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Existing Soil Carbon Models Do Not Apply to Forested Wetlands

C.C. Trettin, B. Song, M.F. Jurgensen, and C. Li

The Authors

C.C. Trettin, Project Leader, USDA Forest Service, Southern Research Station, Charleston, SC; **B. Song**, Assistant Professor, Belle W. Baruch Institute of Coastal Ecology and Forest Science, Clemson University, Georgetown, SC; **M.F. Jurgensen**, Professor, Michigan Technological University, School of Forestry and Wood Products, Houghton, MI; and **C. Li**, Research Professor, University of New Hampshire, Complex Systems Research Center, Durham, NE, respectively.

Cover: Bottomland hardwoods along the Edisto River ACE Basin, South Carolina. Photo by Bill Lea

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Asheville, NC 28802

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Abstract

When assessing the biological, geological, and chemical cycling of nutrients and elements—or when assessing carbon dynamics with respect to global change—modeling and simulation are necessary. Although wetlands occupy a relatively small proportion of Earth's terrestrial surface (< 3 percent), they contain a disproportionate share of the terrestrial carbon pool (15 to 22 percent). Models that do not accurately represent wetland soil processes cannot, therefore, provide reasonable simulations. We evaluated 12 widely used soil C models to determine their applicability to wetland ecosystems: CANDY, CENTURY, DAISY, DNDC, ITE, MBL-GEM, NCSOIL, QSOIL, ROTHC, SOMM, VVV, and WMEM. Only three (CENTURY, DNDC, and WMEM) allow for anaerobic conditions; none contains components for anoxia, ground water hydrology, multiple organic and physical soil layers, or a daily time-step, all of which are necessary when modeling soil C in wet soils. Accordingly for any land area that includes wetlands, none of the individual models would produce reasonable simulations based on soil processes. We present a wetland soil C model framework based on desired attributes, the DNDC model, and components of the CENTURY and WMEM models. Our proposed synthesis would be appropriate when considering soil C dynamics at multiple spatial scales and where the land area considered includes both wetland and upland ecosystems.

Keywords: Carbon, model, organic matter, soil, wetland.

Introduction

Anaerobic conditions in wetland soils alter the rate of organic matter decomposition, often yielding soils that have significant accumulations of organic matter, i.e., histosols. Organic matter turnover and accumulation in wetlands has significant affects on hydrology, biogeochemical cycling, and plant community dynamics. Organic matter dynamics in wetlands are also thought to have a major role in global carbon cycling, containing an estimated 15 to 22 percent of the terrestrial soil carbon (soil C) and being a major source of atmospheric methane (Eswaran and others 1995, Gorham 1991). The carbon balance in wetlands is sensitive to environmental and land management factors. For example, soil C pools may be significantly reduced following some forest management practices such as water management and site preparation (Trettin and others 1995). In contrast, other management considerations, e.g., restoration, are being suggested to realize the carbon sequestration potential of wetland soils as an approach to help mitigate carbon dioxide emissions. Despite the recognition that soil C in wetlands is important at multiple scales, from internal ecosystem dynamics to global climate change, little attention has been given to the models now used, either implicitly or explicitly, to assess ecosystem functions and responses to management, restoration, or other anthropogenic effects. Models that contain wetland processes are essential for assessing management and conservation options for this important ecological resource.

In response to issues such as global warming, climate change, acid deposition, and the effects of forest management, numerous carbon and nutrient cycling models have been developed over the past 20 years. However, those efforts focused on upland forests, grasslands, and agricultural ecosystems. Comparisons of carbon and or nitrogen process among upland models have been thoroughly reported using data sets from long-term upland studies (De Willigen 1991; McGill 1996; Otter-Nacke and Kuhlman 1991; Pan and others 1996, in press; Parton 1996; Ryan and others 1996a, 1996b; Shao and Henderson-Sellers, in press; Smith and others 1997; VEMAP Members 1995). Findings using those models adequately characterize long-term soil C changes, and there is relatively good coherence among the models. However, many of the models have been applied at scales that transcend upland boundaries and in landscapes dominated by wetlands. The derived estimates may be suspect if the model does not represent inherent ecosystem processes that control carbon dynamics, e.g., anoxia, alternating hydroperiods, and complex interactions of soil chemistry and abiotic processes that are inherent to wetland soils.

We were concerned that current soil C models do not adequately represent the carbon cycle in wetlands, and that applying them to wetlands or on a landscape scale would be inappropriate. We evaluated widely used soil C process models to determine if they would be applicable to wetland ecosystems. Rather than conducting evaluations using wetland data sets, we evaluated model structure and function to determine if critical wetland ecosystem components and processes were included in them. If so, we could justify using wetland data sets. If not, an alternative model framework would be appropriate. The latter proved to be the case. The soil C model we suggest includes surface and ground water hydrology, as well as redox soil chemistry, and would facilitate assessment of the role of wetlands in carbon cycling at the landscape or regional scale. These capabilities are particularly useful in assessments that consider the opposing carbon functions of wetlands (as a carbon sink and methane source), factors that are considered in climate-change research. A wetland soil C model would also necessarily integrate other important biogeochemical processes, e.g., nitrogen cycles, and facilitate the assessment of various management activities on wetland sustainability and ecosystem restoration. A model specific to wetlands also would be useful in identifying critical research needs.

Approach

Comparison of Current Soil C Models

Jenkinson (1990) grouped soil C models into four categories: (a) a single, homogeneous compartment model, which is the simplest form describing the soil C decomposition rate using a linear equation; (b) a two-compartment model, where organic matter from plant residue is split into two compartments, one decomposing much slower than the other; (c) the noncompartmental decay model, which assumes that decomposition occurs on a continuum (Bosatta and Ågren 1985) (because of its mathematical complexity, this approach has not been broadly applied); and (d) multicompartmental models, which divide carbon cycling processes into various compartments, each with decomposition-rate constants that are multiplied by one or more rate modifiers to reflect biotic and abiotic factors, i.e., environmental constraints. Multicompartmental models are the most commonly used, especially when simulating long-term dynamics, i.e., years to centuries.

We selected multicompartmental models because they are best suited for studying mechanisms controlling soil C processes, and they have been most broadly applied. We identified 12 soil C models from the literature and used them in this study. The models were: Carbon-Nitrogen-Dynamics (CANDY) (Franko 1995), CENTURY (Parton and others 1987), DAISY (Hansen and others 1991), DeNitrification and DeComposition (DNDC) (Li and others 1994), Institute of Terrestrial Ecology (ITE) (Thornley and Verberne 1989), Marine Biological Laboratory General Ecosystem Model (MBL-GEM) (Rastetter and others 1991), NCSOIL (Molina and others 1983), QSOIL (Bosatta and Ågren 1985), Rothamsted C Model (ROTHC) (Jenkinson and others 1987), Soil Organic Matter Model (SOMM) (Chertov 1990), VanVeen/Verberne (VVV) (Verberne 1992), and Wetland Methane Emission Model (WMEM) (Cao 1996). We selected these models because they have been widely used and are well documented in the literature. Smith and others (1997) compared 9 soil C models (CANDY, CENTURY, DNDC, DAISY, NCSOIL, ROTHC, SOMM, ITE, and VVV) using 12 data sets from long-term experiments. They found that ROTHC, CANDY, DNDC, CENTURY, DAISY, and NCSOIL have better fits than the SOMM, ITE, and VVV models when applied to upland soils. Accordingly, most of the selected models have proved useful in assessing soil C dynamics. Among the selected models, CENTURY is representative of the carbon process models that are used at large scales (from regional to global) in global change assessments (Pan and others 1996, VEMAP Members 1995). BIOME2, BioGeochemistry Cycles (BIOME-BGC), CENTURY, Dynamic Global Phytogeography Model (DOLY), Mapped Atmosphere-Plant Soil System (MAPSS), and Terrestrial Ecosystem Model (TEM). Each of these large-scale models has been used for distinct vegetation types ranging from arid shrublands, grasslands, savannas, forests, and tundra.

The structure and attributes of these 12 models were examined in light of important ecosystem variables that influence soil C processes and site conditions in wetlands. Attributes were: (1) environmental variables that control organic matter turnover, (2) temporal and spatial scales, (3) hydrology, (4) soil profile characterization, (5) soil physical properties, and (6) soil chemical properties. The following tabulation shows each attribute with respect to specific conditions important to modeling wetlands (each model was evaluated to determine the extent to which it had those desired attributes):

Model attribute	Specific factors
Environmental variables	Climatic variables: air temperature, precipitation. Soil abiotic variables within soil layers: temperature, moisture.
Scale	Temporal scale, resolution of hourly to daily needed.
Hydrology	Vertical water movement; ground water input; flooding.
Soil profile characteristics	Presence of multiple soils layers. Organic subsoil layers.
Soil physical properties	Clay content, and important factor affecting carbon.
Soil chemical properties	Redox processes within soil layers, which affect carbon and nitrogen pathways.

Results and Discussion

Review of Existing Carbon Models

Design attributes—The model structures reflected various levels of detail and represented a range of ecosystem processes. However, all structures except WMEM represented upland ecosystems exclusively and, therefore, are not appropriate for wetland ecosystems. Model comparison results are presented in table 1. Anaerobic condition, a critical component in wetland carbon cycles, was a factor in only three of the models. In the CENTURY model, anaerobic conditions are divided into three classes and used as a multiplier, between 0 and 1, to represent rates of decomposition. The DNDC and WMEM models also consider anaerobic conditions to represent decomposition, and methane emissions as well. None of the 12 models considered ground water, the critical controlling variable; and only 2 considered vertical water movement. Six differentiated among vertical soil layers, another important soil characteristic; but none provided for organic subsurface horizons. Model time-step ranged from hourly to centurial, the latter being beyond the range to reasonably model wetland dynamics. Accordingly, only CENTURY, DNDC, and WMEM contained attributes necessary when considering wetlands.

The CENTURY model has been widely used to assess carbon cycling in various ecosystem studies, especially relative to global climate change. The compartments in this model are fairly simple, but they retain ecological relevance. The model includes a water budget submodel and uses soil temperature and moisture at various depths in the soil profile to regulate decomposition. It is one of only two models (the other one is MBL-GEM) that include lignin to N ratios of organic matter substrates as an indicator of substrate quality; the other models rely on the C to N ratio. The time increment of the model is 1 month. The CENTURY model does not include detailed nitrogen mineralization processes, nitrification, denitrification, or methane emission.

The DNDC model was designed to assess organic matter decomposition and denitrification in fields (Li and others 1996); however, the model recently has been used successfully in upland forests (Li and others 2000, Stange and others 2000). The DNDC includes multiple soil layers, moisture and temperature controls on organic matter turnover, provisions for methane emission, and a nitrogen submodel. The time increment in the DNDC model can be as short as 1 hour, which is an advantage when considering redox chemistry in response to alternating hydroperiods. Organic matter includes litter, microbial, and humad pools; each has multiple compartments that are tracked within each soil layer, including the forest floor. The DNDC has a soil

Table 1—Comparison of 6 factors critical to soil carbon cycling in wetlands among 12 models

	Environmental variable status		Scale			Hydrology		Anaerobic conditions	Soil texture	Soil profile	
Model	Dynamic	Constant	Hours	Months	Centuries	Vertical soil water flow	Ground water flow	Redox process	Clay content	One layer	Different layers
CANDY	X			X					X		X
CENTURY	X				X	X		X	X		X
DAISY	X			X					X		X
DNDC	X		X	X		X		X	X		X
ITE	X			X						X	
MBL–GEM	X				X				X	X	
NCSOIL		X	X							X	
QSOIL		X			X					X	
ROTHC	X				X				X	X	
SOMM	X			X							X
VVV	X			X					X		X
WMEM	X			X				X	X	X	

water submodel that provides for vertical soil water movement and DOC transport.

The WMEM model was designed to simulate methane (CH_4) emissions from rice soils; it subsequently has been used for other ecosystems. The WMEM is the only model specifically developed for wetlands, but because it was designed to measure only one compound, it does not contain attributes necessary for a generalizable wetland soil C model. Specific limitations include—that the soil water balance is driven by precipitation and does not include ground water, the soil is considered as only a single layer, and the time-step is too long to consider transient redox conditions.

Model output attributes—Carbon output variables for 10 of the models are shown in table 2; the QSOIL and MBL-GEM models were not included because output descriptions were incomplete. Each of the 10 models simulates the total residue mass in the forest floor and soil organic matter content. Five models divide residue, microbial, and soil pools into two functional groups according to their turnover rate: labile and resistant. The CANDY, ITE, NCSOIL, SOMM, and WMEM did not divide residue into labile and resistant components, while CANDY, ITE, SOMM, and WMEM did not include microbial pools. Five models considered inert soil organic matter. Only two models (CENTURY and DNDC) included a soil leaching component. Five of the ten models calculated CO_2 emissions, and two (DNDC and WMEM) simulate methane production. The DNDC and CENTURY models give the largest number of output categories. The DNDC and NCSOIL can generate daily outputs, but most models generate monthly-to-yearly outputs. Among these 10 models, only CENTURY and DNDC provide the requisite outputs to adequately characterize wetland soil C dynamics.

Eight models include nitrogen cycling components (table 3). Most nitrogen pools were calculated based on the C to N ratio. Thus, the output variables for nitrogen pools are similar to the ones in carbon pools. All models that simulate the nitrogen process include the output of nitrogen from the total dead residue, and nitrogen in soil organic matter. All models also calculate total mineral nitrogen, and four models consider two forms of mineral nitrogen (NH_4 and NO_3). Only DNDC measures nitrogen gas fluxes.

Framework for a Wetland Model

Based on this review of structural design and attributes, it is evident that the 12 models do not adequately account for anoxia, alternating hydroperiods, complex interactions of soil chemistry and abiotic factors, and time-steps that are important to wetland soil processes. Development of a wetland soil C model that includes anoxia, surface and ground water flows, and soil chemistry would allow assessment of the role wetlands have in carbon cycling at the landscape or regional scale. This capability will be necessary to assess sustainability, the opposing radiative functions of wetlands as a carbon sink and methane source, carbon sequestration potential, and interactions with land management practices.

Using a wetland ecosystem concept and the basic framework of DNDC, with selected attributes of the CENTURY and WMEM models, we developed a conceptual model for soil C dynamics that incorporates important controlling processes for organic matter decomposition in wetlands. Improvements over the existing models include: (1) anaerobic conditions for different soil layers are taken into account; (2) redox potential is used to control the decomposition and methane emission factor; (3) it allows for surface and ground water flows that may go up, instead of only down as in current water budget models; (4) it recognizes multiple soil layers including a surface organic layer, and the potential for subsurface layers to be either organic or inorganic; and (5) methane flux, nitrification, and denitrification are controlled by redox and soil moisture. The carbon model is presented schematically in figure 1. It includes the attributes mentioned.

The model soil is considered to have multiple layers that may be either mineral or organic horizons. Hydrologic control is the principal factor that differentiates uplands from wetlands. Accordingly, the soil water submodel is the critical component of the wetland soil C model (fig. 2). Similarly, because carbon dynamics are inextricably linked to nitrogen, a nitrogen component must reflect the complex dynamics in both aerated and reduced conditions (fig. 3). We intend these components to be organized into the general modeling framework of DNDC, which provides for climatic, vegetation, and management inputs and controls (Li 1996). The merit of this model framework is that it includes the primary factors that control carbon cycling in wetlands. Conceptually, it is valid for both peatlands and mineral soil wetlands. Another important attribute is that it is based on existing models, thereby alleviating many developmental hurdles.

Summary

Modeling soil C dynamics is a critical process in assessing biogeochemical cycling of nutrients and elements, and in

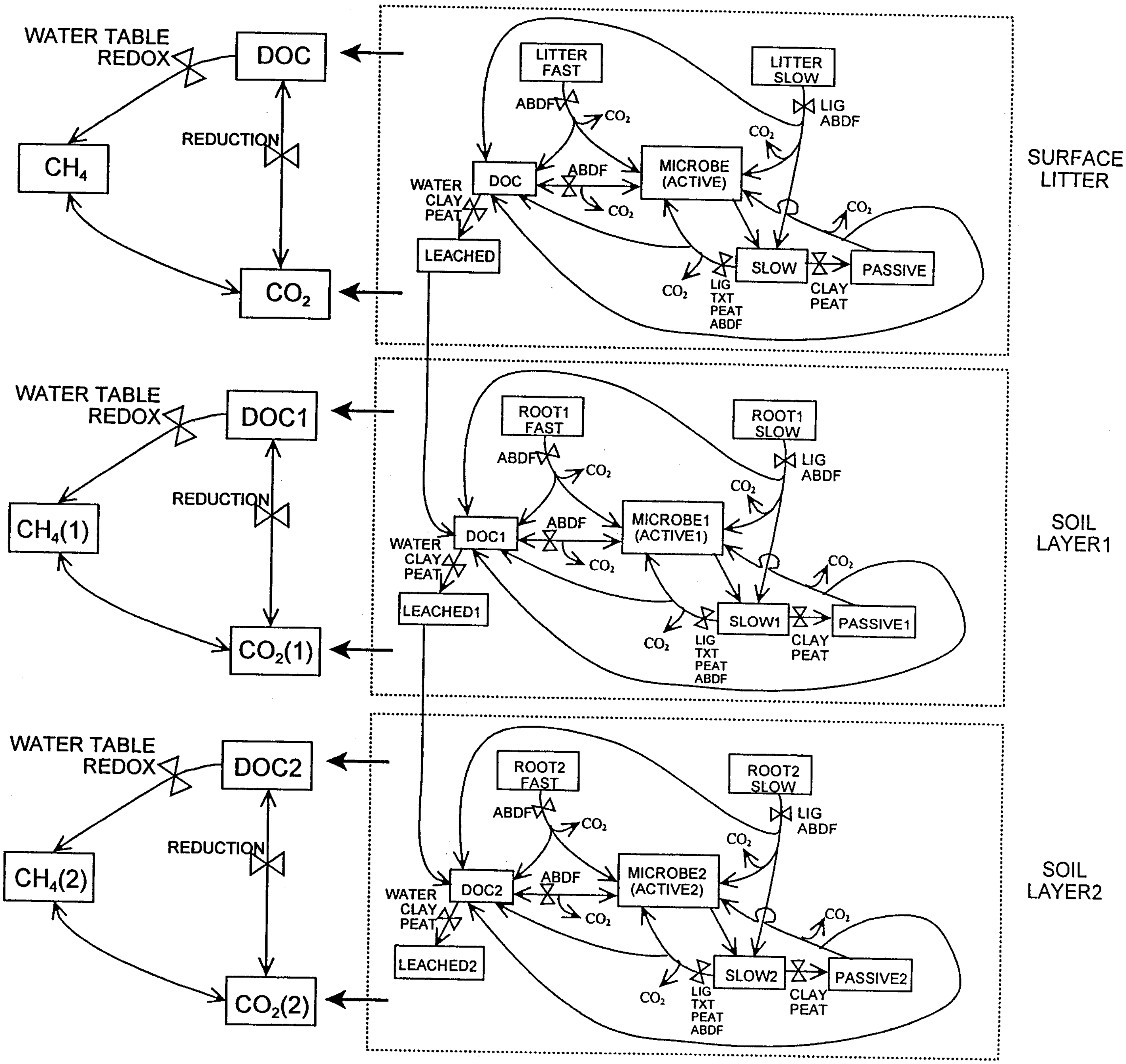
Table 2—Carbon output variables for 10 selected models

Model	Residue - carbon[a]			Soil - carbon										Temporal output Scale range
	Labile residue	Resistant residue	Total dead (labile + resistant) carbon	Microbial biomass			Labile SOM	Resistant SOM	Passive SOM	Total SOM (labile + resistant + passive)	DOC	Gas		
				Labile	Resistant	Total						CO_2	CH_4	
	- - - - Grams per square meter - - - -													
CANDY			X				X	X	X	X				Month - years
CENTURY	X	X	X	X	X	X	X	X	X	X	X	X		Year - century
DAISY	X	X	X	X	X	X	X	X		X		X		Month - years
DNDC	X	X	X	X	X	X	X	X	X	X	X	X	X	Day - years
ITE			X							X				Month - years
NCSOIL			X	X	X	X	X	X		X				Day - years
ROTHC	X	X	X			X	X	X		X		X		Year - century
SOMM			X					X	X	X				Year - century
VVV	X	X	X	X	X	X	X	X	X	X				Year - century
WMEM			X							X		X	X	Year - century

Table 3—Nitrogen output variables for 10 selected models

Model	Residue			Soil - nitrogen												Temporal output scale range
	Labile residue	Resistant residue	Total dead (labile + resistant)	Microbial biomass			Labile SOM	Resistant SOM	Passive SOM	Total SOM	Gas			DON	Gas (NH_3, N_2, N_2O)	
				Labile	Resistant	Total					NH	NO	Total mineral			
	- - - - Grams per square meter - - - -															
CANDY			X				X	X	X	X	X	X	X	X	X	Month - years
CENTURY	X	X	X	X	X	X	X	X	X	X			X	X		Year - century
DAISY	X	X	X	X	X	X	X	X		X			X			Month - years
DNDC	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Day - years
ITE			X							X	X	X	X			Month - years
NCSOIL			X	X	X	X	X	X		X	X	X	X			Day - years
ROTHC																Year - century
SOMM			X					X	X	X			X			Year - century
VVV	X	X	X	X	X	X	X	X	X	X			X			Year - century
WMEM																Year - century

SOM = soil organic matter; DON = dissolved organic matter.



ABDF = f(temp, moist, redox)	Lig = Lignin
Water = f(soil moisture, PPT, GW, ET, PS)	L/N = Lignin/N
Temp = f(insolation, soil, moisture, water)	Txt = Soil texture
Redox = f(water, soil moisture, temp, SOM-H)	Peat = Decayed organic matter

Figure 1—Proposed wetland soil carbon model.

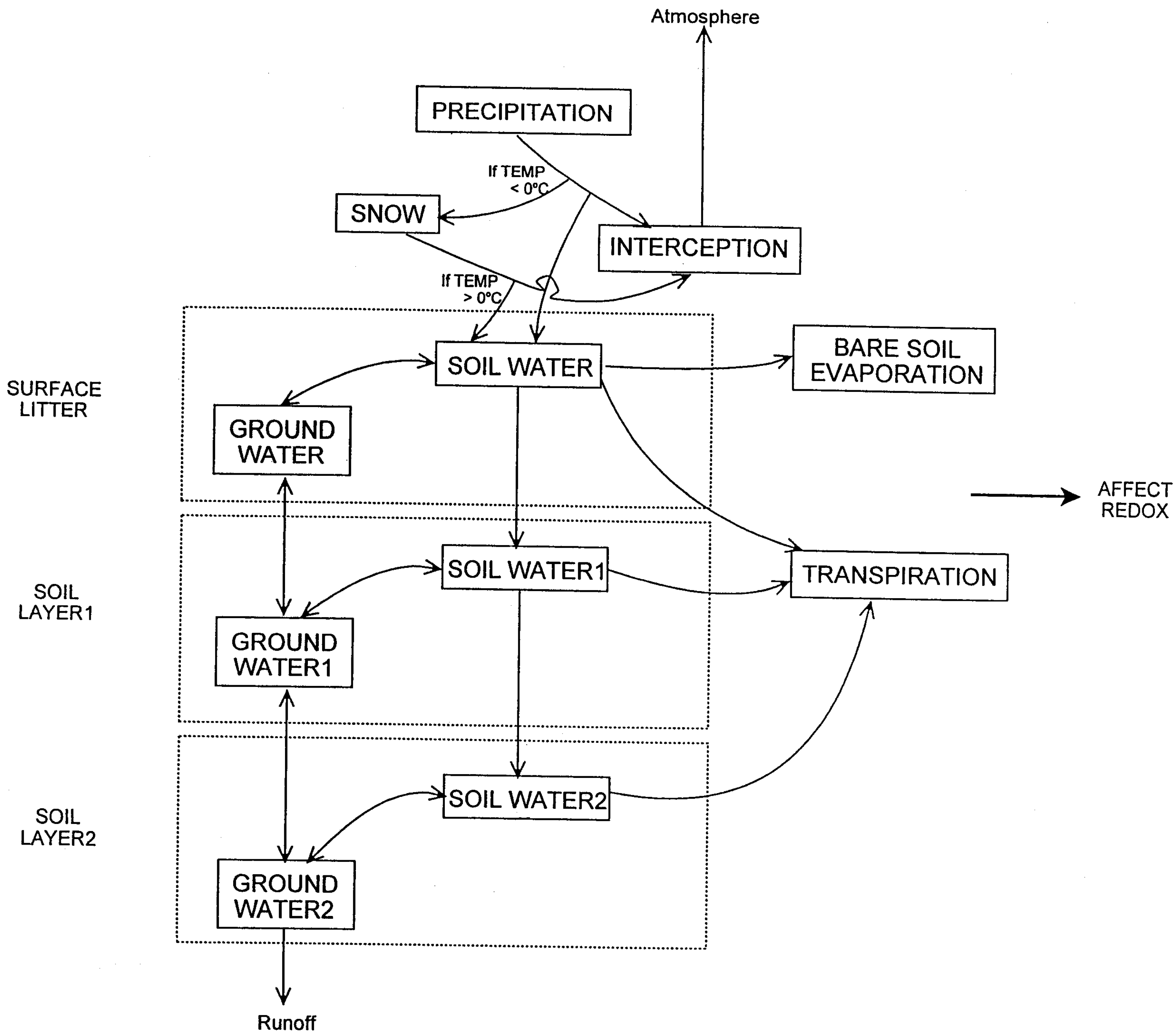


Figure 2—Proposed hydrology submodel to the carbon model.

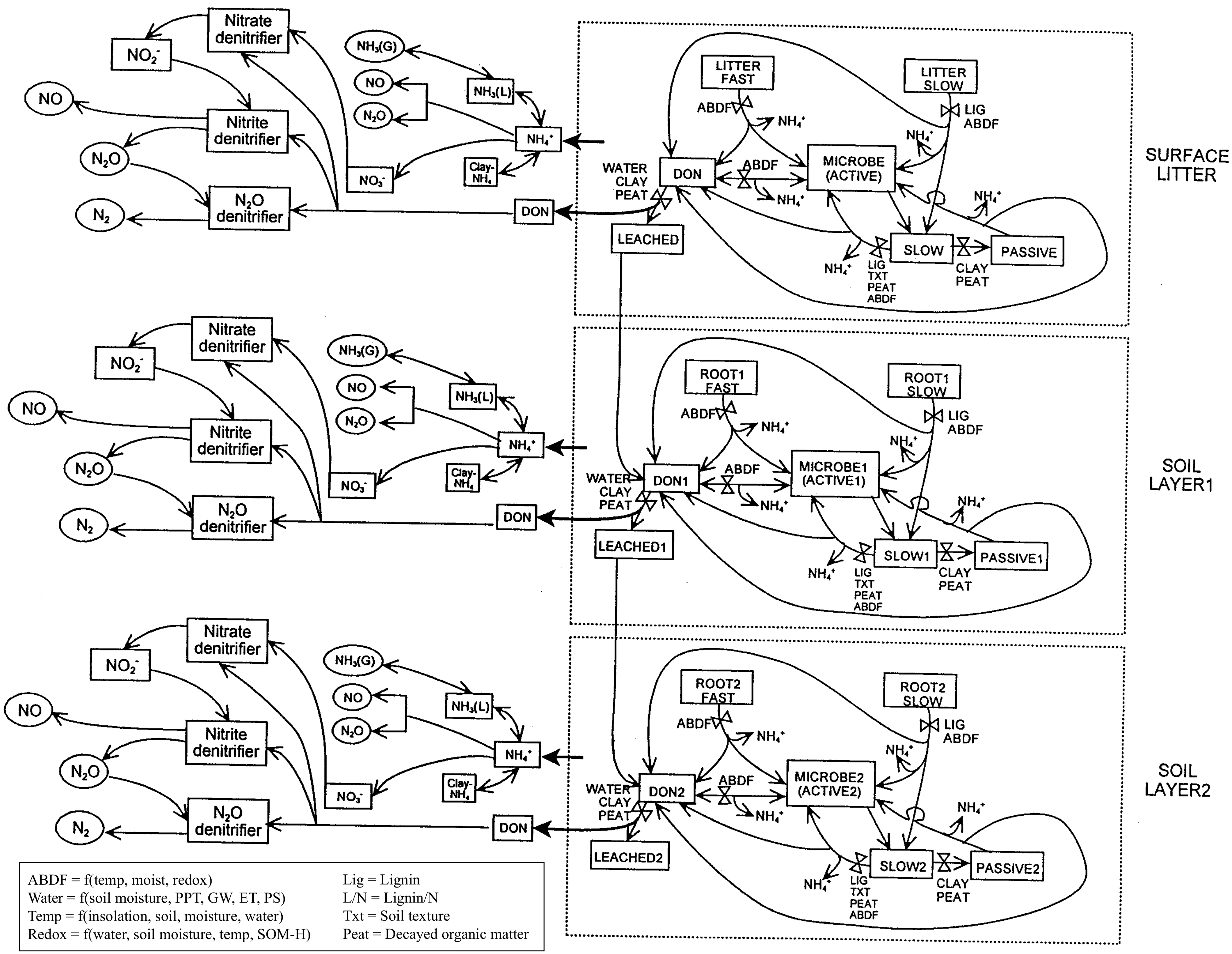


Figure 3—Proposed nitrogen submodel to the carbon model.

assessing carbon dynamics with respect to global change processes. Although wetlands occupy a small proportion of the terrestrial surface of the Earth (< 3 percent), they are reported to contain a disproportionate share of the terrestrial carbon pool (15 to 22 percent). Accordingly, models that do not accurately represent wetland soil processes cannot be expected to provide reasonable simulations. We evaluated 12 widely used soil C models to determine if they could be used when assessing wetland ecosystems. Only three of the models contained provisions for anaerobic conditions; none considered the necessary factors of anoxia, ground water hydrology, multiple organic and physical soil layers, and a daily time-step. Accordingly, simulations conducted using these models cannot be expected to produce reasonable simulations based on soil processes. Using desirable attributes from three of the models, our framework for a wetland soil C model will be appropriate when considering soil C dynamics at multiple spatial scales.

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