

# Passive Regulation of Soil Biogeochemical Cycling by Root Water Transport : Online Supplement

Juan C. Quijano,<sup>1</sup> Praveen Kumar,<sup>1</sup> Darren T. Drewry,<sup>2,3</sup>

## 1. Fine Root Response to Drought

During dry periods, the scarcity of rainfall and the constant demand for moisture from the plants and the atmosphere results in a reduction in soil water potential. This reduction in soil water potential can be severe in locations experiencing Mediterranean climates, where dry seasons are correlated with high temperatures and radiative forcings.

As soil water potential drops it may be advantageous for plants to reduce their hydraulic conductivity. In this study we simulate the response of roots to dry periods by a reduction of the radial conductivity of the root system,  $K_r$ . This reduction is calculated using a fine root conductivity loss function (FRCL). FRCL is defined as the fraction of root conductivity that is lost in the fine roots at a given root water potential. This percentage loss is used as a proxy to simulate the loss in radial conductivity of the root system. Equation 1 shows how  $K_r$  is affected by FRCL.

$$K_r = K_{r_{\text{pot}}}(1 - \text{FRCL}(\psi_r)). \quad (1)$$

In this equation  $K_{r_{\text{pot}}}$  is the potential root radial conductivity occurring if roots are not under water stress. We use the loss conductivity function observed by *Domec et al.* [2004] for ponderosa pine plants of intermediate age. This function is given by:

$$\text{FRCL} = \frac{100}{1 + e^{a(\psi_r - b)}}. \quad (2)$$

In this equation  $\psi_r$  is the root water potential in MPa and  $a$  and  $b$  are parameters. Parameter  $a$  regulates the slope of the curve and parameter  $b$  is the water potential in MPa at which 50% of the conductivity loss occurs. Figure 3d in the manuscript shows the FRCL function used in this study.

The loss of radial conductivity may happen under two different situations.

- i. In the No-HR case whenever  $\psi_r > \psi_s$  there is a complete hydraulic disconnection between the roots and the soil ( $K_r = 0$ ,  $\text{FRCL} = 1$ ) following the definition of No-HR.
- ii. In both cases, HR and No-HR, there is a reduction in  $K_r$  as a response to low water potential. This response occurs gradually and is regulated by the magnitude of the root water potential  $\psi_r$  following Equations 1 and 2.

## 2. C-N Model Equations

This section presents the equations for the C-N model implemented in this study. These equations were initially developed by *Porporato et al.* [2003]; *D'Odorico et al.* [2003]; *Manzoni and Porporato* [2007]. The main advantages of this approach include the simple representation of the dynamics, the consideration of a separate microbial biomass pool, and the capacity to compute analytically the non-linear dynamics that arise between net mineralization and net immobilization of N. In this study we modified the initial framework from a bucket model to a multi-layer approach. We also include the effect of temperature on decomposition and incorporate vertical fluxes of carbon by soil bioturbation processes. In addition, we consider the presence of multiple vegetation species that coexist and impact simultaneously the carbon and nitrogen dynamics in the soil.

The simulation of carbon dynamics is performed by the solution of differential equations that are based on conservation of mass and describe the evolution of carbon concentration in time for each pool. The simulation of nitrogen content in the organic form uses the same differential equations that are used for carbon, but modified by the C:N ratio that is present in the organic pools.

The equations describing the states of carbon and nitrogen in the soil were initially introduced by *Porporato et al.* [2003], where they considered three pools: litter ( $C_l$ ), humus ( $C_h$ ) and microbial biomass ( $C_b$ ). Later, the same framework was implemented by *Manzoni and Porporato* [2007], but considering only two pools: soil organic matter ( $C_s$ ) and microbial biomass ( $C_b$ ). This simplification facilitates the manipulation of the analytical equations involved in the model. In this study, we follow the approach presented by *Manzoni and Porporato* [2007], considering only two pools. In addition, we model the transport of organic matter in the soil column by bioturbation using a diffusive approximation.

The rate of change of carbon in the organic matter pool at each layer, including bioturbation, is given by:

$$\frac{dC_s}{dt} = \text{ADD}_{\text{bio}} + \text{ADD}_{\text{root}} - \text{DEC} + \text{BD}. \quad (3)$$

In equation 3, the term  $\text{ADD}_{\text{bio}}$  is the flux of organic matter due to bioturbation processes in the soil, the term  $\text{ADD}_{\text{root}}$  is the input of organic matter from root turnover, DEC is an output flux from decomposition and BD is the input from microbial death.

The rate of change of carbon in the microbial biomass pool at each layer is given by:

$$\frac{dC_b}{dt} = (1 - r_r)\text{DEC} - \text{BD}. \quad (4)$$

In equation 4 the term  $(1 - r_r)\text{DEC}$  is the fraction of carbon from decomposition that becomes part of the microbial tissues. The remaining,  $r_r\text{DEC}$ , is the fraction of carbon that is released as  $\text{CO}_2$  to the atmosphere.

The rate of decomposition is computed using first order kinetics [*Porporato et al.*, 2003]. In this study it is function of the soil water potential ( $\psi_s$ ) and soil temperature ( $T$ ) (equations 27 and 28):

$$\text{DEC} = \phi f_D(\psi_s) f_D(T_s) k_s C_b C_s. \quad (5)$$

<sup>1</sup>Department of Civil and Environmental Engineering, University of Illinois at Urbana Champaign, Urbana, Illinois, USA

<sup>2</sup>Max Planck Institute for Biogeochemistry, Jena, Germany

<sup>3</sup>now at: Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

The rate of microbial death is computed by a linear dependence on the microbial biomass concentration  $C_b$  [Porporato *et al.*, 2003]. This approach neglects the influence of environmental factors such as soil water potential and soil temperature.

$$BD = k_d C_b. \quad (6)$$

The model for the vertical transport of organic matter implemented here is based on approaches presented in previous studies [Elzein and Balesdent, 1995; Dam *et al.*, 1997; Kaste *et al.*, 2007; Braakhekke *et al.*, 2011]. In this study we include only fluxes due to bioturbation and neglect advective fluxes produced by water transport such as fluxes of dissolved organic carbon. Figure 1 shows a schematic representation of the bioturbation framework. The transport of organic matter by bioturbation is modeled as a diffusion process. Under this framework the rate of change of carbon in the organic matter pool is given by:

$$\frac{dC_s}{dt} = D_b(z) \frac{d^2 C_s}{dz^2}. \quad (7)$$

The term  $D_b$  in Equation 7 is the bioturbation diffusivity. In this study  $D_b$  is assumed to decay exponentially with depth (Equation 8) following the approach presented in Cousins *et al.* [1999].

$$D_b(z) = D_{b,top} \exp(-0.1z). \quad (8)$$

In Equation 8 the term  $D_{b,top}$  represents the bioturbation at the top of the soil where the maximum bioturbation flux occurs. We use  $D_{b,top} = 4 \text{ cm}^2/\text{year}$ , which is in the range of values reported in previous studies [Elzein and Balesdent, 1995; Dam *et al.*, 1997; Kaste *et al.*, 2007]. We noticed little sensitivity of  $D_{b,top}$  on the results reported in this study. Equation 8 simulates the transport of carbon in the mineral soil column from horizon O downward. The top boundary condition is given by the flux of organic matter from the litter layer to horizon O ( $F_{L-O}$ ). The bottom boundary condition is specified as no flux at a maximum depth  $z_{biot}$  at which bioturbation fluxes are considered negligible. The rate of change in the organic matter pool in the litter layer is shown in Equation 9.

$$\frac{dC_{s,litter}}{dt} = BM_{Tt} - F_{L-O} - DEC_{litter}. \quad (9)$$

In this equation the term  $C_{s,litter}$  is the concentration of organic matter in the litter layer,  $BM_{Tt}$  is the flux of carbon in organic matter from above-ground sources (Equation 26) and  $F_{L-O}$  is the flux of carbon from the litter to horizon O.  $F_{L-O}$  flux is composed by several processes such as fragmentation of litter and bioturbation. Equation 10 shows the parameterization of  $F_{L-O}$  implemented in this study.

$$F_{L-O} = C_{s,litter} \Delta z_{litter} k_{litter} f_B(T_{litter}). \quad (10)$$

In Equation 10 the term  $\Delta z_{litter}$  is the litter layer thickness,  $f_B(T)$  is a parameter that accounts for the control of temperature on  $F_{L-O}$  (we use Equation 28), and  $k_{litter}$  is a parameter that regulates the magnitude of  $F_{L-O}$ . In this study we calibrate  $k_{litter}$  in such a way that the mean annual litter thickness,  $\Delta z_{litter}$ , and the mean annual litter concentration  $C_{s,litter}$  remain constant during all the period of simulation matching the observed values recorded in Blodgett Forest (Table 1 in the manuscript).

The equations that describe the rate of change of nitrogen in the organic matter pool and the microbial biomass

pool are based on the equations for carbon (Equations 3 and 4). In order to compute the nitrogen dynamics from Equations 3 and 4, the C:N ratio in these two pools is needed [Porporato *et al.*, 2003].

$$\frac{dN_s}{dt} = \pm \frac{ADD_{bio}}{(C:N)_{s-bio}} + \frac{ADD_{root}}{(C:N)_{ADD}} - \frac{DEC}{(C:N)_s} + \frac{BD}{(C:N)_b} \quad (11)$$

$$\frac{dN_b(t)}{dt} = \frac{DEC}{(C:N)_s} - \frac{BD}{(C:N)_b} - \Phi. \quad (12)$$

In equation 11 the term  $C:N_{s-bio}$  is the C:N ratio in the soil layer from which the bioturbation flux occurs and the term  $\Phi$  takes into account the net contribution from mineralization or immobilization. If  $\Phi > 0$  there is a net mineralization of N. If  $\Phi < 0$  there is a net immobilization of mineral nitrogen by microorganisms. Assuming that the rate of change of the C:N ratio in the microbial biomass remains constant during the simulation period  $\left(\frac{d(C:N)_b}{dt} = 0\right)$  it is possible

to compute an analytical expression for  $\Phi$  [Porporato *et al.*, 2003]. Considering only two pools of carbon ( $C_s$  and  $C_b$ ) the expression for  $\Phi$  is given in Equation 13 (Equation 14 in Manzoni and Porporato [2007]).

$$\Phi = DEC \left[ \frac{1}{(C:N)_s} - \frac{1 - r_r}{(C:N)_b} \right]. \quad (13)$$

Under net immobilization there is a net uptake of mineral nitrogen from the soil by microorganisms. In this condition plants and microorganisms access to the same pool of mineral N. This phenomenon generates a competition between plant and microorganisms for available mineral nitrogen in the soil. During mineralization periods microbial activity enhances the accumulation of mineral nitrogen in the soil facilitating plant uptake.

The nitrification flux, NIT, is simulated using Equation 14 [Porporato *et al.*, 2003]. In this equation  $f_N$  is a factor that represents the impact of soil moisture on nitrification. In this study we used the same approach for  $f_N$  as the one used for decomposition (Equation 27).  $k_n$  is the nitrification factor,  $C_b$  is the microbial biomass concentration and  $N^+$  is the concentration of ammonium in the soil.

$$NIT = f_N(\psi_s) k_n C_b N^+. \quad (14)$$

The uptake of nitrogen by plants is considered as the addition of two different mechanisms [Porporato *et al.*, 2003]: (i) the mineral nitrogen in the soil moisture that reaches the roots with the transpiration flux (water uptake)  $UPN_{wu}$  and (ii) the mineral nitrogen in water that reaches the roots by diffusion and then is taken by the plants  $UPN_{diff}$ . The total mineral nitrogen uptake is then given by  $UPN = UPN_{wu} + UPN_{diff}$ .

The uptake of mineral nitrogen by the transpiration stream is computed as an advective flux. Nitrogen uptake is computed as the amount of mineral ions transported by the water uptake flux toward the roots assuming a homogeneous ion concentration in soil water. The total uptake of nitrogen is given by:

$$UPN_{wu}^{\pm} = \sum_j^{M_{sps}} \sum_{i \in K}^{N_{layers}} \left( \frac{\lambda^{\pm} N_{min}^{\pm}}{\theta} q_{wu,ij} \right). \quad (15)$$

In Equation 15,  $N_{\min}^{\pm}$  refers to the concentration of either  $\text{NO}_3^-$  (-) or  $\text{NH}_4^+$  (+), parameter  $\lambda^{\pm}$  represents the fraction of  $\text{NH}_4^+$  (+) or  $\text{NO}_3^-$  (-) that is dissolved in water,  $M_{\text{sps}}$  is the number of species and  $N_{\text{layers}}$  is the number of soil layers.  $q_{\text{wu},ij}$  is the water uptake by species  $j$  in layer  $i$  and  $\mathbf{K}$  represents all those layers where  $\psi_s > \psi_r$ . Therefore the summation in Equation 15 only accounts for those layers where the flux of water occurs from the soil to the roots. This assumption neglects the release of mineral nitrogen that may be occurring through water fluxes from the root to the soil by the way of HR.

In this study the uptake of water by diffusion fluxes is computed following the initial approach for a bucket model introduced in *Porporato et al.* [2003]. In this approach the uptake of nitrogen is proportional to the concentration of mineral nitrogen in the soil (Equation 16). Following the same principle the total nitrogen uptake from diffusion fluxes is given by:

$$\text{UPN}_{\text{diff}}^{\pm} = \sum_j^{M_{\text{sps}}} \sum_i^{N_{\text{layers}}} N_{\min}^{\pm} k_{\text{diff},ij}. \quad (16)$$

In Equation 16,  $k_{\text{diff},ij}$ , is a proportionality constant defined for a given layer  $i$  and species  $j$ . Following [*Porporato et al.*, 2003] this constant can be calculated as:

$$k_{\text{diff},ij} = \frac{\lambda^{\pm}}{\theta_i n_i \Delta z_i} \left( \frac{\theta_i}{n_i} \right)^d F_{i,j}. \quad (17)$$

In this equation  $\theta_i$  is the soil moisture in layer  $i$ ,  $n_i$  is the porosity in layer  $i$ ,  $\Delta z_i$  is the thickness of layer  $i$ ,  $d$  is a parameter that represents the non-linear behavior of the diffusion process with soil moisture and  $F_{i,j}$  is a scaled diffusion coefficient.  $F$  can be conceptualized as the diffusion capacity of ions to move from the soil toward the roots. In this study we assume that  $F$  is proportional to the total amount of fine root biomass. For a given species  $j$  the total magnitude of  $F$  in a given layer  $i$  is given by:

$$F_{i,j} = \text{BM}_{\text{roots},j} F_{\text{factor}} f_{r,i,j}. \quad (18)$$

In Equation 18,  $\text{BM}_{\text{roots},j}$  is the total amount of fine root biomass in species  $j$ ,  $f_{r,i,j}$  is the fine root fraction in layer  $i$  for species  $j$  such that  $\sum_i^N f_{r,i,j} = 1$  and  $F_{\text{factor}}$  is a parameter that quantifies the efficiency of the roots in capturing ions by diffusion for a given fine root biomass. (Table 1 in the manuscript).

In this study we assume that the total amount of fine root biomass at every time is proportional to the total amount of leaf biomass :

$$\text{BM}_{\text{roots}} = \text{km}_r \text{BM}_{\text{leaves}}. \quad (19)$$

Similar to the approach introduced by *Porporato et al.* [2003] for a bucket model, here  $F_{\text{factor}}$  is not related with real diffusion coefficients or measurements. Instead this coefficient is calibrated to regulate the fraction of total mineral uptake that comes from diffusion,  $f_{\text{diff}}$ . This fraction is given by:

$$f_{\text{diff}} = \frac{\text{UPN}_{\text{diff}}}{\text{UPN}_{\text{wu}} + \text{UPN}_{\text{diff}}} = \frac{\text{UPN}_{\text{diff}}}{\text{UPN}} \quad (20)$$

In this study the simulations were performed with  $F_{\text{factor}} = 1.8 \text{ mm d}^{-1} \text{ kg}^{-1}$  corresponding to mean annual net values of  $f_{\text{diff}}$  between 40 and 60%, and we perform a sensitivity analysis of  $F_{\text{factor}}$  on the leaching of nitrogen.

### 3. LAI Dynamics and Litter Production

In the model the input of organic matter from the plant to the soil comes mainly from loss of foliage and fine root turnover. We use observations of changes in LAI to compute the turnover of leaves and the input of organic matter into the soil from above-ground sources. In addition, we assume that the input of carbon from below-ground turnover of fine roots is linearly proportional to the above-ground loss of leaves (Equation 19).

Figure 3 in the manuscript shows the the annual dynamics of LAI. The discrete equation that describes the time evolution of LAI is:

$$\text{LAI}_{t+1} = \text{LAI}_t \pm \text{LAI}_{\text{ph}} - \text{LAI}_{\text{nt}}. \quad (21)$$

In this equation  $\text{LAI}_{t+1}$  is the leaf area index at time step  $t + 1$ ,  $\text{LAI}_t$  is the LAI at timestep  $t$ ,  $\text{LAI}_{\text{nt}}$  is the reduction in LAI in a timestep caused by normal turnover of leaves and  $\text{LAI}_{\text{ph}}$  is the addition or reduction in LAI during that timestep due to either phenological construction or phenological turnover. We assume that in a given tim step either phenological construction or turnover take place, but not both.

$\text{LAI}_{\text{nt}}$ , which is the normal turnover produced by the regular deterioration of leaves, is computed using the expected leaf span  $\text{LS}$ .

$$\text{LAI}_{\text{nt}} = \frac{\text{LAI}_t}{\text{LS}} \Delta t. \quad (22)$$

From Equation 21, the phenological changes in LAI are given by:

$$\mp \text{LAI}_{\text{ph}} = \text{LAI}_{t+1} - \text{LAI}_t + \text{LAI}_{\text{nt}}. \quad (23)$$

$\text{LAI}_{\text{ph}}$  could be either positive or negative depending on the dynamics of turnover or construction. Therefore, the total turnover of leaves in a given timestep, expressed in terms of LAI units, is then given by:

$$\text{LAI}_{\text{Tt}} = \begin{cases} \text{LAI}_{\text{nt}} & \text{if } \text{LAI}_{\text{ph}} \geq 0 \\ |\text{LAI}_{\text{ph}}| + \text{LAI}_{\text{nt}} & \text{if } \text{LAI}_{\text{ph}} < 0 \end{cases} \quad (24)$$

The flux of carbon from above-ground los of leaves that reaches the soil surface is calculated as:

$$F_{\text{above}} = \frac{\text{LAI}_{\text{Tt}}}{\text{SCLA}} \quad (25)$$

where  $\text{SCLA}$  is the specific carbon leaf area index that represents the area per unit mass of carbon in the leaf.

The flux of carbon from below-ground turnover of fine roots that goes to the soil is given by:

$$F_{\text{below}} = F_{\text{above}} \text{km}_r. \quad (26)$$

This flux is distributed in the soil for each species independently according to the root distribution  $f_{r,i,j}$

#### 4. Organic Carbon Concentrations and Calibration of $k_s$ and $k_b$

The soil domain is divided into horizons with similar biogeochemical properties. Each horizon may comprise one or more of the layers implemented in the numerical simulation. Table 1 shows the different horizons considered, including depth and the numerical simulation layers that are in each horizon. The depth and thickness of horizons displayed in Table 1 is determined from observations at Blodgett forest [Bird and Torn, 2006; Black and Harden, 1995].

The C-N model requires two main site-specific constants,  $k_s$  and  $k_d$  (Appendix 2). These constants control the rate of organic matter decomposition and microbial death respectively. These two processes are microbially regulated. Therefore,  $k_s$  and  $k_d$  vary with depth according to the type of microbial community that is present in the soil.

The soil column is characterized by strong gradients in soil moisture, soil temperature and carbon and nitrogen concentrations. Shallow layers that are close to the surface are impacted more by the atmosphere. These layers are directly affected by rainfall and incoming solar radiation, and have large fluctuations in temperature and moisture. On the other hand, deeper layers in the soil are less vulnerable to atmospheric conditions. The incoming rainfall and radiative fluxes that reach the surface are filtered throughout the soil column producing more stable conditions of soil moisture and soil temperature at deeper layers. In addition, the input of organic matter and nutrients from plants also follows a distribution with considerably higher fluxes close to the surface.

Strong gradients in environmental variables such as temperature and moisture concentrations throughout the soil column, together with differences in organic carbon input from plants, impact the distribution of microbial communities and their population sizes [Fierer et al., 2003]. In order to capture these processes we calibrate  $k_s$  and  $k_d$  for each layer independently. The calibration of  $k_s$  and  $k_d$  was performed by assuming steady state conditions in Equations 3 and 4, as suggested in D'Odorico et al. [2003]. In order to use this approach we use mean values of soil moisture and soil temperature reported at Blodgett and the computed profiles of carbon concentration in the organic matter and microbial pool (Table 1).

Figure 4 shows the carbon concentrations in the organic matter pool and microbial biomass pool at different horizons. These profiles were obtained by applying observed patterns in other locations [Jobbágy and Jackson, 2000; Fierer et al., 2003], and information gathered at Blodgett [Bird and Torn, 2006; Black and Harden, 1995]. The Blodgett data was mostly available for shallow soil layers.

#### 5. Soil Moisture and Temperature Dependence

Besides the availability of biochemical energy which is found in remnant products of photosynthetic processes, the activity of microorganisms in soils is controlled primarily by soil moisture and soil temperature conditions. Several experimental studies have monitored the influence of these two variables on microbial activity using direct observations of microbial growth and indirect measurements such as organic matter decomposition and respiration rates [Qi and Xu, 2001; Iovieno and Bååth, 2008; Herron et al., 2009]. The complex interactions involved in microbial processes, the immense microbial diversity and the heterogeneity of the soil domain are factors that challenge our understanding of these dynamics.

Biophysical models developed to simulate the fate of organic matter, decomposition, microbial respiration, or microbial growth use reduction factors to include the influence of soil moisture and temperature in microbial activity. The

effect of soil moisture availability has been computed using different mathematical functions. Generally, microbial activity increases with moisture availability. Some models use soil water content as an indicator of available moisture [D.S. Jenkinson, D.E. Adams, 1991; Probert, 1998; Parton et al., 1987; Porporato et al., 2003]. However, experimental studies have shown a strong correlation between soil water potential ( $\psi_s$ ) and microbial activity, [Wilson and Griffin, 1975; Harris, 1981; Kieft et al., 1987; Sylvia et al., 2005]. According to Harris [1981]; Sylvia et al. [2005] microbial activity becomes limited when soil matric potential  $\psi_s < 4$  MPa. Beyond this range the microbial population is composed mainly of fungi which are more tolerant to water stress than bacteria. Some fungi species can sustain growth at lower levels of water potential ( $\psi_s = 40$  MPa). Although some microorganisms can survive water potential levels below  $\psi_s < -10$  MPa the rate of several microbial processes decreases considerably. For example it seems the rate of nitrification is negligible below 4 MPa. In this study we include a correction factor for microbial processes such as decomposition and nitrification as a function of water potential instead of soil moisture. We use the correction factor implemented in Andren [1992] (Equation 27).

$$f_D(\psi_s) = \left( \frac{\text{Log} \left( \frac{\psi_{min}}{|\psi_s|} \right)}{\text{Log} \left( \frac{\psi_{min}}{|\psi_{top}|} \right)} \right). \quad (27)$$

In this equation  $\psi_s$  is the water potential in the soil,  $\psi_{min}$  is the value of  $\psi_s$  below which decomposition become negligible, and  $\psi_{max}$  is the value of  $\psi_s$  above which there is no reduction in decomposition rates. Similarly, several factors have been proposed to consider the influence of temperature in microbial activity [D.S. Jenkinson, D.E. Adams, 1991; Andren, 1992; Probert, 1998]. In this study we use observations at Blodgett [Qi and Xu, 2001; Qi, 2002] that describe the control on decomposition Equation 28.

$$f_D(T_s) = 1.9^{\frac{T_s - 25}{10}}. \quad (28)$$

These factors ( $f_D(\psi_s)$   $f_D(T_s)$ ) are used in Equation 5 to incorporate the regulation of water potential and soil temperature in the decomposition of soil organic matter.



## 6. List of Symbols

Symbol	Description		
HR	Hydraulic redistribution	$\psi_s$	Soil water potential [MPa]
NoHR	Hydraulic redistribution is not present	$\psi_r$	Root water potential [MPa]
HL	Hydraulic lift	$T_s$	Soil Temperature
HD	Hydraulic descent	$\psi_{\min}$	Min $\psi_s$ below which decomposition rates become negligible
LAI	Leaf area index	$\psi_{\text{top}}$	$\psi_s$ above which there is not reduction on decomposition rates
SCLA	Specific leaf area index of carbon	$\theta$	Soil moisture
LAI <sub>t</sub>	Leaf area index at time step t	$n$	Porosity
LAI <sub>t+1</sub>	Leaf area index at time step t+1	$N_s$	Nitrogen content in the soil organic matter pool
LAI <sub>ph</sub>	Leaf area index change from phenological changes	$N_b$	Nitrogen content in microbial pool
LAI <sub>nt</sub>	Leaf area index from normal turn over	Nit	Nitrate pool
LAI <sub>Tt</sub>	Total leaf area index that drop to the soil	Amm	Ammonium pool
F <sub>above</sub>	Total flux of carbon biomass from above drop of leaves	$N_{\min}$	Total mineral nitrogen in the soil
F <sub>below</sub>	Total flux of carbon biomass from below fine roots	$M_{\text{sps}}$	Total number of species
C : N	Carbon to nitrogen ratio	$N_{\text{layers}}$	Total number of layers in the soil
C : N <sub>b</sub>	Carbon to nitrogen in the microbial pool	$UPN_{\text{wu}}^{\pm}$	Plant uptake of water mineral nitrogen from water uptake
C : N <sub>s</sub>	Carbon to nitrogen ratio in organic matter pool	$UPN_{\text{diff}}^{\pm}$	Plant uptake of mineral nitrogen from diffusion in the soil
C <sub>s</sub>	Carbon content in the organic matter pool	$q_{\text{wu},ij}$	Water uptake in the ith soil layer from the jth species
C <sub>s,litter</sub>	Carbon content in the organic matter pool in litter	$d$	Diffusion Parameter $\theta$
C <sub>b</sub>	Carbon content in the microbial pool	$F_{i,j}$	Pot. of ions to diffuse towards the roots
C <sub>s,litter</sub>	Carbon content in the microbial pool in the litter	$F_{\text{factor}}$	Diffusion capacity of ions per unit mass of fine roots
ADD	Input flux of biomass in the soil column	$fr^j$	Distribution of fine roots in the jth species
ADD <sub>bio</sub>	Input flux of biomass from bioturbation	$f_D(\psi_s)$	Water potential factor on decomposition
ADD <sub>root</sub>	Input flux of biomass from fine roots turn over	$f_D(T_s)$	Soil temperature factor on decomposition
DEC	Decomposition rate of soil organic matter	$f_B$	Litter C flux to horizon O Parameter
BD	Death of microbial biomass flux	$k_s$	Parameter that regulates decomposition
$\phi$	parameter that regulates decomposition	$k_d$	Parameter that regulates microbial death
$\Phi$	Net immobilization/mineralization	$k_r$	Root hydraulic conductivity
a	Slope of the FRCL function	$k_{\text{diff},ij}$	Proportionality nitrogen uptake by diff. path.
b	Water Potential at which FRCL is 50%	$D_b$	Bioturbation diffusion parameter
$r_r$	Fraction of decomposition that goes to respiration	$D_{b,\text{top}}$	Net uptake of $CO_2$ through photosynthesis
DEC <sub>litter</sub>	Decomposition flux in the litter layer	$T_{\text{litter}}$	Litter layer temperature
BM <sub>roots</sub>	Total Root Biomass	BM <sub>leaves</sub>	Total Leaves Biomass
BM <sub>Tt</sub>	Total flux of carbon from above-ground	$F_{L-O}$	Total flux of carbon from litter to horizon O
$\Delta z_i$	Thickness of the ith soil layer	$\Delta z_{\text{litter}}$	Thickness of litter layer
$\Delta k_n$	Nitrification rate		

**Acknowledgments.** This research has been funded by NSF Grant ATM 06-28687, Grant EAR 0911205, and University of Illinois Dissertation Completion Fellowship. DTD was also supported by the National Science Foundation's International Research Fellowship Program (IRFP), award OISE-0900556. DTD also acknowledges support of the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.



## References

- Andren, O., Modelling the effects of moisture on barley straw and root decomposition in the field, *Soil Biology and Biochemistry*, 24(8), 727–736, doi:10.1016/0038-0717(92)90246-T, 1992.
- Bird, J. a., and M. S. Torn, Fine Roots vs. Needles: A Comparison of  $^{13}\text{C}$  and  $^{15}\text{N}$  Dynamics in a Ponderosa Pine Forest Soil, *Biogeochemistry*, 79(3), 361–382, doi:10.1007/s10533-005-5632-y, 2006.
- Black, T. A., and J. Harden, Effect of timber harvest on soil carbon at blodgett experimental forest, california, *Can. J. For. Res.*, 25, 1385–1396, 1995.
- Braakhekke, M. C., C. Beer, M. R. Hoosbeek, M. Reichstein, B. Kruijt, M. Schrumpf, and P. Kabat, SOMPROF : A vertically explicit soil organic matter model, *Ecological Modelling*, 222(10), 1712–1730, doi:10.1016/j.ecolmodel.2011.02.015, 2011.
- Cousins, I. T., D. Mackay, and K. C. Jones, Measuring and modelling the vertical distribution of semi-volatile organic compounds in soils. ii: model development, *Chemosphere*, 39(14), 2519 – 2534, doi:10.1016/S0045-6535(99)00165-4, 1999.
- Dam, D., E. Veldkamp, and N. V. Breemen, Soil organic carbon dynamics: Variability with depth in forested and deforested soils under pasture in costa rica, *Biogeochemistry*, 39(3), 343–375, 1997.
- D’Odorico, P., F. Laio, A. Porporato, and I. Rodriguez-Iturbe, Hydrologic controls on soil carbon and nitrogen cycles. ii. a case study, *Advances in Water Resources*, 26(1), 59–70, 2003.
- Domec, J. C., J. M. Warren, F. C. Meinzer, J. R. Brooks, and R. Coulombe, Native root xylem embolism and stomatal closure in stands of douglas-fir and ponderosa pine: Mitigation by hydraulic redistribution, *Oecologia*, 141(1), 7–16, 2004.
- D.S. Jenkinson, D.E. Adams, A. W., Model Estimates of  $\text{CO}_2$  emissions from soil in response to global warming, *Nature*, 1991.
- Elzein, A., and J. Balesdent, Mechanistic simulation of vertical distribution of carbon concentrations and residence times in soils, *Soil Science Society of America Journal*, 59(5), 1328, 1995.
- Fierer, N., J. P. Schimel, and P. A. Holden, Variations in microbial community composition through two soil depth profiles, *Microbiology*, 35, 167–176, 2003.
- Harris, R., *Effect of water potential on microbial growth and activity. Water Potential Relations in Soil Microbiology*, 23-95 pp., Soil Science Society of America Inc., doi:10.1007/s10021, 1981.
- Herron, P. M., J. M. Stark, C. Holt, T. Hooker, and Z. G. Cardon, Microbial growth efficiencies across a soil moisture gradient assessed using  $^{13}\text{C}$ -acetic acid vapor and  $^{15}\text{N}$ -ammonia gas, *Soil Biology and Biochemistry*, 41(6), 1262–1269, doi:10.1016/j.soilbio.2009.03.010, 2009.
- Iovieno, P., and E. Båå th, Effect of drying and rewetting on bacterial growth rates in soil., *FEMS microbiology ecology*, 65(3), 400–7, doi:10.1111/j.1574-6941.2008.00524.x, 2008.
- Jobbágy, E. G., and R. B. Jackson, the Vertical Distribution of Soil Organic Carbon and Its Relation To Climate and Vegetation, *Ecological Applications*, 10(2), 423–436, doi:10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2, 2000.
- Kaste, J. M., A. M. Heimsath, and B. C. Bostick, Short-term soil mixing quantified with fallout radionuclides, *Geology*, 35(3), 243, 2007.
- Kieft, T., E. Soroker, and M. Firestone, Microbial biomass response to a rapid increase in water potential when dry soil is wetted, *Soil Biology and Biochemistry*, 19(2), 119–126, doi:10.1016/0038-0717(87)90070-8, 1987.
- Manzoni, S., and a. Porporato, A theoretical analysis of nonlinearities and feedbacks in soil carbon and nitrogen cycles, *Soil Biology and Biochemistry*, 39(7), 1542–1556, doi:10.1016/j.soilbio.2007.01.006, 2007.
- Parton, W. J., D. Schimel, C. V. Cole, and D. Ojima, *Analysis of factors controlling soil organic matter levels in Great Plains Grasslands*, Springer, 1987.
- Porporato, A., P. D’Odorico, F. Laio, and I. Rodriguez-Iturbe, Hydrologic controls on soil carbon and nitrogen cycles. i. modeling scheme, *Advances in Water Resources Research*, 26(1), 45–58, 2003.
- Probert, M., APSIM’s water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems, *Agricultural Systems*, 56(1), 1–28, doi:10.1016/S0308-521X(97)00028-0, 1998.
- Qi, Y., Temperature sensitivity of soil respiration and its effects on ecosystem carbon budget: Nonlinearity begets surprises, *Ecological Modelling*, 153(1-2), 131–142, doi:10.1016/S0304-3800(01)00506-3, 2002.
- Qi, Y., and M. Xu, Separating the effects of moisture and temperature on soil  $\text{CO}_2$  efflux in a coniferous forest in the Sierra Nevada mountains, *Plant and Soil*, pp. 15–23, 2001.
- Sylvia, D. M., J. J. Fuhrmann, P. G. Hartel, and D. A. Zuberer, *Principles and Applications of Soil Microbiology*, 369–388 pp., Pearson, Prentice Hall, doi:10.1007/s10021, 2005.
- Wilson, J., and D. Griffin, Water potential and the respiration of microorganisms in the soil, *Soil Biology and Biochemistry*, 7(3), 199–204, doi:10.1016/0038-0717(75)90038-3, 1975.

J. C. Quijano, Department of Civil and Environmental Engineering, University of Illinois at Urbana Champaign, Hydrosystems Building, Urbana, IL 61802, USA (quijano2@illinois.edu)

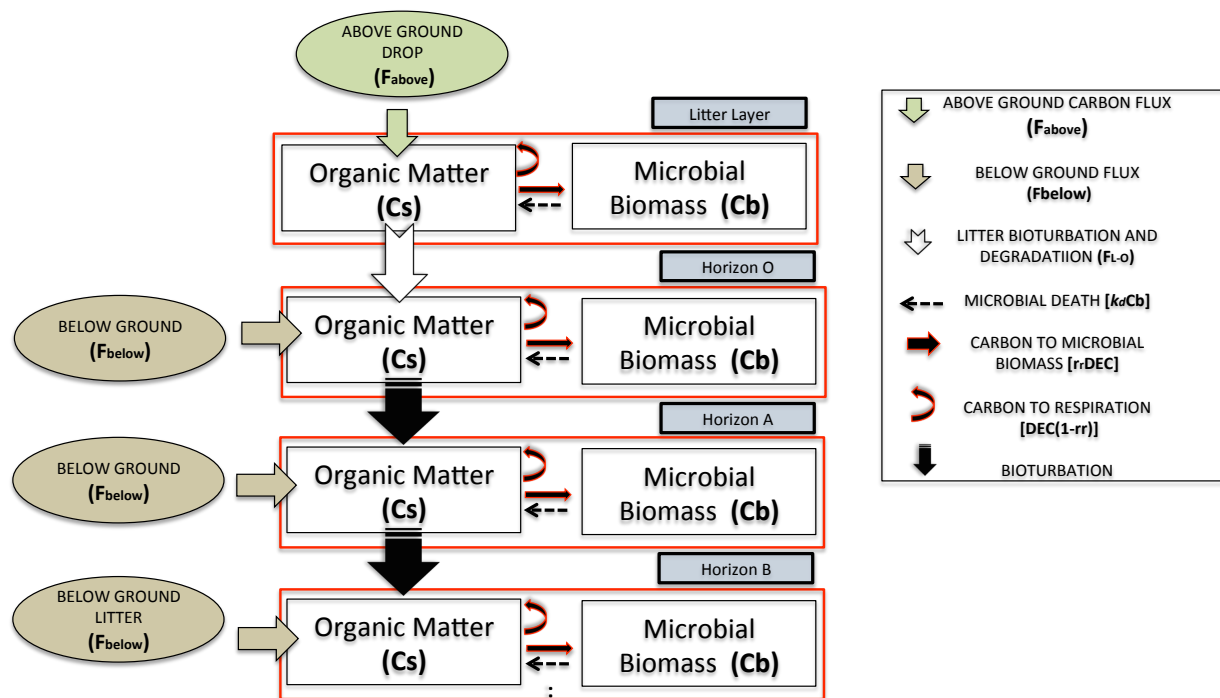
P. Kumar, Department of Civil and Environmental Engineering, University of Illinois at Urbana Champaign, Hydrosystems Building, Urbana, IL 61802, USA (kumar1@illinois.edu)

D. T. Drewry, Jet Propulsion Laboratory, 4800 Oak Grove Drive, m/s 233-300, Pasadena, CA 91109, USA (drewryd@gmail.com)



Table 1: Description of the different horizons included in the simulation.

Depth	Horizon	Layer	Carbon	Carbon
		Simulation	Organic Matter Pool	Microbial Pool
[cm]	[-]	[-]	[kg m <sup>-3</sup> ]	[g m <sup>-3</sup> ]
0 - 2 cm	O	1	46.0	738
2 - 16 cm	A1	2, 3, 4	36.0	396
16 - 30 cm	A2	5	24.0	129
30 - 50 cm	B1	6	15.0	30
50 - 80 cm	B2	7	7.0	15
80 - 230 cm	C1	8,9	2.0	8
> 230 cm	C2	10,11,12	0.3	3



**Figure 1.** Schematic representation of the vertical structure and carbon fluxes below-ground. The main inputs of organic matter come from above-ground loss of leaves and below-ground turnover of fine roots. In each soil horizon the pool of organic matter  $C_s$  and microbial biomass  $C_b$  interact through fluxes such as decomposition and microbial death. The only carbon fluxes that are considered vertically are bioturbation fluxes.