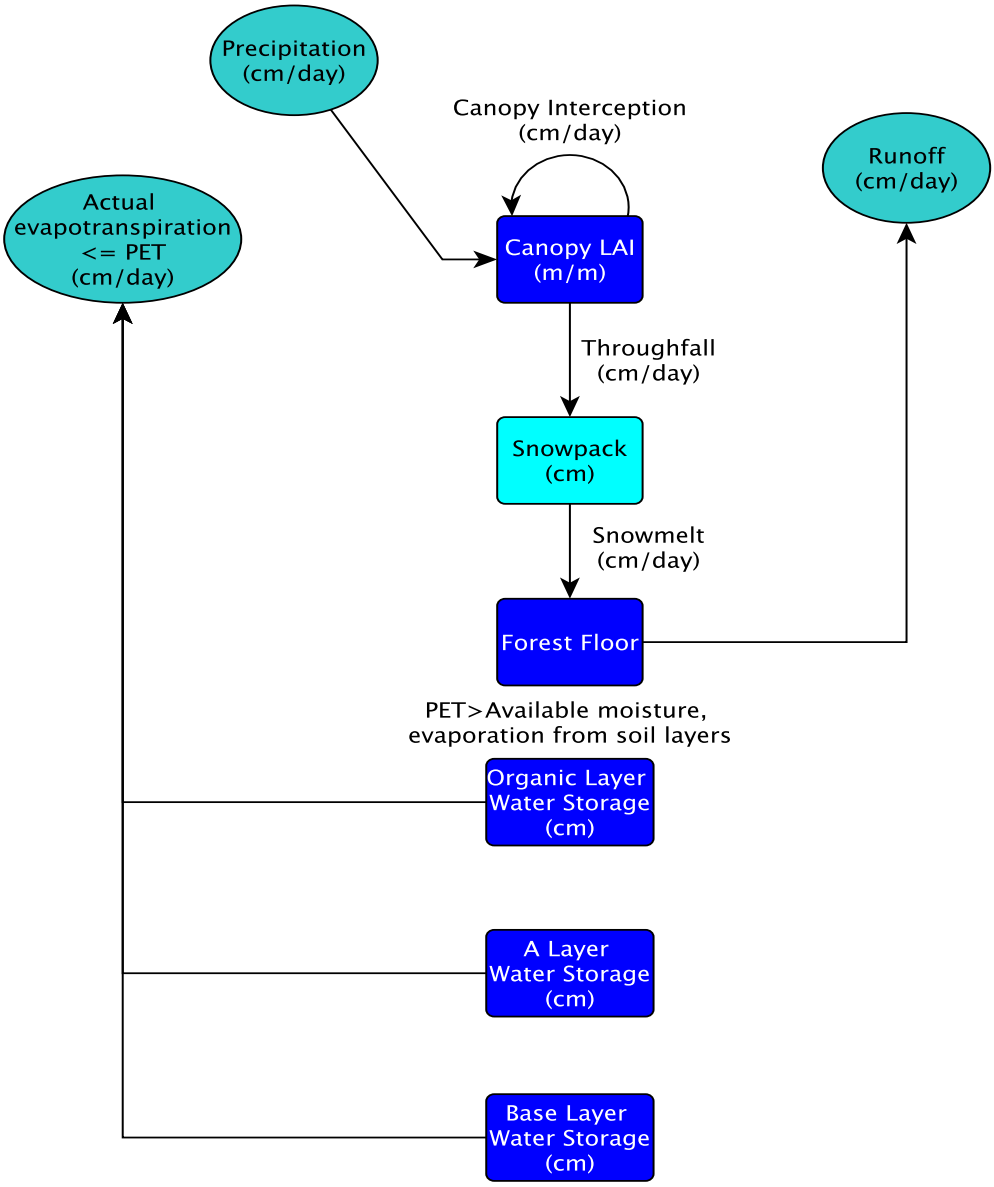

Figure B.2. Schematic of water flow in the soil moisture routine of UVAFME when there is not enough soil moisture or precipitation to meet evaporative demand.

B.2. Soil decomposition

Soil decomposition is also modeled as a three-soil layer model. Inputs for this subroutine are carbon and nitrogen content of the organic and A layers (updated from the Tree Growth and Mortality subroutine), temperature, precipitation, soil moisture (from the Soil Moisture subroutine), and other soil and site input parameters. From this subroutine, plant available nitrogen and carbon in the soil are calculated. Initially, the carbon to nitrogen ratio of the organic layer (AO_{CN}) is calculated:

$$AO_{CN} = \frac{AO_{C0}}{AO_{N0}} \quad \text{(B.30)}$$

where AO_{C0} is the organic layer carbon content (tonnes C ha^{-1}), and AO_{N0} is the organic layer nitrogen content (tonnes N ha^{-1}). Loss of carbon through respiration in the organic layer is calculated as a function of soil moisture, temperature, and current carbon content. First, the effect of soil moisture on organic layer respiration is calculated as:

$$f_{AOw} = \max\left(1.0 - \left(\frac{1.0 - RSWC_{AO}}{0.3}\right)^2, 0.2\right) \quad \text{(B.31)}$$

where $f_{AOw}$is the effect of soil moisture on respiration and $RSWC_{AO}$ is the relative soil water content of the organic layer (cm), defined as:

$$RSWC_{AO} = \min\left(\frac{AO_{w0}}{0.25}, 0.5\right) \quad \text{(B.32)}$$

where AO_{w0} is the organic layer soil moisture (cm). The effect of air temperature on soil respiration is then calculated:

$$f_{t_{AO}} \begin{cases} t_{av_d} \geq -5.0, \; f_{t_{AO}} = 3.0^{0.1\left(t_{av_d} - 1.0\right)} \\ t_{av_d} < -5.0, \; f_{t_{AO}} = 0.0 \end{cases} \quad \text{(B.33)}$$

where $f_{t_{AO}}$ is the effect of air temperature on soil respiration and t_{av_d} is the air temperature (°C). Soil respiration from the organic layer is then calculated:

$$R_{AO} = 5.24E^{-4} f_{Tao} \cdot f_{AOw} \cdot AO_{C0} \quad \text{(B.34)}$$

where R_{AO} is the soil respiration from the organic layer (tonnes C ha^{-1} day^{-1}). The constant 5.24E^{-4} is empirically derived. Next, the amount of nitrogen lost from the organic layer is calculated based on the soil respiration and the C:N ratio of the layer:

$$Nloss_{AO} = \frac{R_{AO}}{AO_{CN}} \quad (B.35)$$

where $Nloss_{AO}$ is the nitrogen loss from the organic layer (tonnes N ha^{-1} day^{-1}). The N content of the organic layer is then updated:

$$AO_{N0} = AO_{N0} - Nloss_{AO} \quad (B.36)$$

Next, the amount of carbon lost due to N immobilization is calculated based on the N loss, and an average C:N ratio for microbes:

$$Closs_{A0N} = 30.0 Nloss_{AON} \quad (B.37)$$

where $Closs_{A0N}$ is the amount of carbon lost to N immobilization. The constant 30.0 is an average C:N ratio of microbial substrate. Finally, the amount of carbon in the organic layer is updated:

$$AO_{C0} = AO_{C0} - Closs_{AON} - R_{AO} \quad (B.38)$$

At this point, the carbon balance for the organic layer is complete, and the subroutine moves on to the A layer. First, the carbon and nitrogen amounts and the C:N ratio of the A layer (SA_{CN}) are calculated:

$$SA_{C0} = SA_{C0} + Closs_{AO} \quad (B.39)$$

$$SA_{N0} = SA_{N0} + Nloss_{AO} \quad (B.40)$$

$$SA_{CN} = \frac{SA_{C0}}{SA_{N0}} \quad (B.41)$$

where SA_{C0} is the carbon content of the A layer (tonnes C ha^{-1}), and SA_{N0} is the nitrogen content of the A layer (tonnes N ha^{-1}). Next, as in the organic layer decomposition simulation, the effect of soil moisture on soil respiration in the A layer is calculated:

$$f_{SAw} = \max\left(1.0 - \left(\frac{1.0 - RSWC_{SA}}{0.8}\right)^2, 0.2\right) \quad \text{(B.42)}$$

where f_{SAw} is the effect of soil moisture on soil respiration in the A layer, and $RSWC_{SA}$ is the relative soil water content of the A layer, defined as:

$$RSWC_{SA} = SA_{w0}SA_{fc} \quad \text{(B.43)}$$

where SA_{w0} is the soil water content of the A layer, and SA_{fc} is the field capacity of the A layer. Next, the effect of air temperature on soil respiration in the A and base layers is calculated:

$$f_t \begin{cases} t_{av_d} \geq -5.0, \ f_t = 2.5^{0.1\left(t_{av_d} - 1.0\right)} \\ t_{av_d} < -5.0, \ f_t = 0.0 \end{cases} \quad \text{(B.44)}$$

where f_t is the effect of air temperature on soil respiration in the A and base soil layers. Soil respiration in the A layer is then calculated:

$$R_{SA} = 1.24E^{-5} f_t \cdot f_{SAw} \cdot SA_{CN} \quad \text{(B.45)}$$

where R_{SA} is respiration from the soil A layer (tonnes C ha^{-1} day^{-1}), and the constant 1.24x10^{-5} is an empirically derived constant. Next, the amount of carbon that will go into the B layer is calculated:

$$SB_{Cinput} = R_{SA}/20.0 \quad \text{(B.46)}$$

where SB_{Cinput} is the amount of C from the A layer traveling to the base layer, and the constant 20.0 is the average C:N ratio of the base layer. Next, the amount of nitrogen in the A layer available for plant use is calculated:

$$N_{avail} = \frac{R_A}{SA_{CN} \max\left(0.5, \frac{(SA_{CN} - 4.0)}{SA_{CN}}\right)} \quad \text{(B.47)}$$

where N_{avail} is the plant available nitrogen in the A layer. Next, C and N values for the A layer are updated:

$$SA_{C0} = SA_{C0} - R_A - SB_{Cinput} \quad \text{(B.48)}$$

$$SA_{N0} = SA_{N0} - N_{avail} \quad (B.49)$$

At this point, the soil decomposition simulation for the A layer is complete, and the subroutine moves to the final layer, the base layer. First, the amount of carbon in the base layer is updated using the input from the A layer:

$$SB_{C0} = SB_{C0} + SB_{Cinput} \quad (B.50)$$

where SB_{C0} is the carbon content of the base layer (tonnes C ha^{-1}). Next, respiration from the base layer is calculated:

$$R_{SB} = 2.74E^{-7} \cdot SB_{C0} \cdot f_t \quad (B.51)$$

where R_{SB} is soil respiration from the base layer (tonnes C ha^{-1} day^{-1}), and $2.74E^{-7}$ is an empirically derived constant. The carbon content for the base layer is then updated:

$$SB_{C0} = SB_{C0} - R_{SB} \quad (B.52)$$

Finally, the total soil respiration is calculated as the sum of respiration from all layers:

$$C_{resp} = R_{AO} + R_{SA} + R_{SB} \quad (B.53)$$

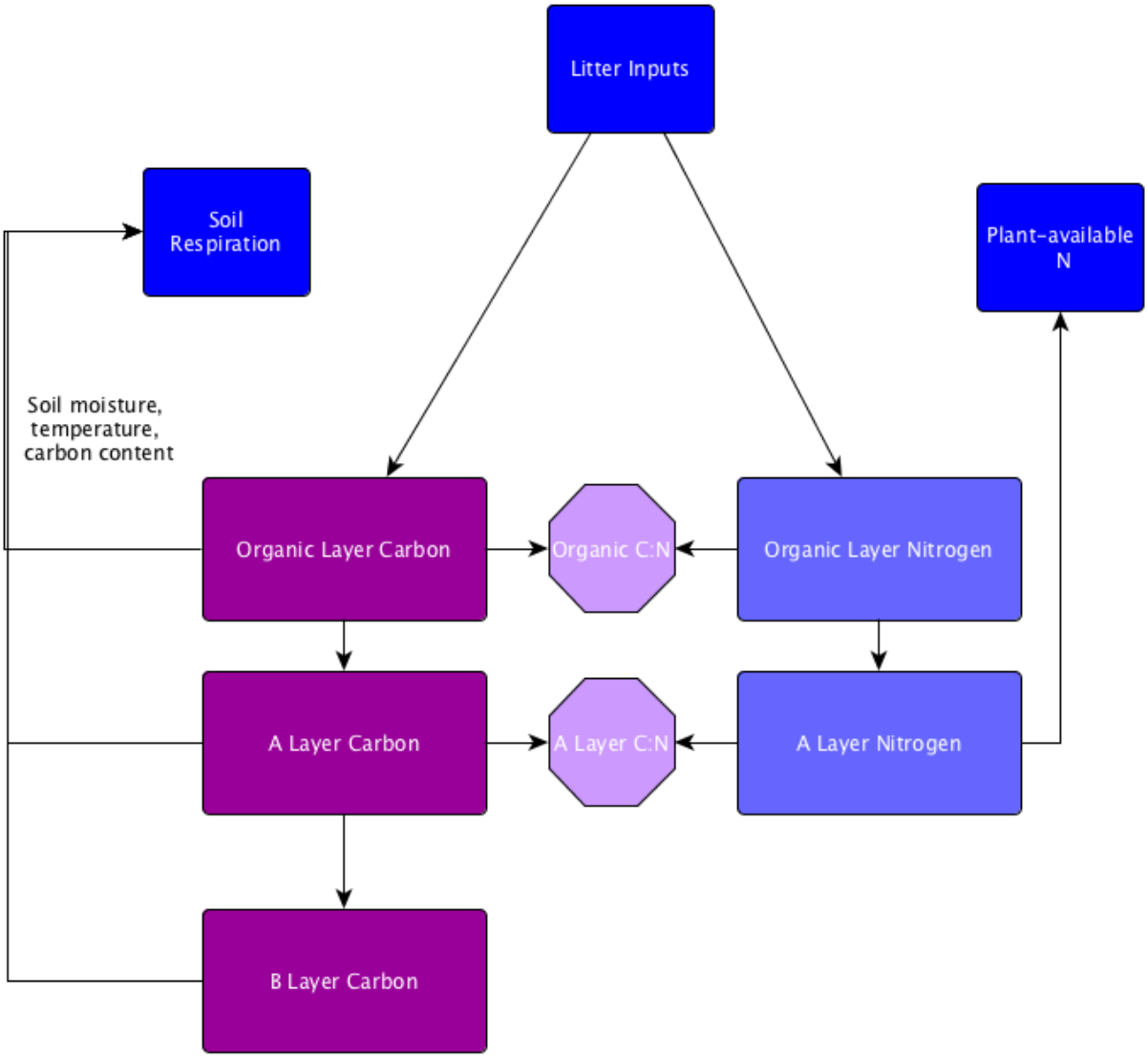

Figure B.3. Schematic of soil nutrient modeling in UVAFME.

C. Tree Canopy Processes

The canopy subroutine is used to calculate light and shading from the canopy, from both deciduous and coniferous trees. If the number of trees on the plot is equal to 0, the model sets the light levels on the plot equal to 1.0: $light_{con} = 1.0$ and $light_{dec} = 1.0$, where $light_{con}$ is an array of light availability at each layer in the canopy for coniferous trees, and $light_{dec}$ is an array of light availability at each layer in the canopy for deciduous trees. If the number of trees on the plot is greater than 0, then the subroutine uses the LAI for each tree on the plot to calculate an overall plot LAI, and then uses this LAI to determine light level at each layer in the canopy. First, the LAI of each tree on the plot is calculated:

$$LAI_{tree} = {D_{bole}}^2 D_L \quad (C.1)$$

where LAI_{tree} is the leaf area index of the individual tree (m m^{-1}), D_{bole} is the diameter of the tree at the bottom of the canopy (i.e. at clear branch bole height) (cm), and D_L is a scalar input parameter of the relationship between leaf area and squared diameter at clear branch bole height of that tree species. Additionally, each tree's LAI is summed to calculate an overall plot LAI:

$$LAI = \sum LAI_{tree} \quad (C.2)$$

Next, the canopy depth (Z_{can}) of each tree is calculated:

$$Z_{can} = \max\left(H_{tree} - H_{bole} + 1, 1\right) \quad (C.3)$$

where Z_{can} is the canopy depth (m), H_{tree} is the total height of the tree (m), and H_{bole} is the clear branch bole height (m). Next, the tree's LAI and the canopy depth are used to calculate the average LAI within a given 1 m layer of the tree's canopy:

$$LAI_{layer} = \frac{LAI_{tree}}{Z_{can}} \quad (C.4)$$

where LAI_{layer} is the LAI in any given 1 m layer of the simulated tree. If the tree in question is coniferous, then for each 1 m layer of the whole plot canopy:

$$LAI_{c1} = LAI_{c1} + LAI_{layer} \quad (C.5)$$

and

$$LAI_{c2} = LAI_{c2} + LAI_{layer} \quad (C.6)$$

where LAI_{c1} and LAI_{c2} are temporary arrays to hold LAI values for each layer in the plot-wide canopy. If the tree is deciduous:

$$LAI_{c1} = LAI_{c1} + LAI_{layer} \quad (C.7)$$

and

$$LAI_{c2} = LAI_{c2} + 0.8LAI_{layer} \quad (C.8)$$

In this way, the LAI for each 1 m layer of each tree is added to overall plot-wide LAI arrays, LAI_{c1} and LAI_{c2}. These two arrays represent overall plot LAI distributed into 1 m sections.

Next, two new arrays (LAI_{c3} and LAI_{c4}) are used to calculate the light level at each layer in the canopy. Initially, the light level at the top of the canopy (i.e. at the maximum height trees in the model are allowed to grow, typically set to 60 m) for each array is set from the previous two arrays:

$$LAI_{c3}(maxH) = LAI_{c1}(maxH) \quad (C.9)$$

and

$$LAI_{c4}(maxH) = LAI_{c2}(maxH) \quad (C.10)$$

Next, the LAI values from the first two arrays are used to calculate cumulative LAI at each layer in the canopy:

$$LAI_{c3}(maxH - ih) = LAI_{c3}(maxH - ih + 1) + LAI_{c1}(maxH - ih) \quad (C.11)$$

and

$$LAI_{c4}(maxH - ih) = LAI_{c4}(maxH - ih + 1) + LAI_{c2}(maxH - ih) \quad (C.12)$$

where ih is the current canopy layer. Using these values, the light availability in each layer of the canopy for both coniferous and deciduous trees ($light_{con}$ and $light_{dec}$, respectively) are calculated using Beer's Law:

$$light_{con}(ih) = e^{\frac{-0.4LAI_{c4}(ih+1)}{plotsize}} \quad (C.13)$$

$$light_{dec}(ih) = e^{\frac{-0.4LAI_{c3}(ih+1)}{plotsize}} \quad (C.14)$$

where $plotsize$ is the user-defined area of each plot (usually set to 500 m^2).

D. Tree Growth

In the tree growth subroutine, the growth of individual trees is calculated based on environmental and allometric factors. For each plot, the model checks to make sure there are trees on the plot. If there are, the model loops through each tree to first calculate the current biomass and height of each tree, and to calculate shading and environmental stressors.

Initially, the variable spp_{avail} is calculated, which represents whether or not a particular species can grow seedlings that year. It is calculated as:

$$spp_{avail} = \max\left(kron(D - D_{max}D_{thresh}), spp_{avail}\right) \quad (D.1)$$

where D is the diameter at breast height of the tree (cm), D_{max} is the average maximum diameter for that species of tree (cm), and D_{thresh} is the minimum annual growth threshold (set to 0.03 cm).

The function $kron(x)$ returns 1.0 if $x > 0.0$ and returns 0.0 otherwise. Thus, if the actual diameter of the tree is less than or equal to the maximum diameter times the growth threshold, the function will return 0.0, otherwise it will return 1.0. In this way, spp_{avail} is either 0 or 1 depending on if that tree is capable of generating seedlings in that plot that year. For example, *Abies lasiocarpa*, or subalpine fir, has a maximum diameter of about 61 cm. In this case, any subalpine fir growing in UVAFME would have to have a diameter at base height

(DBH) greater than 1.83 cm (i.e. 61 cm x 0.03 cm) to be considered "available" for putting out seedlings. Next, the leaf biomass is calculated for each tree as:

$$B_{leafC} = 2.0LAI_{tree} \cdot tree_{LC} \quad (D.2)$$

where B_{leafC} is the leaf biomass of the tree (tonnes C), and $tree_{LC}$ is the average specific leaf area ratio for that species of tree. Next, the maximum diameter increment growth possible for the tree, given optimum environmental conditions is calculated. This is based on allometric equations relating the height and DBH of the tree, calculated using species-specific parameters as well as the current DBH of the tree. It is calculated as follows:

$$D_{opt} = \frac{gD\left(1.0-\frac{D \cdot H_{tree}}{D_{max}H_{max}}\right)}{2.0H_{tree}+s \cdot e^{\frac{-sD}{H_{max}-H_{std}} \cdot D}} \quad (D.3)$$

where D_{opt} is the maximum diameter increment growth possible for that tree, given optimum environmental conditions (cm), g is a species-specific tree growth scalar parameter, D is the current diameter of the tree (cm), H_{tree} is the current height of the tree (m), D_{max} is the average maximum diameter of that tree species, H_{max} is the average maximum height of that tree species, s is the initial height-diameter relationship of that tree species, and H_{std} is the standard height measurement for most tree characteristics (set to 1.3 m in the model).

Next, the shading effects on each tree are calculated. The model uses the available light calculated in the Canopy Processes section (see Section C) and species-specific tolerances to shade to calculate the effect of shading on each tree. If the tree is a conifer, the effect of shading on that tree is calculated as:

$$f_{light} = l_a(1.0 - e^{-l_b(light_{con}-l_c)}) \quad (D.4)$$

where f_{light} is the effect of shading on tree diameter growth, $light_{con}$ is the light available for conifers at the specific tree's height, and l_a, l_b, and l_c are response factors based on species-specific tolerances to shading. If the tree is deciduous, f_{light} is calculated as:

$$f_{light} = l_a(1.0 - e^{-l_b(light_{dec} - l_c)}) \quad (D.5)$$

where $light_{dec}$ is the light available for deciduous trees at the specific tree's height. The shading at the bottom of the canopy is also calculated to determine the effect of shading on the lower branches of the tree. This will later be used to determine if thinning of lower branches will occur. The shade at the bottom of the canopy (f_{can}) is calculated using the same equations as the above two equations, except the $light_{dec}$ and $light_{con}$values are the light level at the clear branch bole height of the tree (i.e. H_{bole}, or height at the bottom of the canopy). Figure D.1 shows the light response of different shade tolerance levels, with 1 being the most shade tolerant, and 5 being the least shade tolerant.

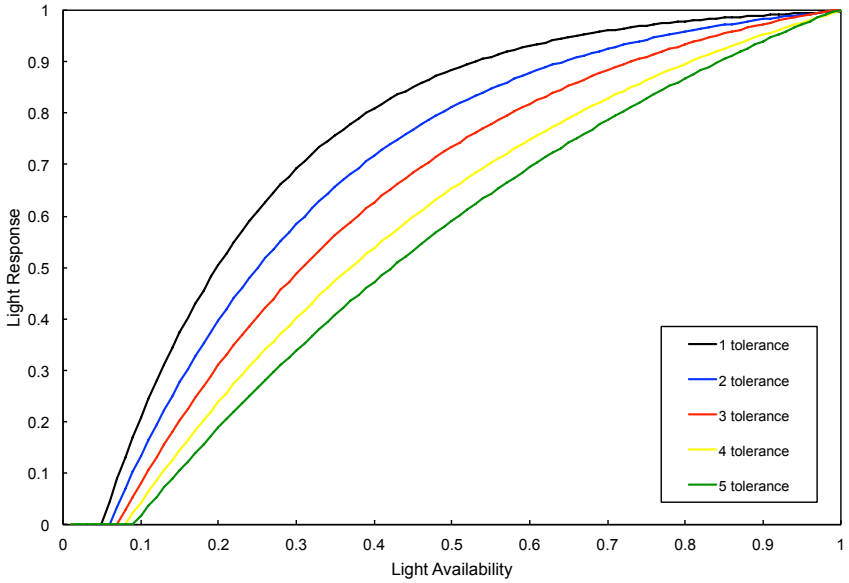

Figure D.1. Tree growth response to light availability for different tolerance levels of trees. A light tolerance of 1 is the most shade tolerant, and a light tolerance of 5 is the least shade tolerant. The light response is used to calculate actual DBH increment growth for the year for each tree.

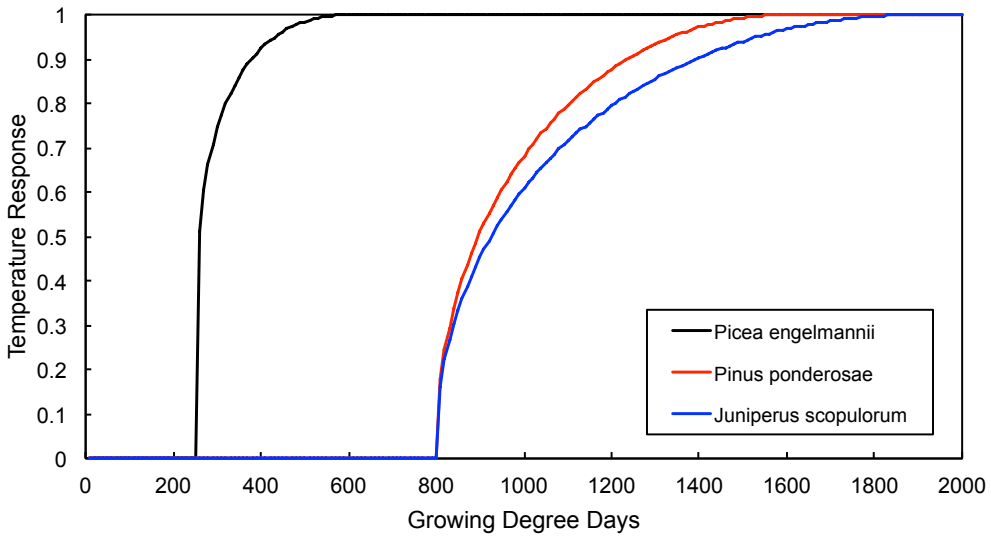

Figure D.2. Tree growth response to growing degree days (proxy for temperature) for three different Rocky Mountain species. *Picea engelmannii* (Engelmann spruce) is a subalpine species, capable of tolerating very low temperatures (DD_{min} = 250, DD_{opt}=600, and DD_{max}=1665). *Pinus ponderosa* is a montane species, existing in the middle elevations of the Rocky Mountains (DD_{min}=800, DD_{opt}=1600, and DD_{max}=2500). *Juniperus scopulorum* is a low-elevation species, capable of tolerating fairly high temperatures (DD_{min}=800, DD_{opt}=1900, and DD_{max}=3200).

Next, other environmental effects on diameter increment growth are calculated. The effect of temperature on growth is calculated using the cumulative number of growing degree days (GDD) in the year. The GDD for the year is defined as the cumulative sum of average daily temperatures above 5°C for the year. The effect of growing degree days on tree growth (f_{temp}) is calculated as:

$$f_{temp} = \left(\frac{GDD - DD_{min}}{DD_{opt} - DD_{min}}\right)^{\frac{DD_{opt} - DD_{min}}{DD_{max} - DD_{min}}} \cdot \left(\frac{DD_{max} - GDD}{DD_{max} - DD_{opt}}\right)^{\frac{DD_{max} - DD_{opt}}{DD_{max} - DD_{min}}} \quad (D.6)$$

where GDD is the growing degree days for the year, DD_{min} is the minimum growing degree days for the tree species, DD_{opt} is the optimum growing degree days for the species, and DD_{max} is the maximum growing degree days for the species. In this function, f_{temp} is equal to 1.0 if $GDD \geq$

DD_{opt}, and f_{temp} is 0.0 if $GDD \leq DD_{min}$. Otherwise, the equation above is used to calculate f_{temp}. Figure D.2 shows the temperature response for three species in the Rocky Mountains.

The effect of drought on tree growth is calculated using the number of "upper dry days" and "base dry days" in the year. The upper dry days are defined as the proportion of growing season days (i.e. days with an average temperature above 5°C) that have a relative A layer soil water and a relative B layer soil water content less than a maximum dry parameter (γ), set to 1.0 in the model. The relative water contents checked against γ are as follows:

$$SA_{RFC} = \frac{SA_{w0}}{SA_{FC}} \quad (D.7)$$

$$SB_{Rmax} = \frac{SB_{w0}}{SB_{wmax}} \quad (D.8)$$

$$SB_{Rmin} = \frac{SB_{w0}}{SB_{wmin}} \quad (D.9)$$

The base dry days for the year are defined as the proportion of growing season days (i.e. days with an average temperature above 5°C) that have a relative A layer water content (relative to the wilting point) less than the maximum dry parameter (γ). This relative water content is calculated as:

$$SA_{Rwp} = \frac{SA_{w0}}{SA_{wp}} \quad (D.10)$$

Once the upper and base dry days for the year are calculated, these, along with species-level drought tolerances, are used to calculate each tree's response to drought for the year:

$$f_{drought} = \sqrt{\frac{\max(dry - drydays, 0.0)}{dry}} \quad (D.11)$$

where $f_{drought}$ is the tree's response to drought, dry is a species-specific parameter based on drought tolerance (ranging from 0.5, most tolerant, to 0.05, least tolerant), and $drydays$ is the

proportion of upper dry days that year. If the tree in question has a drought tolerance of 1 (most tolerant to drought) and it is a conifer, $f_{drought}$ is calculated as:

$$f_{drought} = \max\left(0.33\sqrt{\frac{\max(dry - drydays_{base})}{dry}}, \sqrt{\frac{max(dry - drydays, 0.0)}{dry}}\right) \quad (D.12)$$

where $drydays_{base}$ is the proportion of base dry days that year. If the tree in question has a drought tolerance of 1 and it is deciduous, $f_{drought}$ is calculated as:

$$f_{drought} = \max\left(0.2\sqrt{\frac{\max(dry - drydays_{base})}{dry}}, \sqrt{\frac{max(dry - drydays, 0.0)}{dry}}\right) \quad (D.13)$$

Otherwise, it is calculated using the first drought response equation. Figure D.3 shows the drought response of the 6 different drought tolerances.

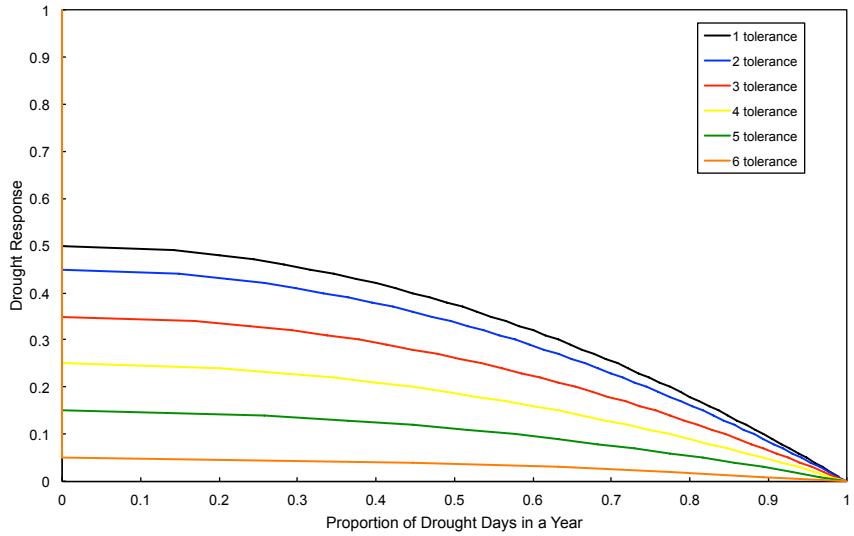

Figure D.3. Tree growth response to drought for the 6 different tolerance levels in the model, 1 being the most drought tolerant, and 6 being the least.

After these three environmental effects are calculated, the overall effect of environmental stressors so far is calculated. UVAFME uses Liebig's Law of the Minimum to calculate

cumulative environmental stress. The tree is only limited by the most limiting environmental factor. Thus, the environmental stress so far is calculated as:

$$f_{env} = \min\left(f_{light}, f_{temp}, f_{drought}\right) \quad \text{(D.14)}$$

where f_{env} is the growth response of the most limiting environmental factor. The model then calculates an intermediate DBH (D', cm) of the tree using the optimum DBH modified by f_{env}:

$$D' = D + D_{opt} f_{env} \quad \text{(D.15)}$$

The model then updates what the height of the tree would be given this calculated diameter using allometric equations relating DBH and height:

$$H'_{tree} = H_{std} + (H_{max} - H_{std})\left(1.0 - \mathrm{e}^{\left(-\frac{sD'}{H_{max} - H_{std}}\right)}\right) \quad \text{(D.16)}$$

Figure D.4 shows DBH-height relationship for four different Rocky Mountain species, each with different maximum heights, maximum diameters, and DBH-height relationships.

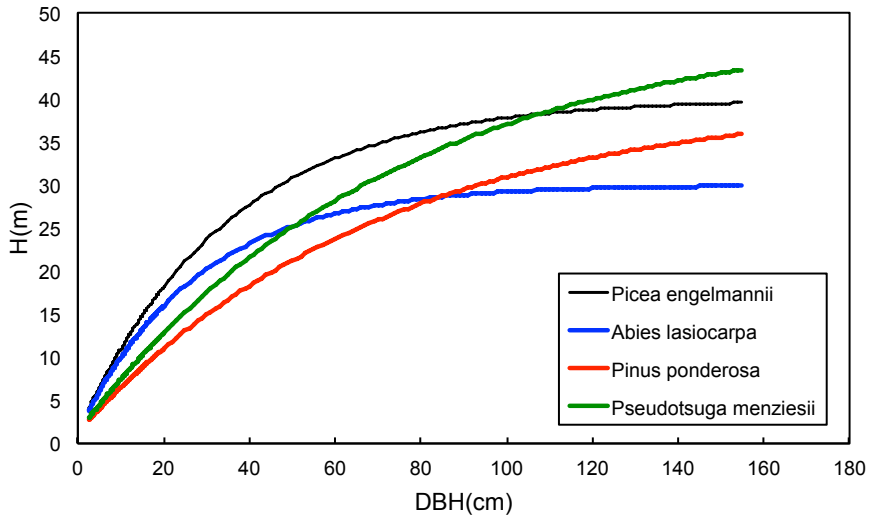

Figure D.4. Height:DBH relationships for four different Rocky Mountain species.

Next, an intermediate value for the diameter at the bottom of the tree's canopy, D'_{bole}, is calculated given these intermediate values. If the total updated height of the tree (H'_{tree}) is less

than last year's value of the height of the bottom of the canopy (H_{bole}) or if H'_{tree} is less than 1.3 m, then the diameter at clear bole height is equal to the tree's current DBH:

$$D'_{bole} = D' \quad \text{(D.17)}$$

Otherwise, D'$_{bole}$ is updated as:

$$D'_{bole} = \frac{H'_{tree} - H_{bole}}{H'_{tree} - 1.3}^{D'} \quad \text{(D.18)}$$

Next, the new leaf biomass for each tree is calculated (B'_{leafC}) as in Equation D.2 using the new height and DBH. Using this information, the nitrogen requirement for the plot is calculated. This N requirement is used to calculate the effect of N stress on tree growth for the year. If the tree in question is a conifer, N_{req} for the plot is updated as:

$$N_{req} = N_{req} + (B'_{leafC} - B_{leafC})/leaf_{CNcon} \quad \text{(D.19)}$$

where $leaf_{CNcon}$ is the conifer C:N ratio, set to 60.0 in the model. If the tree is deciduous, N_{req} is updated as:

$$N_{req} = N_{req} + (B'_{leafC})/leaf_{CNdec} \quad \text{(D.20)}$$

where $leaf_{CNdec}$ is the deciduous C:N ratio, set to 40.0 in the model. In this way, the total N requirement for the plot is updated to include nitrogen required for the leaves added on by conifers that year and for the leaves made by deciduous trees that year. Next, the total biomass for carbon is updated for each tree. This is calculated as a sum of stem, twig, and root biomass. Stem biomass is calculated as:

$$B'_{stemC} = \frac{C\rho_{bulk}\beta}{\beta+2.0} \times D'^2 H'_{tree} 0.9 \quad \text{(D.21)}$$

where B'_{stemC} is an intermediate value for stem biomass (tonnes C), C is a carbon parameter, set to 3.92699x10^{-5} in the model, ρ_{bulk} is the average bulk density of the tree species, and β is a parameter, set to 1.0 in the model. The twig biomass (B'_{twigC}, tonnes C) is calculated as:

$$B'_{twigC} = C\rho_{bulk}\left(\frac{2.0}{\beta+2.0} - 0.33\right) {D'_{bole}}^2 (H'_{tree} - H'_{can}) \quad (D.22)$$

The root biomass (B'_{rootC}, tonnes C) is calculated as:

$$B'_{rootC} = B'_{stemC}\frac{r_{depth}}{H'_{tree}} + \frac{B'_{twigC}}{2.0} \quad (D.23)$$

where r_{depth} is the tree's root depth, set to 0.8 m in the model. The total biomass (B'_{treeC}, tonnes C) is then updated as:

$$B'_{treeC} = B'_{stemC} + B'_{twigC} + B'_{rootC} \quad (D.24)$$

After the new biomass has been calculated, the N biomass for each tree is updated as:

$$B'_{treeN} = B'_{treeC}/stem_{CN} \quad (D.25)$$

where B'_{treeN} is the N biomass of the tree, and $stem_{CN}$ is the stem C:N ratio, set to 450.0 in the model. The N requirement for the plot is then updated as:

$$N_{req} = N_{req} + (B_{treeC0} - B'_{treeC})/stem_{CN} \quad (D.26)$$

where B_{treeC0} is the previous year's tree biomass, and B'_{treeC} is the updated biomass using the new DBH. In this way, N_{req} is the total nitrogen required to grow each tree the amount calculated based on the DBH calculated above. The N requirement is then converted to tonnes ha^{-1} and divided by the available nitrogen to get a relative N available for plant growth (N_R):

$$N_{req} = \max\left(\frac{1000N_{req}}{plotsize}, 0.0\right) \quad (D.27)$$

$$N_R = N_{avail}/N_{req} \quad (D.28)$$

Using this relative available nitrogen, the effect of nitrogen availability on tree growth is calculated using species-specific parameters based on nutrient tolerance:

$$f_{poor} = fert_1 + fert_2 N_R + fert_3 {N_R}^2 \quad (D.29)$$

where f_{poor} is a factor based on nitrogen availability, $fert_1$, $fert_2$, and $fert_3$ are values based on species-specific nutrient tolerance. If f_{poor} is calculated to be greater than 1.0, it is set to 1.0.

Likewise, if it is calculated to be less than 0.0, it is set to 0.0. The effect of nutrient availability on tree growth ($f_{nutrient}$) is then calculated as:

$$f_{nutrient} = f_{poor} N_R \quad (D.30)$$

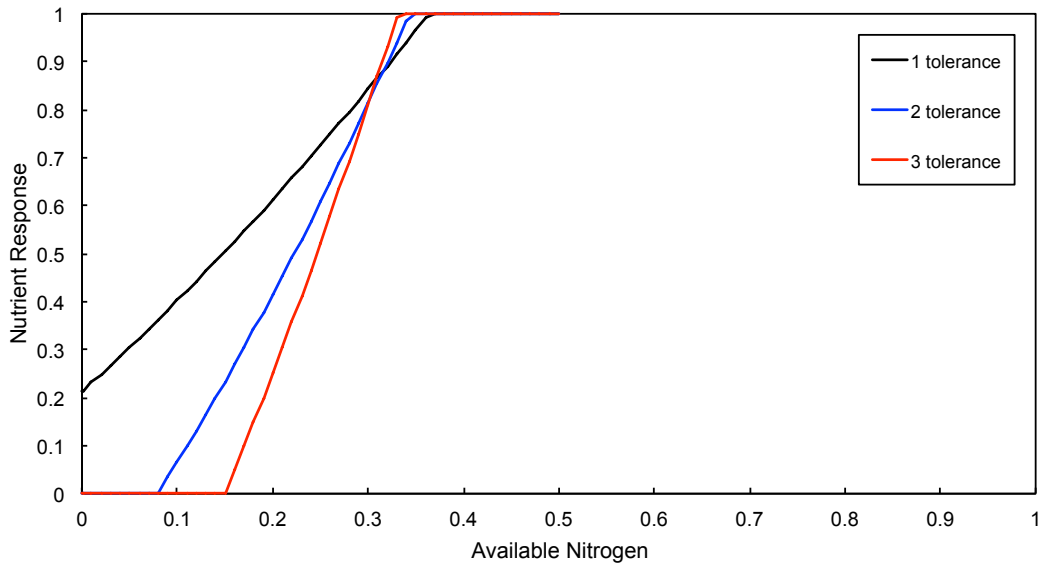

Fig. D.5. Tree growth response to drought for the 3 different tolerance levels in the model, 1 being the most drought tolerant, and 3 being the least.

Figure D.5 shows this nutrient effect for the three different nutrient tolerances. This is used to calculate the actual DBH increment growth for the year. Again, the Law of the Minimum is used the actual DBH growth based on the optimum possible DBH growth, modified by the most limiting factor:

$$D_{incr} = D_{opt}(\min(f_{nutrient}, f_{env})) \quad (D.31)$$

where D_{incr} is the actual DBH increment growth for the year. Next, the DBH for the tree is updated using last year's value and the actual increment growth:

$$D = D + D_{incr} \quad (D.32)$$

Using the increment value, a growth check is made to determine if the tree had enough growth that year to survive stress-related death. Two checks are made, one to see if the increment growth for that year is greater than an allometrically-derived growth check, and one to see if the most limiting environmental factor's effect is greater than another growth check. The allometrically-derived growth check is calculated as:

$$C_A = \min\left(\frac{D_{max}}{AGE_{max}0.1}, D_{thresh}\right) \quad (D.33)$$

where C_A is the growth check, AGE_{max} is that species' average maximum age (yrs) and D_{thresh} is a growth threshold, set to 0.03 cm in the model. The model checks to see if (1) D_{incr} is less than C_A or if (2) the effect of the most limiting environmental factor (i.e. $\min(f_{nutrient}, f_{env})$) is less than D_{thresh}. If this is true, and the tree is a conifer, the tree's mortality counter is increased by one. Once this mortality counter reaches 3 (i.e. three consecutive years of low increment growth and/or high stress), the tree's mortality marker is set to true. This mortality marker is used later in the model to determine if the tree dies from stress-related causes. If the tree passes both growth checks, the mortality counter is set to 0 and the mortality marker is set to false.

After these checks are made, the actual tree height (H_{tree}), diameter at clear branch bole height (D_{bole}), leaf biomass (B_{leafC}), total carbon and nitrogen biomass (B_{treeC}, B_{treeN}) are calculated using the equations described previously. The change in biomass for each tree from last year's run to this year's (ΔB_{treeC}) is then calculated:

$$\Delta B_{treeC} = B_{treeC} - B_{treeC0} \quad (D.34)$$

where B_{treeC0} is last year's tree biomass (not including leaves). Using this value, the total net primary production (NPP) for the plot is updated:

$$NPP = NPP + \Delta B_{treeC} \quad (D.35)$$

in this way, the model adds up each tree's change in biomass to calculate a plot-wide NPP value. The nitrogen used on the plot (N_{used}) is also calculated in a similar fashion:

$$N_{used} = N_{used} + \Delta B_{treeC}/stem_{CN} \quad (D.36)$$

Next, leaves are added to the NPP and N_{used}. If the tree is a conifer, the leaf primary production (PP, tonnes C) is calculated as the amount of added leaf biomass for that year:

$$PP = b_l B_{leafC} - B_{leafC0} \quad (D.37)$$

where B_{leafC0} is last year's leaf biomass, and b_l is equal to 1.0 plus the conifer leaf ratio (set to 0.3 in the model). The NPP and N_{used} for the plot are then updated as:

$$NPP = NPP + PP \quad (D.38)$$

$$N_{used} = N_{used} + \frac{PP}{leaf_{CNcon}} \quad (D.39)$$

where $leaf_{CNcon}$ is the conifer leaf C:N ratio, set to 60.0 in the model. The total biomass (B_C, tonnes C) for the plot is then updated as:

$$B_C = B_C + B_{treeC} + B_{leafC} \quad (D.40)$$

In this way, the total biomass for the plot is calculated as a sum of each tree's total biomass. The total nitrogen (B_N, tonnes N) is also calculated in a similar way:

$$B_N = B_N + B_{treeN} + B_{leafC}/leaf_{CNcon} \quad (D.41)$$

If the tree is deciduous, the NPP and N_{used} are updated as:

$$NPP = NPP + B_{leafC} \quad (D.42)$$

$$N_{used} = N_{used} + B_{leafC}/leaf_{CNdec} \quad (D.43)$$

Here, the model adds the total amount of leaf biomass (rather than just the change) because as a deciduous tree, it has grown back all of its leaves that year. The total plot carbon and nitrogen are then updated as:

$$B_C = B_C + B_{treeC} \quad (D.44)$$

$$B_N = B_N + B_{treeN} \quad (D.45)$$

In this case, the model does not add leaf carbon and leaf nitrogen for deciduous trees to the total plot biomass values.

After the individual tree and plot-level biomass values have been calculated, the model updates the height of the bottom of the canopy (clear branch bole height) for each tree. Here, the model checks to see if the environmental stressors are high enough to cause thinning of the lower canopy branches. This is done by checking to see if the effect of the most limiting factor (either from temperature, drought, shading, or nutrient availability) is less than the growth threshold. This check value is calculated as:

$$C_C = \min\left(f_{temp}, f_{drought}, f_{canshade}, f_{nutrient}\right) \quad (D.46)$$

where C_C is the growth check for canopy thinning, and $f_{canshade}$ is the effect of shading at the bottom of the canopy, calculated in the same manner as is f_{light} (Eq. D.4, D.5) but using the light at height of the bottom of the canopy, rather than at the height of the top of the tree. If C_C is less than or equal to D_{thresh} (set to 0.03 in the model), then the branches at the bottom of the canopy are thinned, and the clear bole height increases by 1:

$$H_{bole} = H_{bole} + 1.0 \quad (D.47)$$

If this new clear branch bole height is less than the total tree height (H_{tree}), H_{bole} is incremented by another 0.1 m. Otherwise, no change is made to the tree's clear branch bole height. If this change is made, the diameter at the height of the canopy (D_{bole}) is updated using the equation previously described (Eq. D.18), and the carbon and nitrogen values for the tree are

updated (B_{treeC} and B_{treeN}, Eq. D.24, D.25). These new biomass values are then used to calculate how much thinning occurred:

$$L_{BC} = B_{treeC1} - B_{treeC} \quad (D.48)$$

where L_{BC} is the amount of stem litterfall (tonnes C), and B_{treeC1} is the biomass of the tree before thinning. This litterfall is added to the soil carbon and nitrogen pools:

$$AO_{Cinto} = AO_{Cinto} + L_{BC} \quad (D.49)$$

$$AO_{Ninto} = AO_{Ninto} + L_{BC}/stem_{CN} \quad (D.50)$$

where AO_{Cinto} and AO_{Ninto} are the carbon and nitrogen pools that will be added to the overall C and N pools for the organic layer. Next, the leaf biomass is updated for the new clear branch bole height and the amount of leaf litter from thinning (L_{BL}) is calculated:

$$L_{BL} = B_{leafC1} - B_{leafC} \quad (D.51)$$

where B_{leafC1} is the leaf biomass before thinning. Next, this leaf litter is added to the organic layer input pools. If the tree is a conifer:

$$AO_{Cinto} = AO_{Cinto} + L_{BL}b_l \quad (D.52)$$

$$AO_{Ninto} = AO_{Ninto} + L_{BL}/leaf_{CNcon}b_l \quad (D.53)$$

And if the tree is deciduous:

$$AO_{Cinto} = AO_{Cinto} + L_{BL} \quad (D.54)$$

$$AO_{Ninto} = AO_{Ninto} + L_{BL}/leaf_{CNdec} \quad (D.55)$$

After these calculations are made, the Growth subroutine is complete and the model moves on to the Mortality subroutine.

E. Tree Mortality

Mortality of individual trees can occur through several different pathways Trees may die because of age or growth-related stressors, or through disturbances. Currently, UVAFME has the

ability to implement probabilistic fire and wind disturbance. The probability of tree death occurring through any one of these methods is determined by species input parameters such as stress tolerance, maximum age and probability of reaching that age, and fire tolerance, as well as disturbance probabilities and characteristics.

In the Mortality subroutine, the model first checks to determine if fire or wind disturbance occurs that year. This is based on uniform random numbers (between 0.0 and 1.0) for fire and wind probability checked against site-specific fire and wind return intervals (i.e. the number of fires or windthrow events in 1000 years). If the fire probability for that year (f_{prob}) is less than the site-wide probability for fire or if the wind probability for that year (w_{prob}) is less than the site-wide probability for wind, the model enters into the disturbance section of the Mortality subroutine, otherwise it moves on to check for age- and growth-related stressors alone.

E.1. Disturbances

If the number of trees on the plot is greater than 0, then these trees are set to be hit by disturbance. If f_{prob} is less than the site-wide return interval for fire, then fire occurs on that plot that year.

E.1.1. Fire

The model first generates an intensity value for this fire. This is generated using a normally distributed random number between 0.0 and 12.0, with a site-specific mean. This mean fire intensity (f_{int}) corresponds to the site-wide average fire intensity, with 0.0 to 4.0 being low-level, brush fires, 5.0 to 8.0 being mid-level fires, and 9.0 to 12.0 being high-level, crown fires. Depending on the mean fire intensity, the distribution of possible fire intensities generated by the model can be shifted to be mostly low level, mostly high level, or mostly mid level. The

normally distributed random number generated with the mean fire intensity value represents the fire category for that year's fire.

Once the fire category for that year's fire is generated (f_{cat}), the model checks to see if the fire intensity is high enough to cause wholescale tree death. If f_{cat} is greater than or equal to 11.0, there is a five-year wait before seedlings can regenerate. As such, when f_{cat} is greater than or equal to 11.0, the variable f_{count} is set to 5. Otherwise, f_{count} is remains at 0.

Next, the model determines the effect the fire will have on each tree. In UVAFME fire affects both individual tree survival and the seedling bank for each species. The effect of fire on each species seedling bank (f_{fire}) depends exclusively on species-specific fire regeneration tolerances (1-6; 1 being the most tolerant, and 6 being the least tolerant). The variable f_{fire} ranges from 100.0 to 0.001, depending on the species' tolerance to fire. Figure E.1 shows how f_{fire} changes with respect to fire tolerance. The seedling bank for each species is then updated as:

$$Sl_{bank} = 10.0s_i + s_p \cdot spp_{avail} \cdot f_{fire} \quad (E.1)$$

where Sl_{bank} is that species' seedling bank, s_i is an input parameter that represents the probability of being a seed invader from outside the plot (the highest value, 1, would be for wind-dispersed seeds), and s_p is a parameter representing whether or not that species is capable of sprouting from stumps (1: yes, 0: no).

After the fire response to the seedling bank is calculated, the model determines which trees will be killed by fire. This is based on the species- and tree size-specific fire tolerance as well as the fire intensity (f_{cat}). All trees less than 12.7 cm in DBH are killed by fire. Trees that are larger than 12.7 cm DBH may be killed by fire based on their species-specific bark thickness coefficient (b_{thick}, cm bark cm DBH^{-1}). First, the crown scorch height (SH, m) is determined

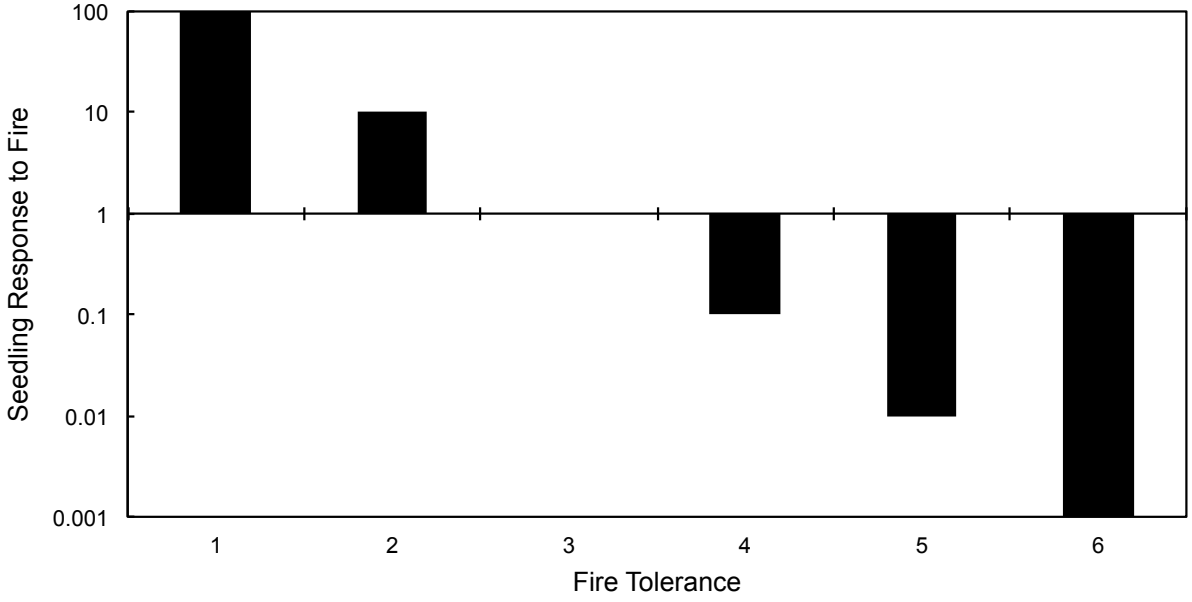

Figure E.1. Seedling bank response to fire for the 6 different fire tolerances. A fire tolerance of 1 corresponds to a high tolerance to fire, and a fire tolerance of 6 corresponds to a low tolerance to fire. In this case, species with a fire tolerance below 3 will benefit from a fire, species with a tolerance above 3 will be hindered by fire, and species with a fire tolerance of 3 will not be affected by fire in terms of their seedling bank size.

based on fire intensity and wind speed.

$$SH = \frac{a \cdot FI^{1.1667}}{(T_{kill} - T_{amb})[b \cdot FI + c \cdot U^3]^{0.5}} \quad (E.2)$$

where a, b, and c are empirical parameters equal to 0.74183 m °C^{-1}, 0.025574 (kW m^{-1})$^{4/3}$, and 0.021433 km^{-1} hr (kW m^{-1})$^{7/9}$, respectively, T_{kill} is the lethal temperature for tree foliage (set to 60 °C in this model), T_{amb} is the ambient air temperature of a fire (set to 20°C), FI is the fire intensity (kW m^{-1}), set to $1000 f_{cat}$, U is the wind speed (km hr^{-1}), generated as a random value

between 0 and 32 km hr^{-1}. This value for wind speed is based on a default wind speed of 32 km hr^{-1} from Reinhardt & Crookston (2003). The length each tree crown that is scorched (CS, m) is then calculated as:

$$CS = SH - (H_{tree} - Z_{bole}) \quad \text{(E.3)}$$

where H_{tree} is the tree height (m), and Z_{bole} is the crown depth (m). Next, the percent of scorched crown volume (CK, %) is calculated for each tree.

$$CK = 100\,\frac{CS(2CL - CS)}{CL^2} \quad \text{(E.4)}$$

Finally, the probability of fire mortality (p_{fire}) is calculated for each tree based on the species-specific bark thickness parameter, DBH, and percent scorched crown volume.

$$p_{fire} = \frac{1}{1+e^{[-1.941+6.32(1-e^{-b_{thick}DBH})-0.00053CK^2]}} \quad \text{(E.5)}$$

The equations for scorch height and percent crown volume scorched are based on the fire module from Fire BGCv2 RMRS-GTR-55 (Kean *et al.* 2011) and from Van Wagner (1973). Probability of fire mortality is based on the mortality equation from Ryan & Reinhardt (1988). The parameters a, b, and c, and the values for T_{kill} and T_{amb} are based on Keane *et al.* (2011). Finally, the species-specific bark thickness values are also based on values published by Keane *et al.* (2011).

If the tree in question will be killed by fire that year, its fire mortality marker is set to true. Otherwise, its fire mortality marker is set to false. Next, the model kills trees that die by fire or through natural death, since in this case, there may be a fire that does not kill all the trees on the plot, but some of the trees that survived the fire may die from age- or stress-related issues. Wind disturbance does not occur when a fire occurs that year.

For each tree on the plot, the model checks to see if it survived the fire and if it survived growth- and age-related stressors. To survive growth-related stressors, the tree has to have a

mortality marker of false (determined in the Growth subroutine, based on that tree's DBH increment growth that year) or it has to pass the random check against growth survival, based on the tree's species-specific stress tolerance. In this case, the model generates a uniformly distributed random number between 0.0 and 1.0 and checks to see if it is less than the variable C_G. This variable ranges from 0.31 to 0.43, depending on the tree species' stress tolerance (ranges from 1 to 5; 1 being tolerant, 5 being intolerant to stress). In this way, even if the tree's mortality marker is set to true, it has a 57 to 69% chance of still surviving, depending on its stress tolerance.

In order to survive age-related stressors, the tree must also pass a random check against age survival. Again, the model generates a uniformly distributed random number between 0.0 and 1.0 and checks to see if it is less than the variable C_O. This age-related check is calculated as:

$$C_O = \varepsilon / AGE_{max} \quad \text{(E.6)}$$

where ε is an input parameter based on that tree species propensity to survive to its maximum age. Higher values of ε denote a lower probability of reaching its maximum age.

If the tree survives age- and growth-related stressors as well as fire, the model copies its attributes, increments the number of trees on the plot for next year by one ($nt = nt + 1$) and calculates the amount of non-thinning litterfall for the year and adds it to the organic layer litter pools. If the tree is a conifer:

$$AO_{Cinto} = AO_{Cinto} + B_{leafC}(b_l - 1.0) \quad \text{(E.7)}$$

$$AO_{Ninto} = AO_{Ninto} + B_{leafC}(b_l - 1.0)/leaf_{CNcon} \quad \text{(E.8)}$$

Otherwise, if the tree is deciduous:

$$AO_{Cinto} = AO_{Cinto} + B_{leafC} \quad \text{(E.9)}$$

$$AO_{Ninto} = AO_{Ninto} + B_{leafC}/leaf_{CNdec} \quad \text{(E.10)}$$

If, however, the tree dies, through age, stress, or fire, the model does not copy its attributes and the model calculates how much carbon and nitrogen the tree puts into the soil. If the tree is a conifer:

$$AO_{Cinto} = AO_{Cinto} + B_{treeC} + B_{leafC} \quad (E.11)$$

$$AO_{Ninto} = AO_{Ninto} + B_{treeC}/stem_{CN} + B_{leafC} b_l / leaf_{CNcon} \quad (E.12)$$

Otherwise, if the tree is deciduous:

$$AO_{Cinto} = AO_{Cinto} + B_{treeC} + B_{leafC} \quad (E.13)$$

$$AO_{Ninto} = AO_{Ninto} + B_{treeC}/stem_{CN} + B_{leafC}/leaf_{CNdec} \quad (E.14)$$

Once the model has finished calculating these values, it moves on to the Renewal subroutine and the number of trees on the plot is updated to be the number of trees that survived fire and stressors that year.

E.1.2. Wind

If, instead, wind disturbance occurs that year (i.e. w_{prob} is less than the site-wide wind probability) all trees are killed on the plot. In this case, there is a three-year lag time before regeneration can start. As such the variable w_{count} is set to 3. Again, fire cannot occur in the same year as wind disturbance. The seedling bank is updated to reflect windthrow effects:

$$Sl_{bank} = Sl_{bank} + s_i + s_p \cdot spp_{avail} \quad (E.15)$$

As all the trees on the plot will be killed by windthrow, the model calculates how much carbon and nitrogen will be added to the soil organic layer from these dying trees. The amount of biomass from leaves (B_{LAI}) that go into the soil is first calculated as:

$$B_{LAI} = 2.0 LAI_{tree} sl_c \quad (E.16)$$

where sl_c is the specific leaf area ratio of the tree. Next, the stem and leaf carbon and nitrogen are added into the organic layer. If the tree is a conifer:

$$AO_{Cinto} = AO_{Cinto} + B_{treeC} + B_{LAI} b_l \quad (E.17)$$

$$AO_{Ninto} = AO_{Ninto} + \frac{B_{treeC}}{stem_{CN}} + \frac{B_{LAI} b_l}{leaf_{CNcon}} \quad (E.18)$$

Otherwise, if the tree is deciduous:

$$AO_{Cinto} = AO_{Cinto} + B_{treeC} + B_{LAI} \quad (E.19)$$

$$AO_{Ninto} = AO_{Ninto} + \frac{B_{treeC}}{stem_{CN}} + \frac{B_{LAI}}{leaf_{CNdec}} \quad (E.20)$$

At this point, the number of trees on the plot is set to 0 as they were all killed by windthrow. The seedling number is also set to 1. This is a plot-level, species-specific value that is equal to 1 if that species' seedling bank is greater than 0.0 and set to 0 if it is not. The model is now finished with the Mortality subroutine and moves on to the Renewal subroutine.

E.2. No disturbances

If no disturbances occur in the year, then the model only checks for age- and growth-related stressors. If the number of trees is greater than 0, then the model loops through and checks for growth and age survival, otherwise the model moves directly to the Renewal subroutine. For each tree on the plot, the model checks to see if the tree survives the growth and age-related checks described above (see section E.1.1). If the tree survives, the model copies its attributes, increments the number of trees on the plot by 1 ($nt = nt + 1$), and then calculates the amount of non-thinning litterfall for the year and adds it to the organic layer litter pools. If the tree is a conifer:

$$AO_{Cinto} = AO_{Cinto} + B_{leafC}(b_l - 1.0) \quad (E.21)$$

$$AO_{Ninto} = AO_{Ninto} + B_{leafC}(b_l - 1.0)/leaf_{CNcon} \quad (E.22)$$

Otherwise, if the tree is deciduous:

$$AO_{Cinto} = AO_{Cinto} + B_{leafC} \quad (E.23)$$

$$AO_{Ninto} = AO_{Ninto} + B_{leafC}/leaf_{CNdec} \quad (E.24)$$

If, however, the tree dies, through age or stress, the model does not copy its attributes and the model calculates how much carbon and nitrogen the tree puts into the soil. If the tree is a conifer:

$$AO_{Cinto} = AO_{Cinto} + B_{treeC} + B_{leafC} \quad (E.25)$$

$$AO_{Ninto} = AO_{Ninto} + B_{treeC}/stem_{CN} + B_{leafC}b_l/leaf_{CNcon} \quad (E.26)$$

Otherwise, if the tree is deciduous:

$$AO_{Cinto} = AO_{Cinto} + B_{treeC} + B_{leafC} \quad (E.27)$$

$$AO_{Ninto} = AO_{Ninto} + B_{treeC}/stem_{CN} + B_{leafC}/leaf_{CNdec} \quad (E.28)$$

Once the model has finished calculating these values, it moves on to the Renewal subroutine and the number of trees on the plot is updated to be the number of trees that survived growth and age stressors that year.

F. Tree Renewal

In Renewal subroutine, the seedling and seed banks for each species are updated and new trees are established on the plots. If the available nitrogen the plot is greater than 0.0 then trees can grow on the site, and the model continues with the Renewal subroutine. Otherwise no trees establish and the soil is updated to reflect N and C inputs and outputs for the year.

F.1. Seed and seedling bank calculations

F.1.1. No windthrow or whole-scale fire disturbance

If windthrow did not occur that year and if there was either no fire at all or only a low- to mid-level fire (i.e. $f_{cat} < 11.0$) then the model makes modifications to the current seedling and

seed banks, and calculates how many trees can be renewed on the plot. First the maximum growth for the plot (g_{max}) is set to 0.0. Then, for each species, the growth cap (g_{cap}) is calculated as:

$$g_{cap} = \min\left(f_{temp}, f_{drought}, f_{nutrient}\right) \quad \text{(F.1)}$$

If there are no trees on the plot, then the seedling regrowth potential (g_R) for that species is set to the growth cap. Otherwise, the model also takes the effect of shading from other trees into account when calculating the regrowth potential for that species:

$$g_R = \min\left(g_{cap}, f_{light}\right) \quad \text{(F.2)}$$

Then, the seedling growth max for the plot is updated as:

$$g_{max} = \max\left(g_{max}, g_R\right) \quad \text{(F.3)}$$

In this way, the g_{max} for the plot is updated as the model goes through each species, so that the plot-wide g_{max} is equal to the g_R of the species with the highest seedling regrowth potential. Finally, if a species' regrowth potential is less than the growth threshold (D_{thresh}; set to 0.03 in the model), then its regrowth is set to 0.0.

Next, the N_{rnew} and N_{rmax} are set up as counters for when new trees are established on the plot. N_{rmax}, the maximum number of trees that can be renewed, is calculated as:

$$N_{rmax} = \min\left((plotsize \cdot g_{max}) - nt, 0.5 plotsize\right) \quad \text{(F.4)}$$

where $plotsize$ is the area of the plot (set to 500 m^2 in the model), and nt is the number of trees on the plot. Then, N_{rnew} is calculated as:

$$N_{rnew} = \min\left(\max(N_{rmax}, 3), (plotsize - nt)\right) \quad \text{(F.5)}$$

The model then moves on to calculate the seedling and seed banks for each plot.

If the seedling number for the plot is equal to 0.0:

If the seedling number for the plot is equal to 0.0, then the model first updates the seedbank for each species as:

$$S_{bank} = S_{bank} + s_i + s_{num} \cdot spp_{avail} + s_p \cdot spp_{avail} \quad (F.6)$$

where S_{bank} is the number of seeds in that species' seedbank, s_{num} is a species-specific input parameter that represents the seed numbers from inside the plot (1 for cones, 10 for samaras or maple keys, and 100 for wind-dispersed birch or populous). If the regrowth for that species (g_R) is greater than or equal to the growth threshold (D_{thresh}), then the seeds in that species' seed bank are added to the seedling bank, and the seed bank is set back to 0.0:

$$Sl_{bank} = Sl_{bank} + S_{bank} \quad (F.7)$$

$$S_{bank} = 0.0 \quad (F.8)$$

Otherwise, if g_R is less than D_{thresh}, the seeds in the seedbank do not become seedlings, and the seedbank is reduced based on a species-specific seed reduction parameter:

$$S_{bank} = S_{bank} \cdot s_{surv} \quad (F.9)$$

where s_{surv} is the seedling reduction parameter. Next, the effect of fire on the seedling bank is calculated as in Equation E.1, and then the seedling bank for each species is updated.

$$Sl_{bank} = Sl_{bank} + s_p \cdot spp_{avail} \cdot f_{fire} \quad (F.10)$$

If there was no fire that year, f_{fire} is equal to 1.0, and thus has no effect on the seedling bank. The seedling number for each plot (Sl_N) is calculated as:

$$Sl_N = \max\left(kron(Sl_{bank}), Sl_N\right) \quad (F.11)$$

In this way, the model loops through each species and modifies the plot-wide seedling number each time. If the seedling bank for the species in question is greater than 0.0, then Sl_N takes the maximum of either 1.0 or the current value of Sl_N. If the seedling bank for that species

is less than 0.0, Sl_N is the maximum between 0.0 and Sl_N. Thus, the seedling number for each plot is either 1.0 or 0.0, depending on if any species has a seedling bank greater than 0.0. Next the seedling bank for the species is converted from a per m^2 value to a general plot number value through:

$$Sl_{bank} = Sl_{bank} plotsize \quad (F.12)$$

Finally, the value p_{sum} for the plot is calculated as the sum of each species' seedling bank times its regrowth:

$$p_{sum} = \sum Sl_{bank} g_R \quad (F.13)$$

At this point, the model has finished calculating the seed and seedling banks and moves on to the tree regeneration part of the Renewal subroutine.

If the seedling number for the plot is not equal to 0.0:

If, however, there are currently seedlings on the plot, (i.e. the seedling number for the plot is 1.0), then the model first calculates the p_{sum} as in Equation F.13. Next, the model updates the seed bank and seedling bank for each species. It first updates the seed bank as in Equation F.6.

If a species' regrowth value is greater than or equal to the grow threshold (D_{thresh}) then the seeds in the seed bank germinate into seedlings:

$$Sl_{bank} = Sl_{bank} + S_{bank} \quad (F.14)$$

$$S_{bank} = 0.0 \quad (F.15)$$

Otherwise, the seed bank is reduced as in Equation F.9. Next, the effect of fire on the seedling bank is calculated as in Equation E.1 and then the seedling bank for each species is updated. Again, if there was no fire that year, f_{fire} is equal to 1.0, and thus has no effect on the seedling bank. Finally, the seedling bank for the species is converted from a per m^2 value to a

general plot number value and the seedling number for the plot is calculated as in Equations F.11 and F.12. At this point, the model has completed computing the maximum possible trees that can be renewed and has finished updating the seed banks and seedling banks for each species. It then moves on to the part of the Renewal subroutine where new trees are established on the plot.

F.1.2. Windthrow or whole-scale fire disturbance

If there was windthrow or whole-scale fire disturbance (i.e. $f_{cat} \geq 11.0$) then the model waits 3 (for wind) or 5 (for fire) years before starting the regeneration process. This is achieved using the f_{count} and w_{count} variables, set up when fire or wind disturbance is first initiated. Each year the model checks to see if either counter is equal to 1. If it is not, it subtracts 1 from the counter and sets the plot value p_{sum} to 0.0.

Once either counter reaches 1, the model first computes the growth cap for each species as in Equation F.1 and it then computes p_{sum} as in Equation F.13. Finally, it converts the seedling bank number for each species from the per m^2 value and computes the seedling number value for the plot as in Equations F.11 and F.12.

With this, the model has finished all the different scenarios for computing the seed and seedling banks and the number of trees that can be renewed on the plot. UVAFME then moves on to generating new trees on the plot.

F.2. Regenerating new trees

If p_{sum} for the plot is greater than 0.0, then the model updates the p_{sp} for each species (where p_{sp} was first calculated as $p_{sp} = Sl_{bank} \cdot g_{cap}$). Otherwise, it sets the previously calculated N_{rnew} (see Equation F.5) to 0 and moves on. If p_{sum} is greater than 0.0:

$$p_{sp} = \frac{p_{sp}}{p_{sum}} \quad \text{(F.16)}$$

In effect this takes each species' p_{sp}, which in general corresponds to its potential for regeneration on that plot, and then divides it by the plot-wide sum of p_{sp} (i.e. p_{sum}), converting p_{sp} into a relative potential for regeneration. Next, the model modifies p_{sp} again:

$$p_{sp(s)} = p_{sp(s-1)} + p_{sp(s)} \quad \text{(F.17)}$$

where s is an index for species. This in effect converts p_{sp} of each species to a cumulative relative potential for regeneration. Next, the model checks to see if N_{renew} is greater than or equal to 1. If it is, the model moves to regenerate trees on the plot. If it is less than 1, the model does not regenerate new trees and moves to the final step in the modeling process for the year. If N_{renew} is greater than or equal to 1, then the model creates N_{renew} new trees on the plot. This is achieved through a random number calling the species of each new tree (modified by p_{sp} so that species with a higher p_{sp} will contribute more new trees than species with a low p_{sp}), and another random number generating the starting DBH of each new tree.

Once a new tree is set to be placed on the plot, the seedling bank for the species of tree that was called is reduced by one. The DBH for each new tree is determined through a normally distributed random number (with a mean of 0.0 and a standard deviation or 1.0) between 0.5 and 2.5. Once the new diameter of the tree is determined, the clear branch bole height of the tree is set to 1 m, and then the total tree height, diameter at clear branch bole height, C and N biomass, and leaf biomass are determined based on Equations D.16, D.18, D.24, D.25, and D.2. Next, the NPP, N_{used}, and litter inputs for the plot are updated. If the tree is a conifer:

$$NPP = NPP + B_{leafC} \cdot l_B + B_{treeC} \quad \text{(F.18)}$$

$$N_{used} = N_{used} + \frac{B_{leafC}}{leaf_{CNcon}} + B_{treeN} \quad \text{(F.19)}$$

$$AO_{Cinto} = AO_{Cinto} + B_{leafC}(l_B - 1.0) \quad \text{(F.20)}$$

$$AO_{Ninto} = AO_{Ninto} + B_{leafC}(l_B - 1.0)/leaf_{CNcon} \quad (F.21)$$

Otherwise, if the tree is deciduous:

$$NPP = NPP + B_{leafC} + B_{treeC} \quad (F.22)$$

$$N_{used} = N_{used} + \frac{B_{leafC}}{leaf_{CNcdec}} + B_{treeN} \quad (F.23)$$

$$AO_{Cinto} = AO_{Cinto} + B_{leafC} \quad (F.24)$$

$$AO_{Ninto} = AO_{Ninto} + B_{leafC}/leaf_{CNdec} \quad (F.25)$$

With this, the model has completed regenerating new trees and updates the number of trees on the plot to reflect the new trees added. Finally, it updates the seedling bank for each species by multiplying the current number of seedlings by a species-specific input parameter that corresponds to annual seedling percent survival (sl_{surv}). The model also converts the seedling bank back to a per m^2 value.

$$Sl_{bank} = Sl_{bank} \cdot sl_{surv}/plotsize \quad (F.26)$$

Finally, the model calculates the plot-level remaining nitrogen using the N_{used} and N_{avail} variables that were calculated throughout the simulation:

$$N_{remain} = N_{avail} - N_{used} \quad (F.27)$$

If the remaining nitrogen is greater than 0.0, the amount of nitrogen going into the organic layer from the A layer is calculated as

$$AO_{Nflux} = N_{remain}(\min\left(\frac{R}{1000.0}, 0.1\right)) \quad (F.28)$$

where R is the runoff for the plot that year. Next, the model updates the nitrogen content of the A layer:

$$A_{N0} = A_{NO} + N_{remain} - AO_{Nflux} \quad (F.29)$$

If N_{remain} was calculated to be 0.0 or lower, the nitrogen flux into the organic layer is 0.0 and the new nitrogen content for the A layer is:

$$A_{N0} = A_{N0} + N_{remain} \quad (F.30)$$

Next, the nitrogen content of the A layer is modified based on the runoff for that year:

$$A_{N0} = A_{NO} - 0.00002R \quad (F.31)$$

The carbon content of the A layer is also modified using the amount of nitrogen that was transferred to the organic layer.

$$A_{C0} = A_{C0} - 20.0AO_{Nflux} \quad (F.32)$$

Next, carbon and nitrogen for the B layer is updated:

$$B_{C0} = B_{C0} + 20.0AO_{Nflux} \quad (F.33)$$

$$B_{N0} = B_{N0} + AO_{Nflux} \quad (F.34)$$

Finally, the N and C from the litter collected is added to the organic layer:

$$AO_{C0} = AO_{C0} + AO_{Cinto} \quad (F.35)$$

$$AO_{N0} = AO_{N0} + AO_{Ninto} \quad (F.36)$$

With these calculations, the model has finished its simulations for the year and moves on to the next year.

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