Appendix

Model Calibration

Calibration of TEM-Hydro involves adjusting several parameters to get the site specific (targeted) carbon in vegetation and soils such as total vegetation and soil carbon, GPP, Nitrogen-limited Net Primary Production (NPP), nitrogen-saturated NPP, and available inorganic nitrogen. The model is calibrated to develop parameter values for photosynthesis (cmax), uptake of inorganic nitrogen (nmax), maintenance respiration (kr), heterotrophic respiration (kd), and vegetation carbon ($\tau_{heartwood}$). Our calibration sites are Harvard Forest, MA for temperate deciduous forest (oak, maple) and temperate coniferous forest (pine), Bonanza Creek, AK for boreal forest (spruce), Pawnee grasslands, CO, a predominantly C4 short grassland, and Curlew shrubland, UT, a mixed C3 deciduous and C4 evergreen shrubland. For C3 vegetation we assume a half saturation constant (kc) of 200 for the effects of CO_2 fertilization, consistent with [*Felzer et al.*, 2009]. For C4 vegetation we assume a low kc value of 40. We assume Pawnee is a 30/70 C3/C4 mix and Curlew is 50/50. Final calibrated values are given in the **Table A1**. Other biome-dependent parameters are given in **Table A2** and biome independent parameters in **Table A3**. Target carbon and nitrogen stock and flux values for each biome are given in **Table A4**. USGS stream gauges used for validation are given in **Table A5**.

Running Means: Many new variables are running means; the timescale used to calculate them is based on the characteristic timescale for turnover of living plant tissue. Some of the specific usages of running means are included in the descriptions below.

Canopy Conductance: The canopy conductance (g_c) is according to Ball et al. [1987]:

$$g_c = gs_{min} \times LAI + gs_a \frac{GPP \times RH}{C_a}$$

$$g_s = \frac{g_c}{LAI}$$

where gs_{min} is minimum stomatal aperture (mmol m^{-2} s^{-1}), gs_a is the stomatal slope (unitless), LAI is the leaf area index, GPP is the Gross Primary Productivity, RH is the relative humidity, C_a is the ambient carbon dioxide concentration, and g_s is the average stomatal conductance.

Aerodynamics and Windspeed: To better account for the effects of broad climatological variations in windspeed on surface energy fluxes, we now read in a windspeed dataset. This is used, together with vegetation height, to determine aerodynamic resistances within the soil-canopy-atmosphere system. These aerodynamic resistances are used in the Shuttleworth and Wallace [1985] evapotranspiration formula. The formulations below are from Choudhury and Monteith [1988], Federer et al. [1996] and Zhou et al. [2006].

$$rac = \frac{100.0 \times neddy \times \left(wleaf \times k\_karman \right)^{0.5}}{2.0 \times LAI \times \left(u* \times \log\left(zh - zd \right) / zo \right)^{0.5} \times \left(1.0 - \exp\left(-0.5 \times neddy\right)\right)} \quad (1)$$

$$ras = \frac{zh \times \exp\left(neddy\right) \times \left(1.0 - \exp\left(-neddy \times \left[zd + zo\right] / zh\right)\right)}{k\_karman \times u* \times neddy \times \left(zh - zd\right)} \quad (2)$$

$$raa = \frac{zh \times \left(\exp\left[neddy \times \left(1.0 - \left(zd + zo\right) / zh\right) - 1.0\right] / \left[neddy \times \left(zh - zd\right)\right]\right) + \log\left(\left[za - zd\right] / \left[zh - zd\right]\right)}{u* \times k\_karman} \quad (3)$$

where *rac* = leaf-to-canopy aerodynamic resistance, *ras* = soil-to-canopy aerodynamic resistance, *raa* = canopy-to-screen height aerodynamic resistance, *wleaf* = biome-dependant parameter, and

$$ua = u \times \frac{\log\left(296.97/0.005\right)}{\log\left(296.97/zo\right)} \times \frac{\log\left(\left[za - zd\right]/zo\right)}{\log\left(10.0/0.005\right)}$$

$$zh = href \times cabove^{kallom}$$

$$za = zh + 2.0$$

$$zd = \min\left(1.1 \times zh \times \log\left[1.0 + \left(0.1 \times LAI\right)^{0.25}\right], 0.9 \times zh\right)$$

$$zo = 0.3 \times zh \times \min\left(0.01 + \left(0.1 \times LAI\right)^{0.5}, 1 - zd/zh\right)$$

$$u* = k\_karman \times ua / \log\left(\left[za - zd\right]/zo\right)$$

$$neddy = 2.306 + 0.194 \times zh$$

where *ua* = windspeed at 2 m above the canopy, *zh* = canopy height, *za* = reference height 2 m above canopy, *zd* = displacement height, *u** = friction velocity, and *neddy* = eddy resistance coefficient. The friction velocity depends on the windspeed and roughness length (*zo*). The roughness length depends on the canopy density and canopy height. The displacement height depends on the canopy height and LAI. Other variables are: *u* = windspeed at 10 m height, *href* = biome-dependent reference height, *kallom* = biome-dependent parameter, *cabove* = total above ground biomass in kg C m^{-2}, *k_karman constant* = 0.41. The canopy aerodynamic resistance (*rac*) decreases as *LAI* and *u** increase; the more air is moving through a denser canopy, the more coupled the canopy is to the air. N_{eddy} is related to a turbulent closure parameterization; as

it increases with vegetation height, the soil is more and more cut off from the atmosphere (e.g. r_{as} becomes larger).

Internal Leaf CO_2: The internal leaf CO_2 (c_i) is now consistent with the calculation of GPP and stomatal conductance, assuming that the CO_2 on the leaf surface is equal to the atmospheric CO_2. The equations to be solved for c_i simultaneously are:

$$GPP = c\max \times fpar \times temp \times fozone \times fh2o \times \frac{c_i}{k_c + c_i} = fp \times \frac{c_i}{k_c + c_i} \quad (4)$$

$$GPP = \frac{gc}{1.563}\left(C_a - C_i\right) \quad (5)$$

$$gc = gs\min \times LAI + \frac{gsa \times (GPP - r_l) \times RH}{c_a} \quad (6)$$

where *cmax* = maximum leaf-level photosynthetic rate, *fpar* = canopy integrated light response function, *temp* = GPP dependence on temperature, *kc* = half-saturation constant of CO_2 fertilization, 1.563 = ratio of molecular diffusivity of water vapor to carbon dioxide ($(44/18)^{0.5}$), c_a = atmospheric CO_2 level, *gsmin* = minimum stomatal aperture (mmol m^{-2} s^{-1}), *gsa* = stomatal slope, r_l = leaf growth and maintenance respiration (mmol m^{-2} s^{-1}), and *RH* = relative humidity. The simultaneous solution of c_i involves the solution to a quadratic equation. The solution is:

$$a = -gs\min \times LAI * c_a \times \left(GPP - r_a\right)$$

$$b = c_a \times \left(gsa \times fd - 1.563\right) \times \left(GPP - r_a\right) + gsa \times RH \times r_a \times k_c + gs\min \times LAI \times c_a \times \left(c_a - k_c\right)$$

$$c = c_a \times k_c \times \left(gs\min \times LAI * c_a - r_a \times \left(gsa \times RH - 1.563\right)\right)$$

$$C_i = \frac{-b - \left(\left[b^2 - 4 \times a \times c\right]^{0.5}\right)}{2 \times a}$$

This solution can be thought of graphically by plotting the equation for GPP from (4) together with the equation for GPP from (5) and (6) (after eliminating gc), as the dependent variable, with the independent variable being ci. C_i tends to lie in between c_a and 0; though for r_a > GPP, it may be larger. When the gsmin*LAI term and r_l are negligible in equation (6), this expression tends toward the open-stomata limit used in Felzer et al. [2009].

Canopy Interception: Canopy interception is now explicitly calculated, along with soil evaporation and transpiration. Canopy interception is a function of precipitation and LAI.

$$can\,\text{int} = ndays \times (1.0 - \exp(-0.005 \times prec)) * (1.0 - \exp(kext \times LAI)) \times 0.1 \times LAI \quad (7)$$

where *ndays* = number of days in a month, *prec* = precipitation, and *kext* = biome-dependent extinction coefficient. The energy flux associated with this term is subtracted from the net radiation in the evapotranspiration computation. This term can be thought of as something like a product of the number of rain events n_{rain} ~ {*ndays* x (1-exp(-0.005 *prec*))}, the probability of a raindrop hitting a leaf p_{int} ~ {1.0-exp(*kext* x *LAI)*}, and the total evaporative capacity of the canopy per rainfall event e_{int} ~ (0.1 x *LAI*). Thus, a wet region with 100 mm month^{-1} of rain (n_{rain} ~12) and an *LAI* of 4 (p_{int} ~ 0.9, e_{int} ~ 0.4) would intercept ~ 4 mm month^{-1}. A more thorough treatment (many exist) would consider the evaporative demand of the atmosphere and would track the stock of leaf-surface water explicitly, but we lack the temporal resolution (in data and other model equations) to perform such calculations. Parameters in the equation, especially the "0.1", could be modified to attempt to better fit data.

Day-Night disaggregation: Energy fluxes and photosynthesis are computed separately for day and night. This requires use of a diurnal temperature range dataset, and calculation of day and night temperature, vapor pressure deficit, and longwave radiation.

Photosynthesis Detailed description is in Felzer et al. [2009]. The temperature term, f_T, now uses the daytime temperature. The canopy conductance, based on Ball et al. [1987] and the related internal CO_2, is now a function of relative humidity rather than a hyperbolic function of vapor pressure deficit, so that is now calculated from using daytime temperature. The photosynthetically active radiation (PAR) is an average daytime value.

Canopy Conductance As detailed above, the moisture dependency is based on relative humidity, which is calculated from vapor pressure and daytime and nighttime temperature.

Evapotranspiration Evapotranspiration is calculated using the Shuttleworth and Wallace [1985] approach. Terms that now include day and night differentiation include net radiation, including soil and snow storage, the rate of change of vapor pressure with temperature (β), which depends upon both temperature and vapor pressure deficit, and vapor pressure deficit itself. Daytime and nighttime temperature and vapor pressure deficit (calculated from the vapor pressures and respective temperatures) are used. In addition, emitted longwave radiation is subtracted from the net radiation term (*rn*) and from the soil radiation (*rnsoil*), and that is based upon daytime and nighttime temperature according to the Stefan-Boltzmann Law.

$$lw = \left(1..0 - 1.24 \times \frac{vpr}{T}^{1.0/7.0}\right) \times cor \times \sigma \times T^4 + ecan + esoil$$

$$cor = 1.6 \times \frac{nirr}{girr} - 0.2$$

where *vpr* = vapor pressure, *T* = temperature in K, σ = Stefan-Boltzman constant, *ecan* = evaporation from canopy interception in W/m^2, *esoil* = soil evaporation in W/m^2, and *cor* = 0.2

or 1.0 depending upon how surface radiation compares to top-of-atmosphere radiation [*Brutsaert*, 1982; *Federer et al.*, 1996].

$$rnsoil = 0.8 \times \left(\left[1-\alpha\right] \times nirr - lw\right) \times \exp\left(-kext \times LAI\right) \quad (8)$$

$$rn = nirr \times \left(1.0-\alpha\right) - lw \quad (9)$$

where α = biome-dependent albedo, which is 0.5 for snowcover and *nirr* = incoming shortwave radiation at the surface.

Soil Evaporation Limitation: A limitation is applied to soil evaporation if available water is much smaller than the field capacity and the soil evaporation is much larger than the precipitation.

If[(availh2o < 0.5 x awcap) and (evap > 0.5 x prec)] then

esoil = 0.5 x prec (10)

where *evap* = soil evaporation calculated from SW approach and *esoil* = evaporated soil water in mm. This equation is derived heuristically and is included to ensure that available water does not become negative.

Drought-stress Function: Roots and stems are required for water transport, and thus more allocation to them should carry benefits for reducing drought stress. These marginal benefits are calculated based on a new drought-stress formula and the marginal benefits vs costs of roots and stems are used to drive allocation.

$$fh2o = 1.0 - \exp\left(-\left[lsc/lsc\,\min\right] \times wfrac\right) \quad (11)$$

$$lsc = \frac{gstem \times stemc \times groot \times rootc}{\left(gstem \times stemc + groot \times rootc\right) \times LAI}$$

$$gstem = \frac{kstem}{1000 \times rhostem \times zh^2}$$

$$wfrac = \frac{availh2o}{awcap}$$

where *lsc* = leaf specific conductance (mmol m^{-2} s^{-1} MPa^{-1}) , *lscmin* = biome-dependent minimum lsc, *gstem* = above-ground hydraulic conductance (mmol m^{-2} s^{-1} MPa^{-1}), *kstem* = biome-dependent sapwood hydraulic conductivity (mmol m^{-1} s^{-1} MPa^{-1}), *rhostem* = biome-dependent stem density (g m^{-3}), *groot* = biome-dependant root hydraulic conductance (mmol gC^{-}

[1] s^{-1} MPa^{-1}), *stemc* = total stem carbon, *rootc* = total root carbon, *availh2o* = total soil moisture, *awcap* = water capacity, which is difference between field capacity and wilting point, now calculated from the Saxton equations [*Saxton et al.*, 1986] based on soil texture, and discussed below. These terms are used in the calculation of GPP and internal CO_2 (*fh2o*), and the marginal benefits of leaves (*fh2o*), stems, and roots (*lsc*, *wfrac*). For grasslands we developed an alternate function:

$$wfrac' = wfrac \times \left(\frac{wfrac}{(0.01 + wfrac)} \right)^2$$

$$fh2o' = 1.0 - \exp\left(-[lsc/lsc\min] \times wfrac^2\right)$$

In this case, *wfrac'* has both has both zero value and zero derivative as *wfrac* goes to zero. This function GPP to approach zero more smoothly as *wfrac* approaches zero.

Saxton Equations: Soil texture of wilting point and field capacity based on Saxton equations [*Saxton et al.*, 1986].

$$pota = 100.0 \times \exp(-4.396 - 0.0715 \times pclay - 0.000488 \times psand^2 - 0.00004285 \times psand^2 \times pclay$$

$$potb = -3.14 - 0.00222 \times pclay^2 - 0.00003484 \times psand^2 \times pclay$$

$$fldcap = rootz \times 1000.0 \times \left(33.0 / pota\right)^{\frac{1.0}{potb}} \quad (12)$$

$$wiltpt = rootz \times 1000.0 \times \left(1500.0 / pota\right)^{1/potb} \quad (13)$$

Optimal Temperature for Photosynthesis: The optimum temperature for photosynthesis (*topt*) in stress-deciduous biomes (i.e. grasslands) is now based on the running mean temperature during the growing season rather than the maximum temperature during the year to allow for lower optimum temperatures in cold grasslands, resulting in larger and more realistic productivity. The functional form is now more symmetrical about an optimum temperature for all biomes.

$$pow = \frac{(topt - t\min)}{t\max - topt}$$

$$temp = \frac{\left((t\max - tair) \times \left(tair - t\min\right)^{pow}\right)}{\left((t\max - topt) \times \left(topt - t\min\right)^{pow}\right)} \quad (14)$$

where *tmax* and *tmin* are biome-dependent parameters. This equation has a parabolic structure, with a broad maximum, if topt = (tmax+tmin)/2. Topt is allowed to acclimate to a given climate, but as it approaches tmax or tmin, the peak of the temperature function becomes sharper. This is intended to reflect the broad temperature tolerance of a given biome, but increased specialization and sensitivity near the temperature limits of a biome. Typically, topt > (tmax+tmin)/2, implying that pow > 1, and the function is concave up at low temperatures.

Heterotrophic Respiration Moisture Term: In the previous version of TEM, the moisture function for heterotrophic respiration ($rhxh_2o$) depended upon volumetric soil moisture (*vsm*) and biome-dependent values for the minimum, maximum and optimum to define the shape of the curve. This function is based on the concept that maximum decomposition rates occur when soils are 50-80% saturated with water [*Alexander*, 1977; *Clark*, 1967], however it does not take into account differences in soil texture. Clay soils, for example, can hold more water than sandy soils, and so their larger soil moisture will result in higher respiration rates.

$$\%\,porosity = 100 \times \left(0.332 - 0.0007251 \times \%sand + 0.1276 \times \log\left(\%clay\right)\right)$$

$$wfps = \frac{100 \times vsm}{\%\,porosity}$$

$$rhxh_2o = \frac{0.2 + 0.8 \times wfps \times (1 - wfps)}{wfps \times (1 - wfps) + (0.6 - wfps) \times (0.6 - wfps)}$$

where *wfps* is the water-filled pore porosity.

Nitrogen-Limitation: In the determination of N-limiting conditions, we now use running means of labile carbon and nitrogen (to determine supply) and allocation and resorption terms (to determine demand). N-limitation occurs when both the running mean of the labile C:N is larger than the running mean of the demand C:N and the instantaneous labile C:N is larger than a target C:N. The target C:N is based on the ratio of the sum of the carbon allocations and growth respiration and labile maintenance respiration with the nitrogen labile allocations, as described in Felzer et al. [2009]. This approach allows for luxury carbon and nitrogen uptake as long as the long term C:N supply is consistent with the C:N demand and avoid combining stocks and fluxes.

$$SupplyC:N = \frac{rlabileC}{rlabileN}$$

$$DemandC:N = \frac{r\left(\sum calloc + r_g\right)}{r\left(\sum nalloc - nresorb\right)}$$

$$cntar = \frac{\sum calloc + r_g}{\sum nalloc}$$

where *r* indicates running means, *calloc* = total carbon allocation too leaves, active stems, and roots, *nalloc* = total nitrogen allocation to leaves, active stems, and roots, *nresorb* = nitrogen resorption to leaves, and r_g = growth respiration.

if (*SupplyC:N* > *DemandC:N* and *labileC/labileN* > *cnprod*) then

$$GPP = \frac{DemandC:N}{SupplyC:N} \quad (15)$$

if(*SupplyN:C* > *DemandN:C* and *labileN/labileC* > *1/cnprod*) then

$$Nuptake = \frac{DemandN:C}{SupplyN:C} \quad (16)$$

where *DemandN:C = 1/DemandC:N* and *SupplyN:C = 1/SupplyC:N*.

Nitrogen availability depends upon the incoming flux, net nitrogen mineralization, and the outgoing flux, plant nitrogen uptake. Net nitrogen mineralization is the difference between gross nitrogen mineralization and immobilization and is unchanged from earlier version of TEM [*Raich et al.*, 1991]. Gross nitrogen mineralization is the product of the ratio of soil organic nitrogen to soil organic carbon with the heterotrophic respiration. Immobilization depends upon available nitrogen and soil moisture. Nitrogen uptake depends upon temperature and is describe fully in Appendix 3 of Felzer et al. [2009].

Dynamic Equilibration: Rather than equilibrating to a long-term average climate and then being "spun up" by 3 40-year transient climate repetitions, it is now possible to equilibrate to the variability found in the observed climate timeseries. This allows interannual variability to be captured in calibration, and hopefully reduces any artifacts of the transition from spin-up to transient climate. Determination of when the model is equilibrated is now based on 40 year means of stocks rather than annual flux values, since annual fluxes generally do not equilibrate in a climate with interannual variability.

Carbon Benefits: Since the expected gains in the carbon formula for GPP don't always translate to actual gains because of N-limitation, we reduce the expected gains to account for this discrepancy. Carbon marginal benefits for all plant compartments are pro-rated by the expected ratio of running means of actual gpp to potential (non-n-limited) gpp. Also, the benefits of roots for nitrogen uptake are now accounted for, and these benefits are converted to carbon currency by the expected c:n of newly produced tissue. Nitrogen-uptake benefits of roots are pro-rated by the difference between potential gpp and actual gpp, as a fraction of potential gpp. More nitrogen limitation means a larger difference, and thus a purer benefit to increasing carbon acquisition by n uptake. If actual gpp is close to potential gpp, then the benefits to carbon acquisition of increasing n uptake are relatively small.

Daily Timestep and new adaptive integrator: The model now uses a base daily timestep (though identical meteorological driving conditions are used within a month) to solve the

differential equations of the ecosystem. The integrator used to numerically solve has been changed to the Bogacki-Shampine 2-3 order Runge-Kutta method, which requires on average 3 calls to delta per timestep. Run speeds are decreased, but by a factor of perhaps 2.5, not 30 as might be expected. This change was implemented to allow a transition to daily data (or coupling with daily output from a climate model), and to ensure numerical stability of some outputs. The previous integrator contained backwards timesteps which would occasionally produce unintended behavior in some of the new routines.

Figures

Figure A1: Moisture stress functions (*fh2o, fh2o'*) for different values of *wfrac* and *lsc/lscmin*=1 and *lsc/lscmin*=4.

Figure A2: Moisture function for heterotrophic respiration for several different soil porosities.

Figure A3: TEM-Hydro carbon cycle is further divided between four vegetation structural pools (fine roots, leaves, sapwood, and heartwood), and a labile pool for storage.

Figure A4: TEM-Hydro nitrogen cycle is further divided between four vegetation structural pools (fine roots, leaves, sapwood, and heartwood), and a labile pool for storage.

Figure A5: Soil evaporation and plant transpiration are determined using a simple bucket model with the [*Shuttleworth and Wallace*, 1985] approach to calculating ET.

References

Alexander, M. (1977), *Introduction to soil microbiology, Second Edition*, John Wiley and Sons, New York, New York.

Ball, J. T., I. E. Woodrow, and J. A. Berry (1987), A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions, *Progress in Photosynthesis Research*, *IV*(Journal Article), ISBN9024734533.

Brutsaert, W. (1982), *Evaporation into the Atmosphere: Theory, History, and Applications*, 299 pp., D. Reidel, Hingham, MA.

Choudhury, B. J., and J. L. Monteith (1988), A four-layer model for the heat budget of homogeneous land surfaces, *Quarterly Journal of the Royal Meteorological Society*, *114*(Journal Article), 373-398.

Clark, F. E. (1967), Bacteria in soil, in *Soil Biology*, edited by A. Burges and F. Raw, pp. 15-49, Academic Press, London, England.

Federer, C. A., C. J. Vorosmarty, and B. Fekete (1996), Intercomparison of methods for calculating potential evapotranspiration in regional global water balance models, *Water Resources Research*, *32*(Journal Article), 2315-2321.

Felzer, B. S., T. W. Cronin, J. M. Melillo, D. W. Kicklighter, and C. A. Schlosser (2009), Importance of carbon-nitrogen interactions and ozone on ecosystem hydrology during the 21st century, *JGR-Biogeosciences*, *114*(Journal Article).

Raich, J. W., E. B. Rastetter, J. M. Melillo, D. W. Kicklighter, P. A. Steudler, B. J. Peterson, A. L. Grace, B. Moore Iii, and C. J. Vorosmarty (1991), Potential net primary productivity in South America: application of a global model, *Ecological Applications*, *1*(4), 399-429.

Saxton, K. E., W. J. Rawls, J. S. Romberger, and R. I. Papendick (1986), Estimating generalized soil-water characteristics from texture, *Soil Sci. Soc. Am. J.*, *50*, 1031-1036.

Shuttleworth, W. J., and J. S. Wallace (1985), Evaporation from sparse crops: an energy combination theory, *Quarterly Journal of the Royal Meteorological Society*, *111*, 839-855.

Zhou, M. C., H. Ishidaira, H. P. Hapuarachchi, J. Magome, A. S. Kiern, and K. Takeuchi (2006), Estimating potential evapotranspiration using Shuttleworth-Wallace model and NOAA-AVHRR NDVI data to feed a distributed hydrological model over the Mekong River basin, *Journal of Hydrology*, *327*(1-2), 151-173.

Table A1: TEM-Hydro Calibration parameters

description	temp. dec.	temp. conif.	boreal forest	shrub-land	grass-land	unit
maximum leaf-level assimilation rate	19.50	11.80	10.55	17.00	26.00	umol CO_2 m^{-2} s^{-1}
stem mortality	54.75	56.00	140.00	13.00	2.30	years
autotrophic respiration coefficent	0.3400	0.2200	0.5000	0.2600	0.1400	umol CO_2 gN^{-1} s^{-1} at topt
heterotrophic respiration coefficient	0.0250	0.0190	0.0110	0.0080	0.0112	fractional decomposition per month
maximum root-system nitrogen uptake rate	685.00	495.00	625.00	625.00	47.00	gN m^{-2} $month^{-1}$
immobilization rate coefficient	12.90	10.00	20.50	53.00	9.75	maximum gN immobilized per gC of r_h

Table A2a: Biome-dependent parameters used in TEM-Hydro

parameter	description	temp. dec.	temp. conif.	boreal forest	shrub-land	grass-land	units
kc	CO_2 response half-saturation constant	200	200	200	120	40	ppmv CO_2
tmin	minimum temperature	0	-1	5	1	0	^oC
toptmin	minimum topt	23	22	17	15.1	13	^oC
toptmax	maximum topt	30.9	30	25	35.1	32.7	^oC
tmax	maximum temp.	40	38	32	44	38	^oC
sla[1]	specifc leaf area	0.0242	0.00863	0.0137	0.0192	0.0356	$m^2\ gC^{-1}$
href	reference height	6	6	6	3	6	meters
krnup	half-saturation constant for vegetation n uptake (wrt root extent)	128.3	97.4	21.8	60.5	2.48	g rootC m^{-2}
kallom	allometric coefficient for height	0.467	0.467	0.467	0.5	0.5	N/A
cnleaf	C:N leaf	23.8	47.5	50	25	30.5	gC gN^{-1}
cnsapwood	C:N sapwood	300	500	500	200	34.5	gC gN^{-1}
cnheartwood	C:N heartwood	300	500	500	200	34.5	gC gN^{-1}
cnroot	C:N root	44.6	57.7	50	49.7	40.5	gC gN^{-1}
cnseed	C:N seed	44.6	57.7	50	25	40.5	gC gN^{-1}
fsaplive	fraction of sapwood that is alive	0.17	0.07	0.07	0.13	0.5	gC living gC $sapwood^{-1}$
phen	phenological class	1	0	0	0	2	0 = evergreen; 1 = cold-deciduous; 2 = stress-deciduous
wleaf	width of leaf[2]	0.01	0.002	0.002	0.01	0.005	meters
[3]gsa	slope of photosynthesis-conductance relation	9	6	6	6	4	N/A
gsmin	min. stomatal conductance	10	10	10	10	25	mmol $m^{-2}\ s^{-1}$
kext	extinction coefficient	0.5	0.5	0.5	0.3	0.5	fraction

albedo	albedo	0.18	0.14	0.14	0.21	0.2	fraction
lscmin	min. leaf specific conductance	0.1	0.1	0.1	0.25	0.25	$mmolm^{-2}s^{-1}MPa^{-1}$
groot	root hydraulic conductance	0.02	0.0269	0.0269	0.025	0.002	$mmol\ gC^{-1}\ s^{-1}\ MPa^{-1}$
kstem	sapwood hydraulic conductivity	200000	72200	72200	50000	50000	$mmol\ m^{-1}\ s^{-1}\ MPa^{-1}$
rhostem	C density in sapwood	250	209	209	250	250	$gC\ m^{-3}$
rootzc	constant coefficient for rooting depth	2	2	2	5	1.5	meters
vegtauleaf	leaf lifetime	1	2	2	2	1	years
vegtauroot	root lifetime	1	1	1	1	1	years
vegtauseed	seed lifetime	1	1	1	1	1	years
microbelcclnc	reference C:N of litter, used to adjust decomposition rate	70.87	67.4	67.4	70.87	57.1	$gC\ gN^{-1}$
microbecnsoil	target c:n of soil organic matter	20	20	29.73	11.9	11.12	$gC\ gN^{-1}$
vegcnltr	c:n of leaf litter	57.3	48.8	60	30	75	$gC\ gN^{-1}$
o3para	damage coefficient for ozone exposure	2.6	0.7	0.7	2.6	3.9	

[1]Schulze, E. D., Kelliher, F. M., Korner, C., Lloyd, J., and Leuning, R. 1994. Relationships among maximum

[2]Choudhury, B. J. and Monteith, J. L. 1988. A four-layer model fo the heat budget of homogenous land

[3]calibrated to match annual et (yreet)

Table A2b: Biome-independent parameters used in TEM-Hydro

parameter	description	value	units
ki	light response half-saturation constant	75	cal cm^{-2} day^{-1}
[1]raalpha	respiration parameter regarding curve shape	0.01	N/A
[1]rabeta	minimum temperature of ra	-5	^{o}C
[1]ragamma	maximum temperature of ra	55	^{o}C
[1]raqref	reference "Q10" of ra	2.07	N/A
[1]ratref	reference temperature for ra	25	^{o}C
kn1	half-saturation constant for vegetation n uptake (wrt N-concentration)	0.0042	vsm^3 g AVLN (kg soil H20)^-1
[2]cdleaf	drag coefficient of leaf	0.1	N/A
[3]rhalpha	respiration parameter regarding curve shape	0.009	N/A
[3]rhbeta	minimum temperature of rh	-10	^{o}C
[3]rhgamma	maximum temperature of rh	100	^{o}C
[3]rhqref	reference "Q10" of rh	1.83	N/A
[3]rhtref	reference temperature for rh	25	^{o}C
kn2	half-saturation constant for microbial n uptake (wrt N-concentration)	0.0042	
rssmin		400	
rssslope	increase in soil surface resistance with 1 mm of depletion below field capacity	40	s m^{-1} mm^{-1}

[1]Hanson, P. J., Amthor, J. S., Wullschleger, S. D., Wilson, K. B. Grant, R. F., Hartley, A., Hui, D., Hunt, E. R. Jr., Johson, J. S., King, A. W., Luo, Y., McNulty, S. G., Sun, G., Thornton, P. E., Wang, S., Williams, M., Baldocchi, D. D>, and Cushman, R. M. 2004. Oak forest carbon and water simulations: model intercomparisons and evaluations against independent data. Ecological Monographs. 74(3): 443-489. (LaRs reference)

[2]Choudhury, B. J. and Monteith, J. L. 1988. A four-layer model fo the heat budget of homogenous land surfaces. Quarterly Journal of the Royal Meteorological Society. 114: 373-398.

[3]Lloyd, J. and Taylor, J. A. 1994. On the temperature dependence of soil respiration. Functional Ecology. 8: 315-323.

Table A3: TEM-Hydro Target Values parameterization

Harvard Forest Coniferous (Temperate Coniferous Forest)

Variable	*Value*	*Units*	*Source*
VEGC	10800	gC m^{-2}	based on *McClaugherty et al.* [1982; *Pastor et al.* [1984], and K.J. Nadelhoffer (unpublished data, 1991)
SOILC	8290	gC m^{-2}	based on *Gaudinski et al.* [2000] – all carbon above bottom of BW1 horizon
SOILN	414.5	gN m^{-2}	assume soil C:N ratio of 20
AVALN	1.9	gN m^{-2}	based on *Vitousek et al.* [1982]
NPP	600	gC m^{-2} yr^{-1}	based on *McClaugherty et al.* [1982; *Pastor et al.* [1984], and K.J. Nadelhoffer (unpublished data, 1991)
GPP	1130	gC m^{-2} yr^{-1}	based on *Waring et al.* [1998]
NPPSAT	750	gC m^{-2} yr^{-1}	assume N saturation effect is 25%
NUPTAKE	8.9	gN m^{-2} yr^{-1}	based on Figure 2 of *Aber et al.* [1983] – assume N up = N min.
pleafc	0.42		same as for NPP
pstemc	0.25		same as for NPP
prootc	0.33		same as for NPP
LAI(target)	4.4		[*Barford et al.*, 2001]
yrEET	569	mm	Lternet website: http://intranet.lternet.edu/archives/documents/Publications/climdes/siteclim.toc.html

Harvard Forest Deciduous (Temperate Deciduous Forest)

Variable	*Value*	*Units*	*Source*
VEGC	17440	$gC\ m^{-2}$	based on *McClaugherty et al.* [1982; *Pastor et al.* [1984], and K.J. Nadelhoffer (unpublished data, 1991)
SOILC	8290	$gC\ m^{-2}$	based on *Gaudinski et al.* [2000] – all carbon above bottom of BW1 horizon
SOILN	414.5	$gN\ m^{-2}$	assume soil C:N ratio of 20
AVALN	2.2	$gN\ m^{-2}$	based on *Vitousek et al.* [1982]
NPP	730	$gC\ m^{-2}\ yr^{-1}$	based on *McClaugherty et al.* [1982]; *Pastor et al.* [1984], and K.J. Nadelhoffer (unpublished data, 1991)
GPP	1380	$gC\ m^{-2}\ yr^{-1}$	based on *Waring et al.* [1998]
NPPSAT	912.5	$gC\ m^{-2}\ yr^{-1}$	assume N saturation effect is 25%
NUPTAKE	10.3	$gN\ m^{-2}\ yr^{-1}$	based on Figure 2 of *Aber et al.* [1983] – assume N up = N min.
pleafc	0.29		same as for NPP
pstemc	0.36		same as for NPP
prootc	0.35		same as for NPP
LAI(target)	4.4		[*Barford et al.*, 2001]
yrEET	569	mm	Lternet website: http://intranet.lternet.edu/archives/documents/Publications/climdes/siteclim.toc.html

Bonanza Creek (Boreal Forest)

Variable	*Value*	*Units*	*Source*
VEGC	9000	$gC\ m^{-2}$	[*Oechel and Van Cleve*, 1986; *Van Cleve et al.*, 1983]
SOILC	11000	$gC\ m^{-2}$	[*Van Cleve et al.*, 1983]
SOILN	370	$gN\ m^{-2}$	[*Van Cleve et al.*, 1983]
AVALN	0.5	$gN\ m^{-2}$	
NPP	220	$gC\ m^{-2}\ yr^{-1}$	[*Van Cleve et al.*, 1983; *Weber and Van Cleve*, 1984]
GPP	550	$gC\ m^{-2}\ yr^{-1}$	[*Viereck et al.*, 1983]
NPPSAT	330	$gC\ m^{-2}\ yr^{-1}$	[*Chapin III et al.*, 1986; *Van Cleve and Zasada*, 1976]
NUPTAKE	2.3	$gN\ m^{-2}\ yr^{-1}$	[*Oechel and Van Cleve*, 1986; *Van Cleve et al.*, 1983]
pleafc	0.65		same as for NPP
pstemc	0.08		same as for NPP
prootc	0.27		same as for NPP
LAI(target)	2.65		[*Scurlock et al.*, 2001]
yrEET	194	mm	Lternet website: http://intranet.lternet.edu/archives/documents/Publications/climdes/siteclim.toc.html

Pawnee Shortgrass Steppe (Shortgrass prairie)

Variable	*Value*	*Units*	*Source*
VEGC		gC m^{-2}	allow TEM to calculate – do not calibrate
SOILC	3436	gC m^{-2}	grandfathered
SOILN	309	gN m^{-2}	grandfathered
AVALN	2.0	gN m^{-2}	grandfathered
NPP	184	gC m^{-2} yr^{-1}	[*Michunas and Laurenroth*, 1992]
GPP	357	gC m^{-2} yr^{-1}	based on old GPP/NPP ratio of 1.94
NPPSAT	368	gC m^{-2} yr^{-1}	assume N saturation effect is 100%
NUPTAKE	4.2	gN m^{-2} yr^{-1}	[*Schimel et al.*, 1985] average N mineralization for summit, backslope, and footslope
pleafc	0.21		same as for NPP
pstemc	0.23		same as for NPP
prootc	0.56		same as for NPP
LAI(target)	0.55		[*Knight*, 1973]
yrEET	372	mm	

Curlew (Xeric Shrubland)

Variable	*Value*	*Units*	*Source*
VEGC	540	gC m^{-2}	[*Caldwell et al.*, 1977]
SOILC	2500	gC m^{-2}	[*Bjerregaard*, 1971; *McGuire et al.*, 1995]
SOILN	210.1	gN m^{-2}	[*Bjerregaard*, 1971]
AVALN	1.6	gN m^{-2}	[*Gist et al.*, 1978]
NPP	110	gC m^{-2} yr^{-1}	[*Caldwell et al.*, 1977; *Raich and Nadelhoffer*, 1989]
GPP	235	gC m^{-2} yr^{-1}	[*Caldwell et al.*, 1977]
NPPSAT	120	gC m^{-2} yr^{-1}	[*Lajtha and Whitford*, 1989]
NUPTAKE	2.7	gN m^{-2} yr^{-1}	[*McGuire et al.*, 1995]
pleafc	0.2		same as for NPP; also based on [*Knapp*, 1985]
pstemc	0.19		same as for NPP; also based on [*Knapp*, 1985]
prootc	0.6		same as for NPP
LAI(target)	2.08		[*Scurlock et al.*, 2001]
yrEET	152	mm	

References

Aber, J. D., et al. (1983), Potential sinks for mineralized nitrogen following disturbance in forest ecosystems, *Ecological Bulletin (Stockholm)*, *35*, 179-192.

Barford, C. C., et al. (2001), Ecological measurements to compliment eddy-flux measurements at Harvard Forest.

Bjerregaard, R. S. (1971), The Nitrogen Budget of Two Salt Desert Shrub Communities of Western Utah, Utah State University, Logan.

Caldwell, M. M., et al. (1977), Carbon balance, productivity, and water use of cold-winter desert shrub communities dominated by C3 and C4 species, *Oecologia*, *29*, 275-300.

Chapin III, F. S., et al. (1986), The nature of nutrient limitation in plant communities, *The American Naturalist*, *127*(1), 48-58.

Gaudinski, J. B., et al. (2000), Soil carbon cycling in a temperate forest: radiocarbon-based estimates of residence times, sequestration rates and partitioning of fluxes, *Biogeochemistry*, *51*, 33-69.

Gist, C. S., et al. (1978), A computer simulation model of nitrogen dynamics in a Great Basin desert ecosystem, in *Nitrogen in Desert Ecosystems*, edited by N. E. West and J. Skujins, pp. 182-206, Dowden, Hutchinson and Ross, Stroudsberg, PA.

Knapp, A. K. (1985), Effect of fire and drought on the ecophysiology of Andropogon gerardii and Panicum vergatum in a tallgrass prairie, *Ecology*, *66*(4), 1309-1320.

Knight, D. H. (1973), Leaf area dynamics of a shortgrass prairie in Colorado, *Ecology*, *54*(4), 891-896.

Lajtha, K., and W. G. Whitford (1989), The effect of water and nitrogen amendments on photosynthesis, leaf demography, and resource-use efficiency in Larrea tridentata, a desert evergreen shrub, *Oecologia*, *80*, 341-348.

McClaugherty, C. A., et al. (1982), The role of fine roots in the organic matter and nitrogen budgets of two forested ecosystems, *Ecology*, *63*, 1481-1490.

McGuire, A. D., et al. (1995), Equilibrium responses of soil carbon to climate change: empirical and process-based estimates, *Journal of Biogeography*, *22*, 785-796.

Michunas, D. G., and W. K. Laurenroth (1992), Carbon dynamics and estimate of primary production by harvetst, ^{14}C dilution, and ^{14}C turnover, *Ecology*, *73*(2), 593-607.

Oechel, W. C., and K. Van Cleve (1986), The role of bryophytes in nutrient cycling in the taiga, in *Forest Ecosystems in the Alaskan Taiga*, edited by K. Van Cleve, et al., pp. 121-137, Springer-Verlag, New York.

Pastor, J., et al. (1984), Biomass prediction using generalized allometric regressions for some Northeast tree species, *Forest Ecol. Manag.*, *7*(265-274).

Raich, J. W., and K. J. Nadelhoffer (1989), Belowground carbon allocation in forest ecosystems: Global trends, *Ecology*, *70*, 1346-1354.

Schimel, D. S., et al. (1985), Biogeochemistry of C, N, and P in as soil catena of the shortgrass steppe, *Ecology*, *66*(1), 276-283.

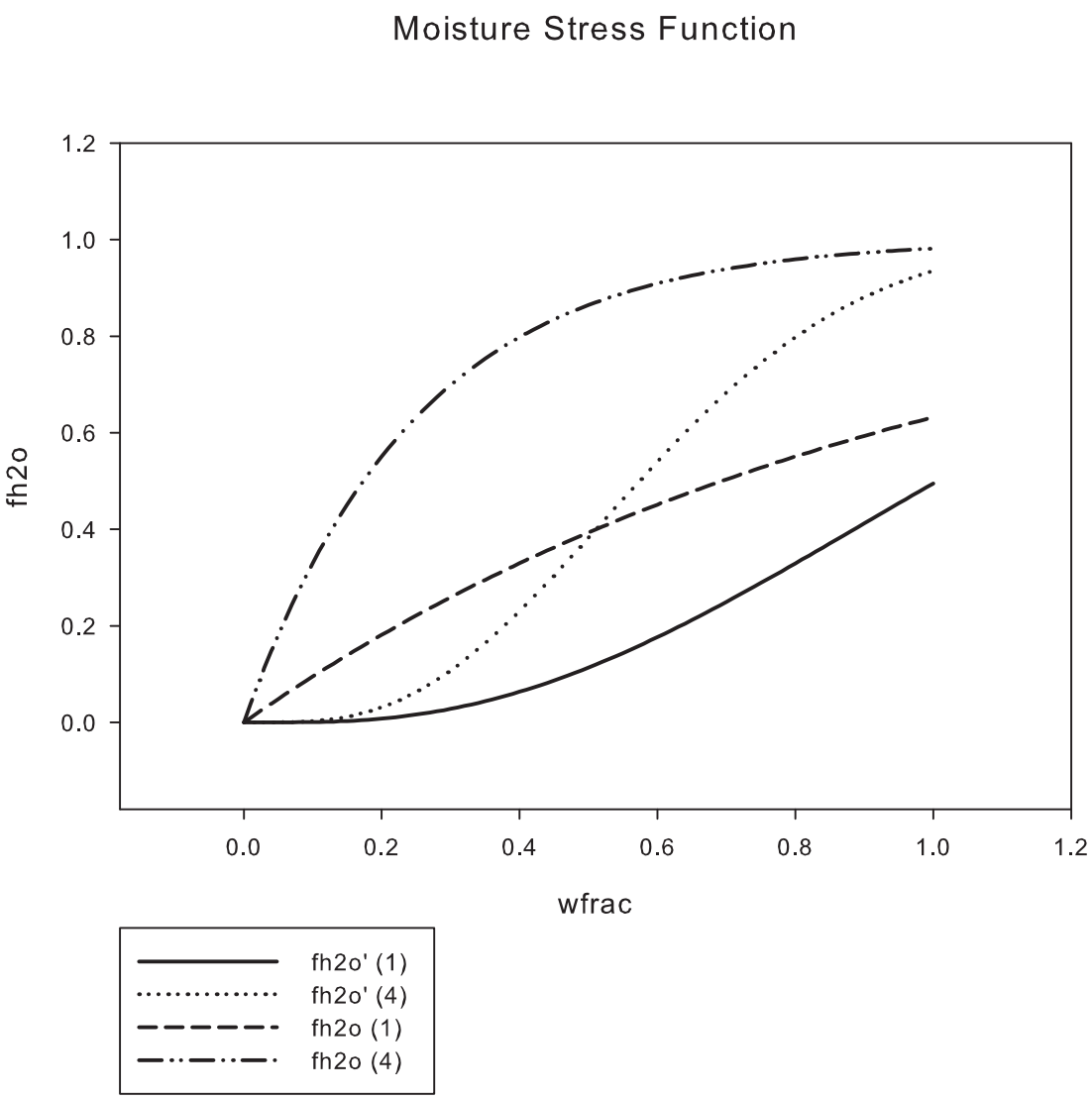
Scurlock, J. M. O., et al. (2001), Global Leaf Area Index Data from Field Measurements, 1932-2000., Oak Ridge National Laboratory, Oak Ridge, TN.

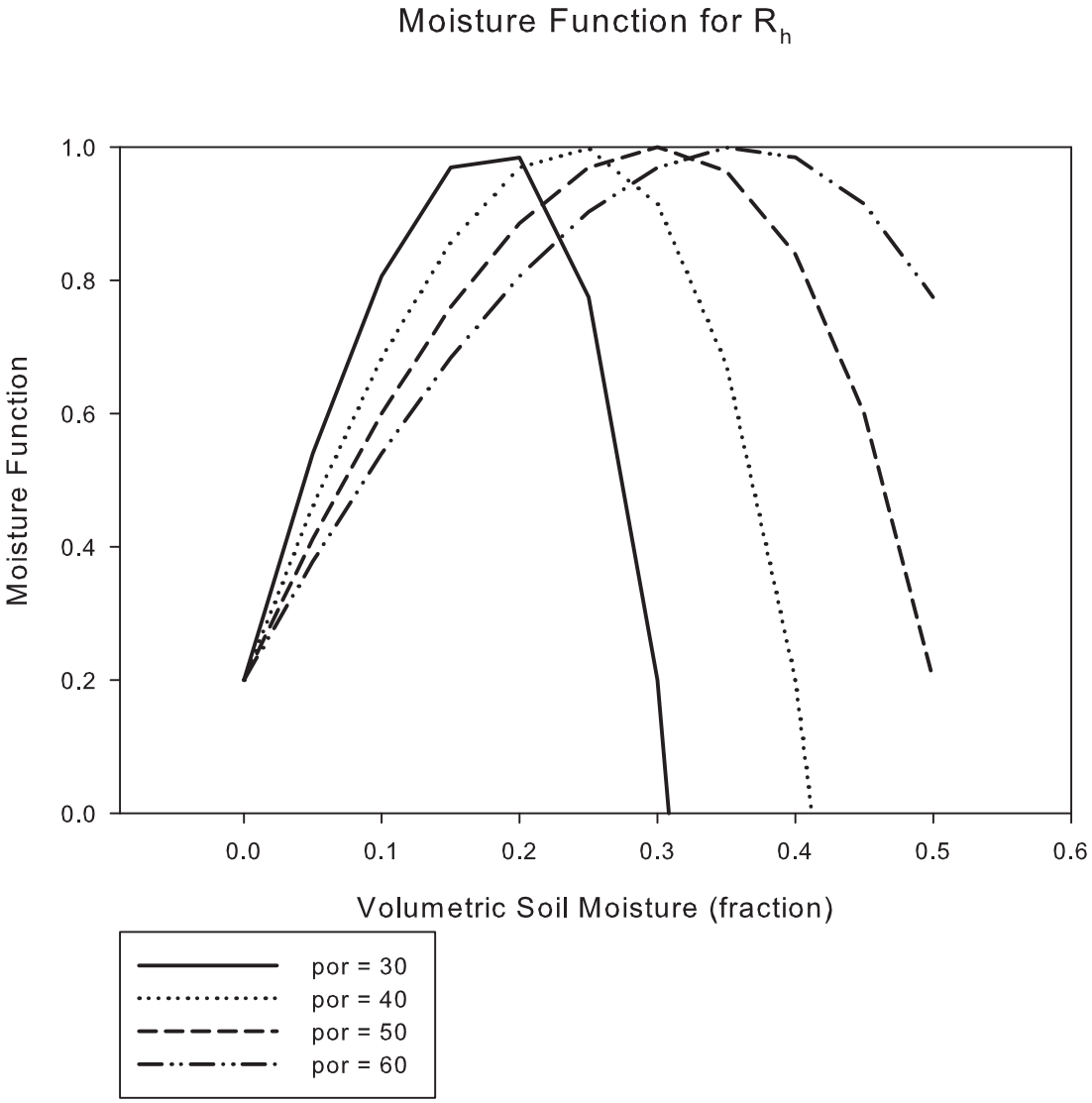
Van Cleve, K., and J. Zasada (1976), Response of 70-year-old white spruce to thinning and fertilization in interior Alaska, *Can. J. For. Res.*, *6*, 145-152.

Van Cleve, K., et al. (1983), Productivity and nutrient cycling in taiga forest ecosystems, *Can. J. For. Res.*, *13*, 747-766.
Viereck, L. A., et al. (1983), Vegetation, soils, and forest productivity in selected forest types in interior Alaska, *Can. J. For. Res.*, *13*, 703-720.
Vitousek, P. M., et al. (1982), A comparative analysis of potential nitrification and nitrate mobility in forest ecosystems, *Ecological Monographs*, *52*, 155-177.
Waring, R. H., et al. (1998), Net primary production of forests: a constant fraction of gross primary production?, *Tree Physiol.*, *18*, 129-134.
Weber, M. G., and K. Van Cleve (1984), Nitrogen transformations in feather moss and forest floor layers of interior Alaska black spruce ecosystems, *Can. J. For. Res.*, *14*, 278-290.

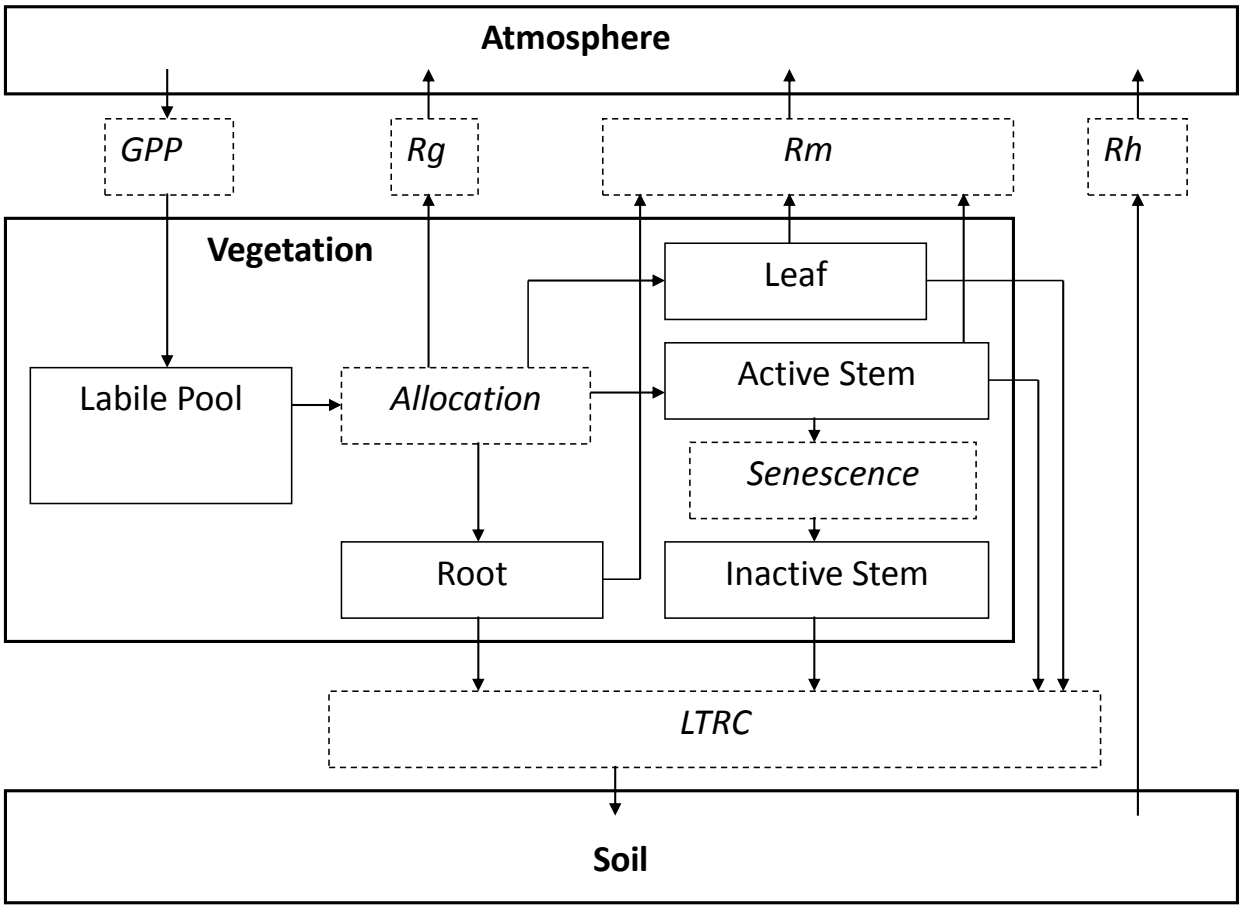
Table A4: River basins used for model checking

Station Name	**Area (km^2)**	**Biome**	
Pantano Wash near Vail, AZ	1169.92	Grass	
Paria R. at Lees Ferry, AZ	3609.60	Shrub	
Salt R. near Roosevelt, AZ	11023.36	Shrub	
Maggie Ck above Maggie Ck Canyon near Carlin,NV	849.92	Grass	
South Fork Humboldt above Tenmile Ck near Elko, NV	2298.88	Shrub	
Rock Ck near Battle Mountain, NV	2211.20	Grass	
Bruneau R. at Rowland, NV	977.92	Grass	
Little Colorado near Cameron, AZ	67735.04	Shrub	
Verde R. below Tangle Creek, above Horseshore Dam, AZ	14996.48	Shrub	
Big Sandy R. near Wikieup, AZ	7019.52	Shrub	
Little Colorado R. at Woodruff, AZ	20664.32	Shrub	
Muddy R. near Moapa, NV	9779.20	Shrub	
AMERICAN R A FAIR OAKS CA	4717.54	Trees	
EEL R A FORT SEWARD CA	5319.34	Trees	
TRINITY R NR BURNT RANCH CA	3737.49	Trees	
UNCOMPAHGRE RIVER AT DELTA, CO.	2718.01	Trees	
GUNNISON RIVER NEAR GUNNISON, CO.	2133.51	Trees	
WHITE RIVER BELOW MEEKER, CO	2747.72	Trees	
NF CLEARWATER RIVER NR CANYON RANGER STATION ID	3730.83	Trees	
SF CLEARWATER RIVER AT STITES ID	3101.54	Trees	
Bitterroot River near Darby MT	2843.77	Trees	
TRUCKEE R AT RENO,NV	2776.47	Trees	
MIDDLE FORK WILLAMETTE RIVER AT JASPER, OR	3750.44	Trees	
ROGUE RIVER AT DODGE BRIDGE, NEAR EAGLE POINT, OR	2905.89	Trees	
SANTIAM RIVER AT JEFFERSON, OR	4402.15	Trees	
COLVILLE RIVER AT KETTLE FALLS, WA	2547.29	Trees	
COWLITZ RIVER BELOW MAYFIELD DAM, WA	3572.83	Trees	
SNOHOMISH RIVER NEAR MONROE, WA	3992.59	Trees	

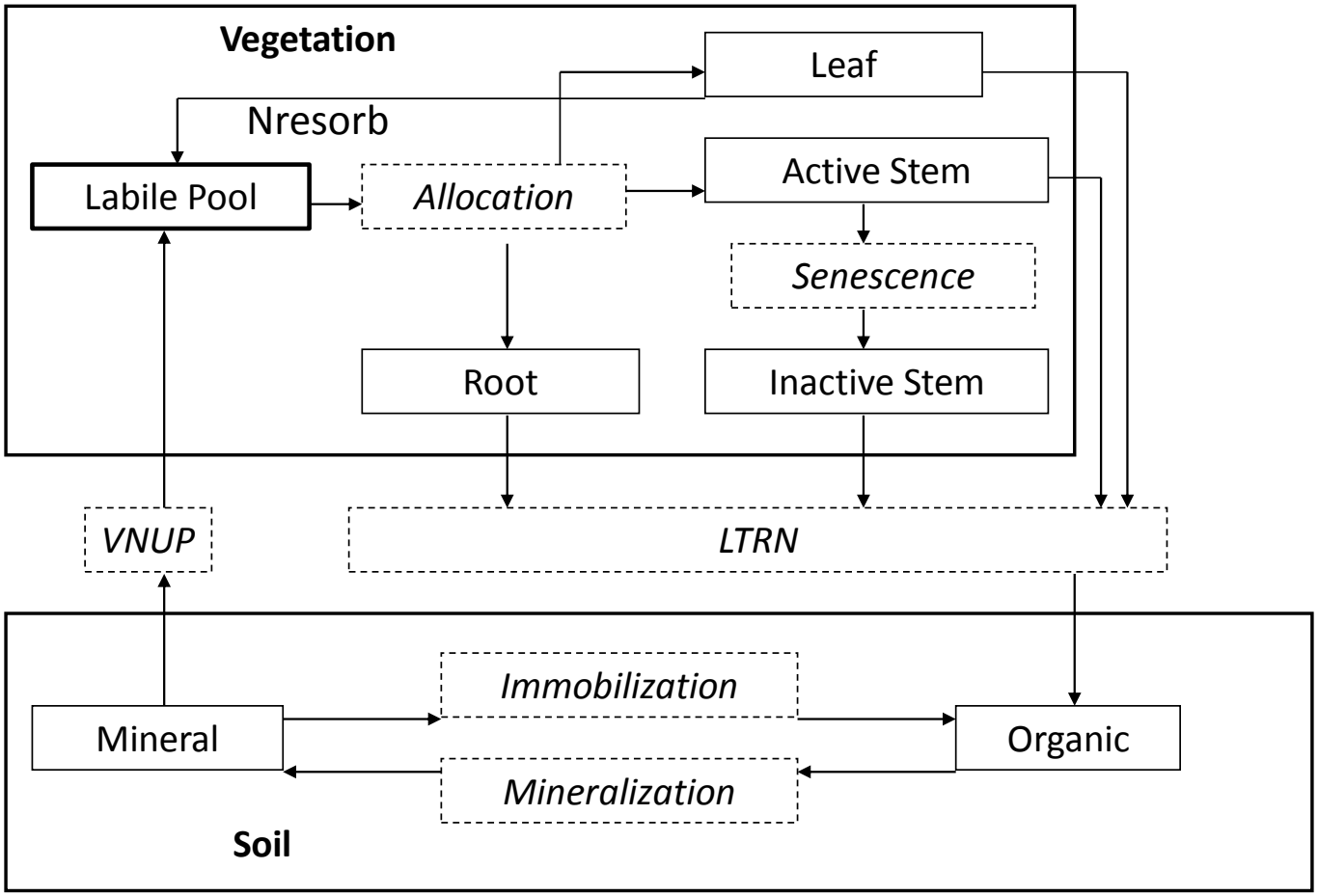

Moisture Stress Function
1.2
1.0
0.8
0.6
0.4
0.2
0.0
fh2o
0.0
0.2
0.4
0.6
0.8
1.0
1.2
wfrac
fh2o' (1)
fh2o' (4)
fh2o (1)
fh2o (4)


Moisture Function for R_h
Moisture Function
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Volumetric Soil Moisture (fraction)
por = 30
por = 40
por = 50
por = 60

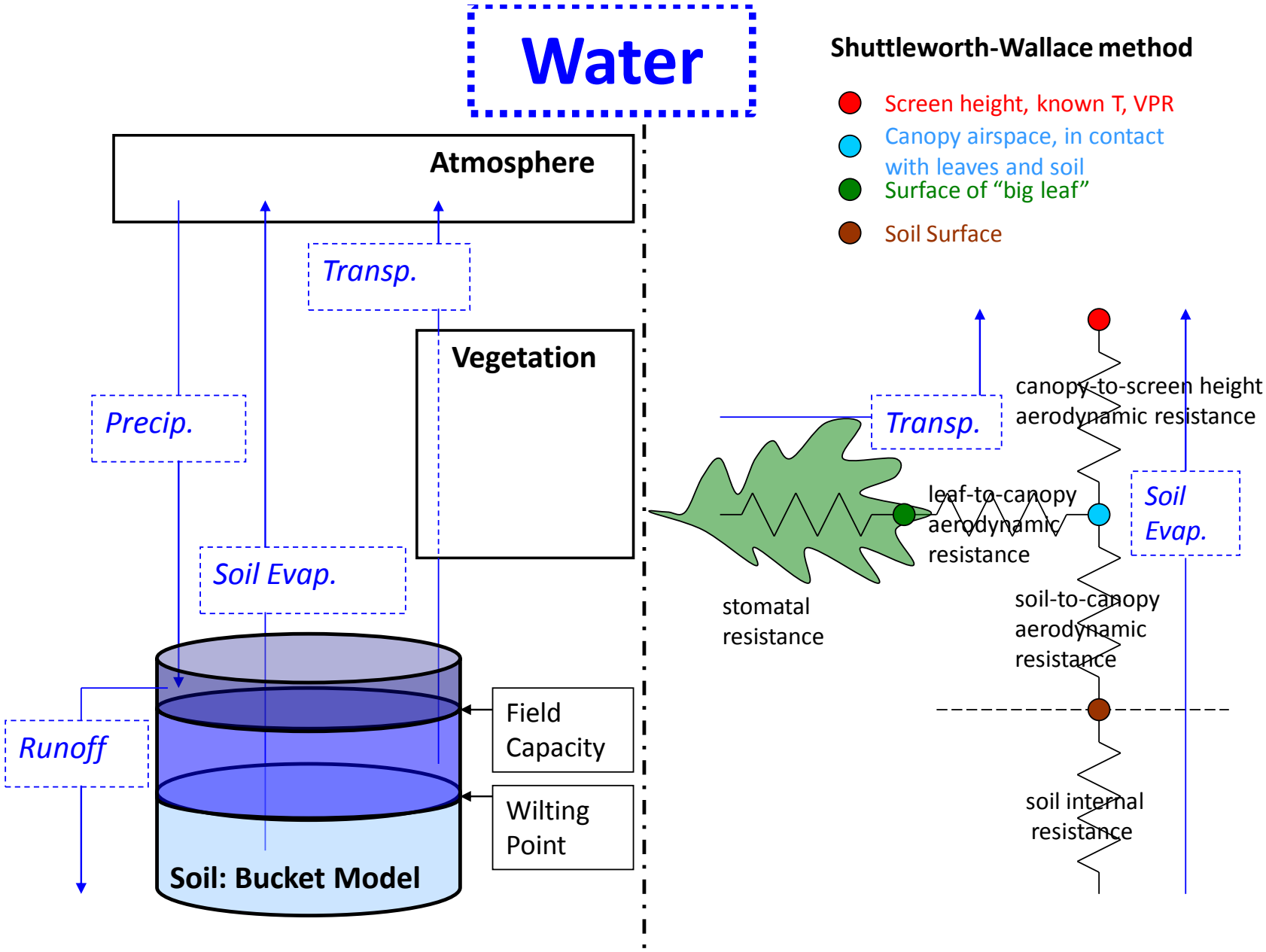
Carbon


Atmosphere
GPP
Rg
Rm
Rh
Vegetation
Leaf
Labile Pool
Allocation
Active Stem
Senescence
Root
Inactive Stem
LTRC
Soil

Nitrogen


Vegetation
Leaf
Nresorb
Labile Pool
Allocation
Active Stem
Senescence
Root
Inactive Stem
VNUP
LTRN
Immobilization
Mineral
Organic
Mineralization
Soil

Water


Atmosphere
Transp.
Vegetation
Precip.
Soil Evap.
Runoff
Field Capacity
Wilting Point
Soil: Bucket Model
Shuttleworth-Wallace method
Screen height, known T, VPR
Canopy airspace, in contact with leaves and soil
Surface of "big leaf"
Soil Surface
Transp.
canopy-to-screen height aerodynamic resistance
leaf-to-canopy aerodynamic resistance
Soil Evap.
stomatal resistance
soil-to-canopy aerodynamic resistance
soil internal resistance