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Local Soils Information Needed to Define the Root Zone in Process Models on the Gulf Coastal Plain

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Abstract

We combined published information and our own experimental results from the Gulf Coastal Plain to evaluate how soil aeration and strength interact with loblolly pine root growth. Our results demonstrate that soil aeration and strength differ by soil series and year and are subject to vertical and horizontal spatial variation. Comparison of loblolly pine root phenology and seasonal redox potential indicates that oxygen is frequently limiting to new root growth. The strength of these soils may also restrict loblolly pine root growth. Physiological process models that predict southern pine productivity should apply accurate calculations of plant-available soil in simulations of potential root zone water storage and plant-available water. We propose a conceptual root zone submodel that predicts the volume of plant-available soil with soil aeration, strength, and water retention by horizon. Model parameters are components of the Natural Resources Conservation Service (NRCS) Soil Interpretation Record (SIR) database collected across the United States.

Keywords: Soil aeration, soil strength, spatial variation, redox potential, root phenology, root zone sub-model.

Introduction

While the demand for pine timber in the United States is increasing, some reports show a decline in net annual pine productivity in the South (Bechtold and others 1991, Ruark and others 1991, U.S. Department of Agriculture, Forest Service 1989). Land use changes have contributed to this decrease with hardwood encroachment on nonindustrial private land and conversion of timberland to crop, pasture, and urban uses (U.S. Department of Agriculture, Forest Service 1989). To meet present and future timber demands, land managers must maximize southern pine productivity while sustaining site quality.

Process models that predict forest productivity and sustainability in response to climate and site variables are valuable forest management tools. Existing models express forest productivity relative to the horizontal crown position, age, and retention of foliage (McMurtrie and others 1990, McNulty and others 1996, Wang and Jarvis 1990). Models with parameters that predict root zone size may also assist forest managers.

Process Model Applications

Physiological process models combine important relationships among climate, physiology, and resource availability to predict carbon fixation and subsequent forest productivity. New tools have led to predictions of tree and stand productivity in response to environmental change. For example, TREGROW evaluates the effects of environmental stress on potted red spruce *(Picea rubens* Sarg.) saplings (Weinstein and Beloin 1990). Simulations provide information on ozone-induced imbalances between the carbon, water, and nutrient dynamics of woody plants (Weinstein and Beloin 1990, Weinstein and others 1991).

Other process models serve as intensive forest management tools. The process model BIOMASS predicts the productivity of managed Monterey pine (*Pinus radiata* D. Don.) plantations based on simulated water and carbon balances (McMurtrie and Landsberg 1992, McMurtrie and others 1990). Using SPM (slash pine model), Cropper and Gholz (1993) successfully simulated the stem growth of 22-year-old slash pine (*P. elliottii* Engelm. var. *elliottii*) on a Florida flatwoods site. Both BIOMASS and SPM provide information on the carbon dynamics of managed pine in response to fertilization (Cropper and Gholz 1993, McMurtrie and Landsberg 1992).

Process models can predict forest productivity at the regional level with fewer parameters and can represent more generalized ecophysiological relationships than tree- and stand-level process models (Landsberg and Gower 1997). For example, when Running and Coughlan (1988) used the process model FOREST-BGC to predict forest productivity at seven sites with different climates, the ranking of simulated hydrologic and carbon balances corresponded to measurements in mature forests near each site. After validation at the ecosystem level, PnET-II predicted regional water and carbon responses to elevated temperature and carbon dioxide (Aber and Federer 1992, Aber and others 1995). Such process models have potential to predict forest responses to climate change.

Successful validations suggest that process models can answer contemporary forest management questions. At the same time, forest managers should address examples of failed or questionable validations before using process models to guide decisions. For example, McMurtrie and others (1994) found good correlation between the observed and predicted growth of Monterey pine saplings in Australia and New Zealand with BIOMASS. In the same analysis, however, they noted discrepancies between measured and predicted aboveground net primary productivities of 2-year-old Monterey pine in New Zealand, 28-year-old red pine (*P. resinosa* Ait.) in Wisconsin and 22-year-old slash pine in Florida. They suggested that BIOMASS was a poor predictor of slowly growing stands. With PnET-II during periods of water deficit in northern red oak *(Quercus rubra* L.) -red maple (*Acer rubrum* L.) and in red pine stands, Aber and others (1995) found that rates of carbon exchange did not correspond with predicted rates. One explanation for the failed validation was the assumption that available water was constant across the region.

Role of the Root Zone in Process Models

Field capacity defines the potential amount of water stored in the root zone, and both field capacity and permanent wilting point define the amount of plant-available water in the root zone. Generally, field capacity is -0.004 to 0.03 MPa, and permanent wilting point is -1.5 MPa (Marx 1988, McMurtrie and others 1990, McNulty and others 1996, Soil Survey Staff 1996). With this information, plant-available water simulated by a water balance submodel is applied to process model predictions of carbon fixation and allocation (Aber and Federer 1992, Aber and others 1995, McMurtrie and others 1990, McNulty and others 1996, Running and Coughlan 1988). BIOMASS, for example, calculates net photosynthesis and stomatal conductance as a function of plant-available water (McMurtrie and Landsberg 1992, McMurtrie and others 1990). FOREST-BGC quantifies leaf water potential as a function of actual soil water content divided by soil water content at field capacity. These values help determine canopy conductance and net photosynthesis (Running and Coughlan 1988). PnET calculates net photosynthesis as a function of water stress (Aber and Federer 1992; Aber and others 1995; McNulty and others 1996, 1997). Specifically, PnET and PnET-II use plant-available water to quantify actual transpiration; they express water stress as the product of actual and potential transpiration (Aber and Federer 1992, Aber and others 1995). In PnET-IIS, water stress is a function of average growing season soil water divided by soil water content at field capacity (McNulty and others 1996, 1997).

Conceptual Root Zone Submodel

Forest productivity is dependent on the amount of plant-available mineral nutrients and water in the soil and on their acquisition by the absorbing roots of trees. Phosphorus and nitrogen deficiencies and severe water deficits commonly occur on the Gulf Coastal Plain (Allen and others 1990, Dougherty 1996). Root system proliferation plays a critical role in soil resource uptake throughout this physiographic region.

Soil physical properties influence the size and shape of tree root systems and, therefore, the volume of soil available for water and mineral nutrient uptake (Bennie 1996, Rogers and Head 1969). Seasonal precipitation and soils with low porosities and water-holding capacities, aquitards, and high bulk densities all constrain root proliferation. Specifically during periods of elevated precipitation, water table dynamics may result in limited oxygen availability for root metabolism. Alternatively with reduced precipitation, soil strength may increase to levels that mechanically impede root elongation.

With experimental results and published information, we propose a conceptual submodel that uses limiting soil physical properties to define the root zone. Once developed, this model will broaden the range of sites where physiological process models are valid and can increase the accuracy of physiological process model predictions. To do so, we must define the root zone, potential root zone water storage, and plant-available water based on seasonal and spatial changes in soil physical properties. Although we base our root zone submodel on observations from the Gulf Coastal Plain, it can serve as a template to characterize the root zone in other physiographic regions.

Materials and Methods

At 10 installations of the North American Long-Term Soil Productivity (LTSP) Program and at 1 site on the Bienville National Forest in central Mississippi, investigators have intensively monitored the soil environment. At another location on the Gulf Coastal Plain, we are investigating the ecophysiology and growth of plantation loblolly pine (*P. taeda* L.).

Soil environment studies—Of the LTSP Gulf Coastal Plain installations, three each are located on the Davy Crockett National Forest in eastern Texas and the DeSoto National Forest in eastern Mississippi, and four are located on the Kisatchie National Forest in central Louisiana (Tiarks and others 1993, 1997). Installations initially supported mature loblolly pine forests, ages 39 to 55, that were uniform in stand structure, productivity potential, aspect, topography, and soil series. We retained a nonharvested portion of each stand adjacent to all installations. The Texas and Mississippi installations were on Kurth fine sandy loam and Freest fine sandy loam soil series, respectively (table 1). The Louisiana installations were on Glenmora silt loam, Malbis fine sandy loam, Mayhew silty clay loam, or Metcalf silt loam soil series. On the Bienville National Forest in central Mississippi, the soil environment was an Ichusa silty clay loam. These soil series, which commonly support loblolly pine, are characterized by a flat to gently sloping topography, a relatively low saturated hydraulic conductivity, and an aquitard that restricts percolation.

At all LTSP installations, we applied three levels each of organic matter removal and soil compaction to nine treatment plots (0.4 ha) in a 3- by 3-factorial design (Tiarks and others 1993). In Mississippi and Texas, installations on the same soil series represent three blocks of a randomized complete block design. To eliminate organic matter, we removed stems, whole trees, or all aboveground biomass plus the forest floor. On plots that were stem-only harvested, we uniformly distributed logging slash. Levels of soil compaction were severe, moderate, and no compaction (Tiarks and others 1993). We planted installations at 2.5 by 2.5 m with 10 genotypes of container-grown loblolly pine.

To monitor soil redox potential (Eh), we equipped an adjacent nonharvested area at one LTSP installation each in Texas and Mississippi and at all installations in Louisiana between 1990 and 1997 (Tiarks and others 1995). We also monitored Eh at the Bienville National Forest location between 1995 and 1999.

At three microsites 2 m apart at each LTSP location, we installed a platinum electrode at two depths (50 and 100 cm) to measure Eh. At the Bienville National Forest, we placed six electrodes randomly at a 25-cm depth within a 25-m^2 area. We calibrated readings to reflect the millivolt difference between platinum and standard hydrogen electrode readings by adding 244 mV to electrical current readings (Tiarks and others 1995). Because soil pH at the depth of sensor placement was approximately 5.0, we did not adjust the data to account for the effect of soil pH on Eh (Tiarks and others 1995). We used data recorded by a data acquisition unit at 5-minute intervals to calculate hourly means.

We determined bulk densities of the Malbis soil at one Louisiana LTSP installation by coring to a depth of 180 cm (Veihmeyer 1929), with six samples taken at 30-cm increments in depth. We cored at five randomly selected locations in each plot and in an adjacent nonharvested area. At the three LTSP installations in Mississippi, we measured soil strength using a recording penetrometer equipped with a 30^o conical tip, 10 mm^2 in area. We recorded resistance at 10-cm increments to a depth of 60 cm and averaged 35 measurements from random locations in each plot by depth increment.

Ecophysiology study—At the ecophysiology study site on the Kisatchie National Forest in central Louisiana (Sword and others 1998a), the soil is a Beauregard silt loam (table 1). In 1981, we planted container-grown loblolly pine from a genetically unimproved source at a 1.8- by 1.8-m spacing. In 1988, we established twelve 0.06-ha plots, 13 by 13 trees each. In early 1989, we applied 2 levels each of thinning (not thinned: 2,990 trees per ha; thinned: 749 trees per ha) and broadcast fertilizer application with diammonium phosphate (none; 135 kg N and 150 kg P per ha) in a factorial design to 3 replications. In early 1995, we rethinned the 13-year-old thinned plots (18.1 m^2 per ha) from below (not thinned: 40.4 m^2 per ha; thinned: 15.4 m^2 per ha) and refertilized the fertilized plots by broadcast application of urea, monocalcium phosphate, and potash (200 kg N, 50 kg P, and 50 kg K per ha).

Based on the influence of topography on soil drainage, we chose two replications as blocks for measurement of root system growth, soil environment, and crown physiology. At 2- to 4-week intervals in 1993 through 1998, we quantified root elongation in three (1993) to five (1994–98) vertical Plexiglas rhizotrons (0.3 by 35.4 by 76 cm) per plot (Sword and others 1998a, 1998b). We expressed net lateral root elongation as mm per dm^2 per day. In 1994 through 1998, we measured the volumetric water content of the soil at 2-week intervals by time domain reflectometry (TDR) with one sensor placed at a depth of 15 cm through a port in each of three randomly chosen rhizotrons per plot. We calibrated the TDR measurements to gravimetric soil-water content values. Radio towers and wooden walkways provided access to the canopy. In 1998, we identified three south-facing branches in the upper crown of three dominant or co-dominant trees per plot of one replication and measured net photosynthesis at 1100, 1300, and 1500 hours between June and November (Tang and others 1999).

Results and Discussion

Soil Aeration

In normal years, Gulf Coastal Plain soils are characterized by aquic conditions (Soil Survey Staff 1998). In aquic soils, during periods of high precipitation and low evapotranspiration, low saturated hydraulic conductivity results in episaturation and the formation of a perched water table within 200 cm of the soil surface (Soil Survey Staff 1998). In Gulf Coastal Plain soil series descriptions, the high or

Table 1—Descriptive characteristics relative to water table dynamics of eight Gulf Coastal Plain soil series

Soil series	Location	Family	Texture class	High water table depth	Drainage class	Depth to gray mottles[a]
				- - - - *cm* - - - -		- - - - *cm* - - - -
Beauregard	Kisatchie National Forest, Louisiana	Fine-silty, siliceous, thermic Plinthaquic Paleudults	Silt loam	46 – 91	Moderately well drained	30 – 76
Freest	DeSoto National Forest, Mississippi	Fine-loamy, siliceous, active, thermic Aquic Paleudalfs	Fine sandy loam	46 – 76	Moderately well drained	46 – 76
Ichusa	Bienville National Forest, Mississippi	Fine, smectitic, thermic Aquic Dystuderts	Silty clay loam	46 – 91	Somewhat poorly drained	10 – 28
Glenmora	Kisatchie National Forest, Louisiana	Fine-silty, siliceous, thermic Glossaquic Paleudalfs	Silt loam	61 – 91	Moderately well drained	25 – 76
Kurth	Davy Crockett National Forest, Texas	Fine-loamy, siliceous, semiactive, thermic Oxyaquic Glossudalfs	Fine sandy loam	76 – 102	Moderately well drained	46 – 76
Malbis	Kisatchie National Forest, Louisiana	Fine-loamy, siliceous, subactive, thermic Plinthic Paleudults	Fine sandy loam	76 – 127	Well drained or moderately well drained	76 – 180
Mayhew	Kisatchie National Forest, Louisiana	Fine, smectitic, thermic Chromic Dystraquerts	Silty clay loam	0 – 30	Poorly drained	0 – 10
Metcalf	Kisatchie National Forest, Louisiana	Fine-silty, siliceous, semiactive, thermic Aquic Glossudalfs	Silt loam	46 – 76	Somewhat poorly drained	41 – 58

[a] Redox depletions with chromas less than those of the matrix (Soil Survey Staff 1998).

winter water table represents the depth to the perched water table. In the present study, for example, the Mayhew soil has a high water table within 30 cm of the soil surface; whereas that of the Malbis soil occurs between 76 and 127 cm (Soil Survey Staff 1997c, 1997d) (table 1). High water table depths of the Beauregard, Freest, Glenmora, Ichusa, Kurth, and Metcalf soils are intermediate between those of the Mayhew and Malbis soils (Soil Survey Staff 1997a, 1997b, 1999a, 1999b, 1999c, 1999d). Waddell (1997) also reported distinct differences among the high water table depths of Malbis, Glenmora, and Mayhew soils.

Loblolly pine is tolerant of low concentrations of soil oxygen associated with flooding in winter and spring (Schultz 1997). For a limited period, adaptations to low soil oxygen, such as accelerated anaerobic respiration (DeBell and others 1984) and development of hypertrophied lenticels and aerenchyma (Hook 1984, Topa and McLeod 1986), allow maintenance respiration and survival of loblolly pine root systems.

Lorio and others (1972) reported the effects of prolonged anaerobic conditions on loblolly pine root growth; they observed root growth parallel to the soil surface where the high water table was shallow. A greater number of roots were vertically oriented in soil that was less saturated. On sites where mineral nutrient deficiencies are common, constrained root growth may limit stand productivity. For example, Haywood and others (1990) evaluated the productivity of 10-year-old loblolly and slash pine on three sites with different high water tables. Less productivity occurred on the Caddo soil that had a high water table depth of 4 to 14 cm than on the Beauregard soil and the Acadia-Beauregard-Kolin soil complex that had high water table depths of 19 to 49 cm and 23 to 38 cm, respectively. In an earlier study, Tiarks and Shoulders (1982) surveyed the productivity of 20-year-old loblolly and slash pine growing on six soil series with different high water table depths in Mississippi. They found a strong positive relationship between tree height and high water table depth. Moreover, this relationship was stronger on soil series with high water table depths <60 cm.

Aerobic respiration requires oxygen as an electron acceptor. As oxygen becomes less available, the concentration of electrons, and, therefore, the reducing strength of the soil, increases. Soil redox potential is a measure of soil reducing strength (Lindsay 1979, Wolt 1994). Depending on soil pH, the Eh of oxidized soil ranges from 400 to 1000 mV (Lindsay 1979, Wolt 1994). In the Gulf Coastal Plain with an average soil pH of 5.0, complete depletion of oxygen occurs at Eh values of approximately 300 mV (Faulkner and Patrick 1992, Patrick and Jugsujinda 1992).

During 1993 through 1997 in 12- to 16-year-old loblolly pine on a Beauregard silt loam soil in the Kisatchie National Forest, maximum net new root elongation occurred during late April through late July (fig. 1). Also in the Kisatchie on Glenmora soil, which is similar to Beauregard soil, values of Eh averaged from late April through late July suggested that

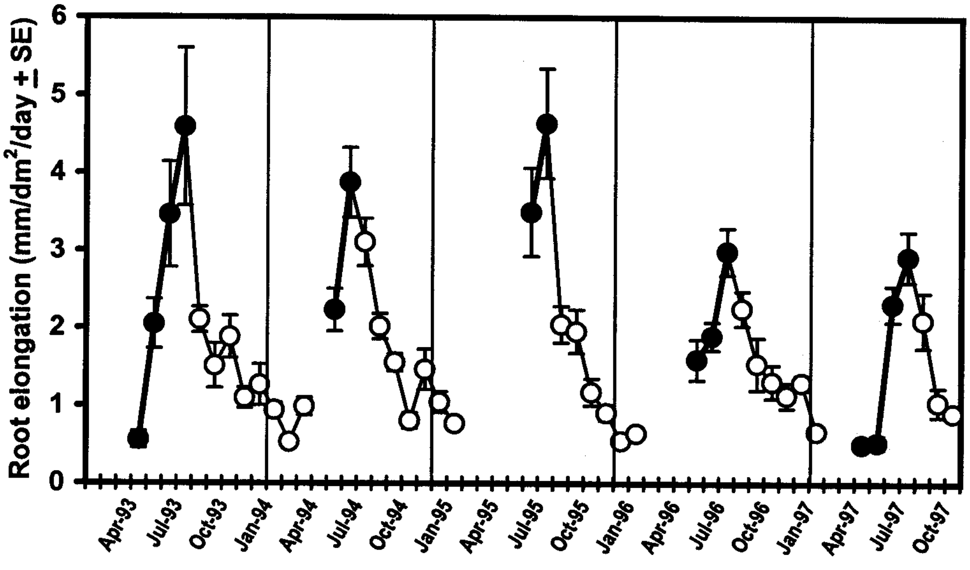

Figure 1—Net lateral root elongation averaged among thinning and fertilization treatments of 12- to 16-year-old plantation loblolly pine in the 0-to 30-cm depth of rhizotrons on a Beauregard soil in the Kisatchie National Forest, Louisiana. Maximum root elongation generally occurred in midspring (April) through midsummer (July) (black symbols).

oxygen deficiency limited aerobic metabolism at the 50-cm depth in 1993 and 1994 and at the 100-cm depth in 1993 to 1995 (table 2). On the drier Malbis soil, average Eh values at the 50- and 100-cm depths were within the range associated with oxygenated soil. However, minimum Eh values of the Malbis soil indicate that at least one of three sensors at the 50-cm depth in 1993 and at the 100-cm depth in all three years was exposed to anaerobic conditions. Waddell (1997) reported similar results for a Metcalf soil in May through July where Eh at 50 cm ranged between 230 and 330 mV in 1995 and 410 and 610 mV in 1996. We conclude that the depth of oxygenated soil and the volume of soil available for root proliferation during midspring through midsummer vary by soil series and year.

Spatial variation also affects the oxygenation of Gulf Coastal Plain soil series. Between the winters of 1995 and 1999, we measured Eh at the 25-cm depth with six sensors in a newly established loblolly pine stand on an Ichusa silty clay loam in Mississippi. In 1995 in midspring through midsummer, average Eh between 370 and 488 (fig. 2). Values >300 mV suggested that soil oxygen was not limiting and, therefore, did not hinder root survival and growth. However during this period, approximately 25 percent of the Eh sensors indicated anaerobic conditions. Similarly in 1997 and 1998, approximately 25 percent of the Ichusa soil area at the 25-cm depth was not oxygenated in midspring through midsummer when the rate of new root growth may have been greatest.

Soil Strength

Ultisols predominate on the Gulf Coastal Plain (Barrett 1995), and a fragipan commonly occurs on poorly drained Ultisols (Buol and others 1980). A fragipan is a subsurface horizon with a lower macroporosity and a higher bulk density than proximal horizons; when dry, it limits root penetration (Buol and others 1980, Soil Survey Staff 1998). As soils dry on the Gulf Coastal Plain during the growing season and fragipan characteristics develop, soil strength may limit root elongation (Wraith and Wright 1998). Average penetrometer resistance measurements demonstrated the strength of a Freest fine sandy loam soil in Mississippi (table 3). Although measured during winter and spring when water availability was high, average values at the 10- to 20-cm depth approached or exceeded 2 MPa, which can impede root growth (Whalley and others 1995). Because mechanical impedance to root elongation increases as soil water potential decreases (Bennie 1996, Eavis and Payne 1969), soil strengths >2 MPa may have occurred throughout the soil profile as the growing season progressed.

In addition to strength, bulk density measurements of the soil indicate low macroporosity and the likelihood of reduced root elongation. Bulk densities exceeding 1.55 g per cm^3 potentially inhibit the elongation of tree roots in fine texture soils (Pritchett 1979). However, because soil texture and macropore distribution affect root elongation, growth-limiting bulk density differs by soil horizon (Daddow and Warrington 1983). For the Malbis fine sandy loam soil in Louisiana, we predicted the growth-limiting bulk densities at six depth increments (Daddow and Warrington 1983) (fig. 3). Our data indicated that bulk density limited root elongation at approximately 35 cm.

On the Freest fine sandy loam soil in Mississippi, we observed maximum soil strength at the 10- to 20- and 50- to 60-cm depths both before and 6 years after the application of soil compaction and organic matter removal treatments (table 4). Coefficients of variation associated with Freest soil strengths indicated that a larger amount of variation generally occurred in the 0- to 30-cm depth than in the 30- to 60-cm depth (table 3). On the Malbis soil in Louisiana, the variation associated with bulk density also differed by

Table 2—Mean and minimum hourly soil redox potential (Eh, mV) at the 50- and 100-cm depths of Glenmora and Malbis soils in the Kisatchie National Forest, Louisiana, during late April through late July of 1993, 1994, and 1995

		50-cm depth			100-cm depth		
Soil series	Statistic	1993	1994	1995	1993	1994	1995
Glenmora	Mean	265	265	355	226	271	209
	Minimum	-120	-132	-142	-144	15	-75
Malbis	Mean	566	673	727	309	449	504
	Minimum	294	355	560	-108	-52	299

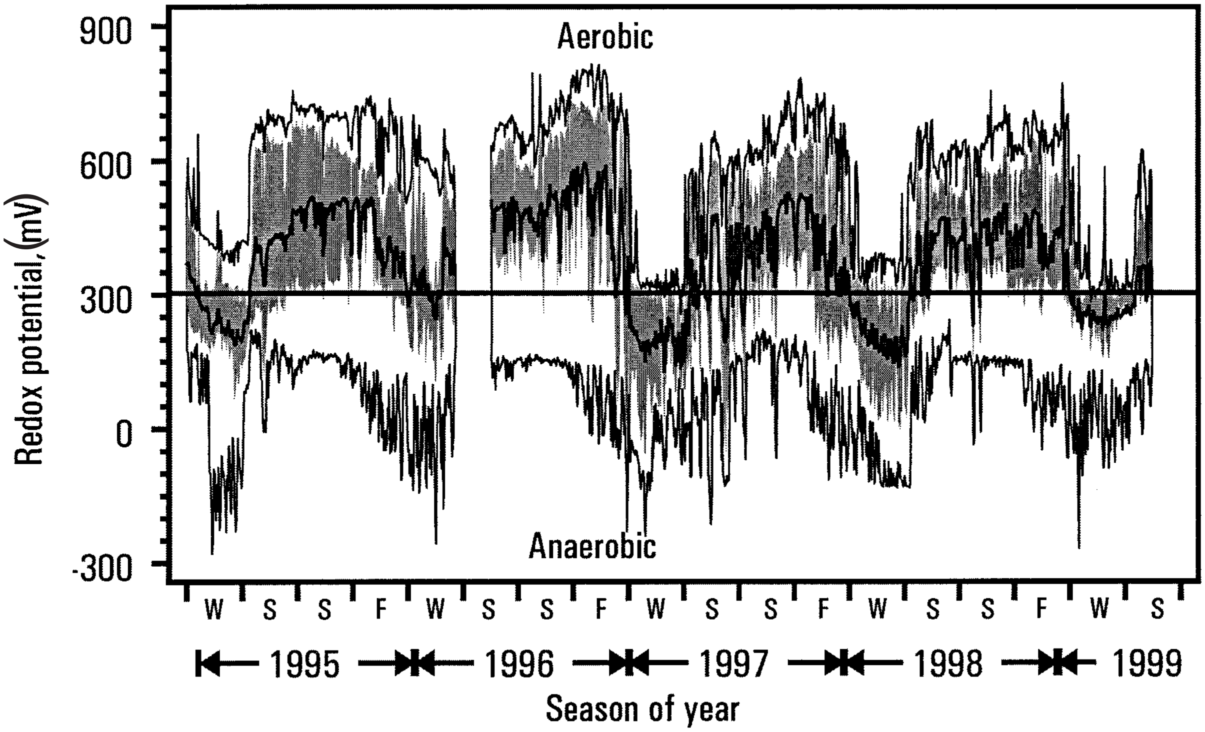

Figure 2—Redox potential at the 25-cm depth of an Ichusa soil in the Bienville National Forest, Mississippi, between the winters of 1995 and 1999. We recorded data from six sensors placed randomly in a 25-m^2 area at 5-minute intervals to calculate daily means (center black line). Upper and lower black lines present the minimum and maximum range of daily average Eh (n = 6). Shaded and open bands around the mean distinguish 25th, 50th, 75th, and 100th percentiles. The soil is considered anaerobic at Eh 300 mV.

depth with more variation at the 20- to 75-cm depth than at the 0- to 20- and 75- to 180-cm depths (fig. 3).

Although average values of soil strength and bulk density may inhibit root elongation at a particular depth, the spatial variation associated with these variables suggests that a portion of the soil volume is continuously available for root system expansion. For example, on the Malbis fine sandy loam soil in Louisiana, we compared the range of 50 bulk density measurements and the predicted growth-limiting bulk density at each of six depth increments (Daddow and Warrington 1983) (fig. 3). At the 0- to 30-cm depth, 15 percent of the bulk density measurements exceeded the growth-limiting bulk density. Below the 30-cm depth, more than 50 percent of the bulk density measurements were greater than the growth-limiting bulk density. If root system access to the soil is based on bulk density alone, <40 percent of the Malbis soil volume below 30 cm is available for root system advancement.

The majority of southern pine roots occur in the upper portion of the soil profile where mineral nutrient availability is highest (Farrish 1991, Mou and others 1995, Parker and Van Lear 1996, Torreano and Morris 1998, Van Rees and Comerford 1986). However on sites that experience drought, vertical roots must extend deep in the soil profile for water uptake. Day and others (1998) found significant horizontal and vertical water flow through interconnecting prism faces of a sandy loam fragipan. The occurrence of redoximorphic features on prism faces in the fractured fragipan suggested that prism interfaces were channels for vertical water and root movement.

In soil horizons with a high proportion of block- or prism-like peds, roots elongate vertically into interped spaces (Parker and Van Lear 1996). Old root channels left by previous vegetation also serve as conduits for root elongation (Nambiar and Sands 1992, Van Rees and Comerford 1986). On a sandy soil with a compacted layer that impaired root growth, plants benefited from deep soil access (Nambiar and Sands 1992). Vertical elongation of Monterey pine seedling roots in perforations that were uniformly distributed over 0.2 percent of the compacted layer eliminated the negative effect on growth of surface soil water deficit.

Table 3—Means and probabilities of a greater F-value associated with the soil strength of a Freest soil in response to two levels each of soil compaction and organic matter removal

	No compaction—level of OM removed		Severe compaction—level of OM removed	
Depth	None	All aboveground	None	All aboveground
cm				
	Preharvest soil strength (MPa)			
0–10	1.06 (71)[a]	0.96 (74)	0.94 (66)	1.13 (65)
10–20	1.82 (51)	1.74 (57)	1.53 (58)	1.95 (52)
20–30	1.32 (47)	1.23 (46)	1.25 (53)	1.34 (57)
30–40	1.08 (32)	1.19 (40)	1.17 (41)	1.31 (40)
40–50	1.26 (35)	1.41 (32)	1.34 (41)	1.45 (28)
50–60	1.51 (46)	1.72 (43)	1.50 (43)	1.72 (34)
	Age 6 soil strength (MPa)			
0–10	0.89 (64)	0.83 (48)	1.17 (62)	1.71 (61)
10–20	1.22 (66)	1.12 (70)	1.94 (53)	2.45 (49)
20–30	.88 (50)	.88 (68)	1.16 (54)	1.25 (59)
30–40	.94 (35)	.98 (38)	1.17 (39)	1.24 (31)
40–50	1.14 (41)	1.16 (33)	1.43 (43)	1.44 (28)
50–60	1.52 (48)	1.48 (52)	1.78 (43)	1.80 (41)

	- - - - - - Probability > F-value - - - - - -	
Effect (df)	Preharvest	Age 6
Block (2)	0.0001	0.0001
COMP (2)	.5333	.0001
OM (2)	.0059	.0550
DEPTH (5)	.0001	.0001
COMPxOM (1)	.0589	.0158
COMPxDEPTH (5)	.9461	.0001
OMxDEPTH (5)	.6891	.5180
COMPxOMxDEPTH (5)	.4037	.1711

COMP = soil compaction treatment with levels of no compaction and severe compaction. Severe compaction is defined as 80 percent of the difference between the growth-limiting bulk density and the bulk density of noncompacted soil (Tiarks and others 1993);OM = organic matter removal treatment with levels of no removal and removal of all vegetation and forest floor material.

[a] Coefficients of variation in parentheses reflect the standard deviation of 315 measurements.

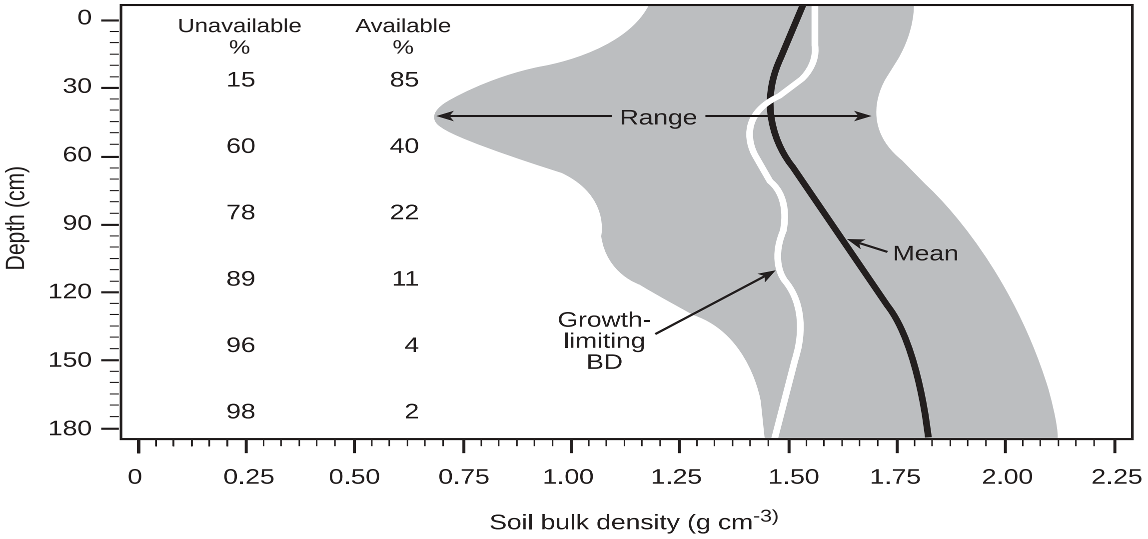

Figure 3—Mean bulk density (BD) and predicted growth-limiting bulk density (Daddow and Warrington 1983) 10 years after planting on a Malbis soil in the Kisatchie National Forest, Louisiana. Because the LTSP soil compaction and organic matter removal treatments were not significant 10 years after planting, we composited data for each of six 30-cm-depth increments (n = 50). We determined the percentage of soil available for root growth by the range of measured bulk densities and the growth-limiting bulk density at each depth interval.

Table 4—Mean soil strength (MPa) by depth of a Mississippi LTSP installation on a Freest soil before harvest and 6 years after planting loblolly pine seedlings

Depth	Preharvest	Age 6
cm		
0–10	1.02 e	1.15 b
10–20	1.76 a	1.68 a
20–30	1.29 c	1.05 c
30–40	1.19 d	1.08 c
40–50	1.37 c	1.29 b
50–60	1.61 b	1.65

Means in each column associated with different letters are significantly different by the LSD test at $P \leq 0.05$.

The range of soil strength measurements on the Freest fine sandy loam soil in Mississippi reflects the influence on soil variation of soil structure, old root channels, and anomalies such as old animal burrows and stump holes. For example, on one plot that received no soil compaction or organic matter removal, soil strength ranged between 0.01 and 4.6 MPa.

On a Beauregard silt loam soil after reduced precipitation during the first half of 1998, soil water content in June and July at the 15-cm depth was 40 percent less than the average measured in the previous 4 years (fig. 4). In June and July 1998, loblolly pine root elongation in the 0- to 30-cm depth was 76 percent lower than the average of the previous 5 years (fig. 5). In mid-July, we observed the appearance of hydraulic lift of water from deep to shallow soil with a surge of root elongation in 9 of 24 rhizotrons. July root growth was not related to thinning, fertilization, or recent precipitation. Of the trees measured for fascicle physiology, we simultaneously evaluated six for root growth in rhizotrons, and we observed a significant relationship between net photosynthesis in the upper crown and root elongation in rhizotrons (fig. 6). We speculate that fractures and old root channels in dry subsurface soil facilitated deep

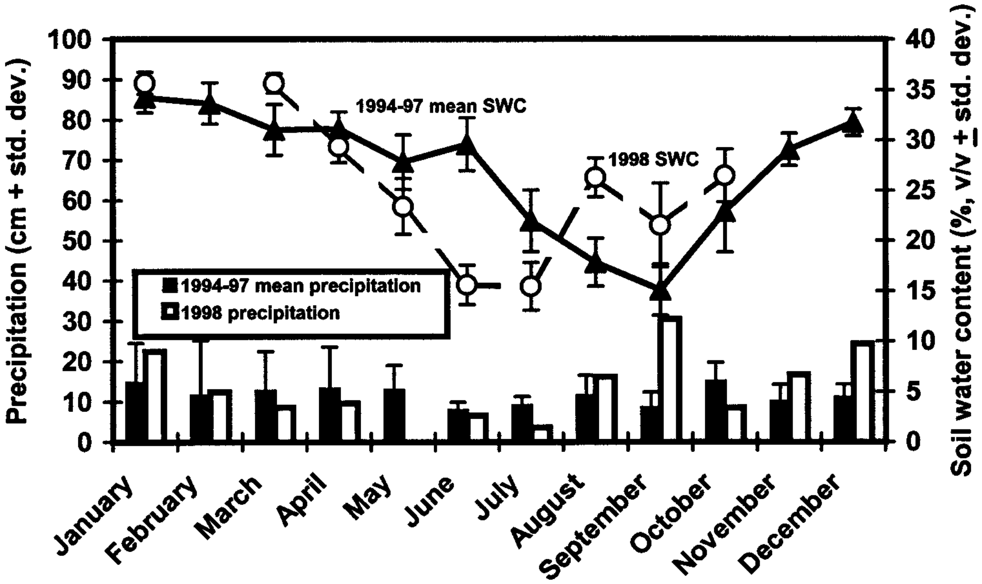

Figure 4—Average monthly precipitation and soil water content at a soil depth of 15 cm in 1994 through 1997 and in 1998.

root growth, water acquisition, and physiological activity of some loblolly pine trees at the site.

Development of the Root Zone Submodel

Where soils contain multiple layers with unique properties that affect plant-available water and root proliferation, a root zone submodel should predict the function of each distinct layer. In their water balance submodel, Whitehead and Kelliher (1991) assumed that plants extract water uniformly from one root zone soil layer. They validated their submodel in a New Zealand Monterey pine plantation with a soil characterized by three texturally distinct layers. The surface soil to a 0.5-m depth was sandy loam to loamy sand overlying a sand and gravel layer, and the subsoil to a rooting depth of 3.5 m was sandy loam to silt loam. Although matric potential functions for the 0- to 1-, 1- to 1.4- and 1.4- to 3.5-m depths were considerably different, they applied the matric potential function of the 0- to 1-m depth to the entire 3.5-m root zone for calculation of transpiration. They observed a large discrepancy between predicted drainage and measured streamflow and attributed the poor validation to errors in rainfall and streamflow measurement. Application of one matric potential function to the entire root zone may have also introduced error in predictions of plant-available water, transpiration, and drainage.

Previous modeling efforts have evaluated soil productivity as a composite of environmental conditions in soil layers (DeJong and Shaykewich 1981, Gale and others 1991, Kiniry and others 1983, Phillips and others 1989). Kiniry and others (1983) summed the rooting indices (RI) of 10-cm-depth increments to determine the sufficiency of soil for the root growth of agricultural crops. They determined the RI of each depth increment by potential root zone water storage, aeration, bulk density, pH, and electrical conductivity. Based on the model of Kiniry and others (1983), Gale and others (1991) developed a Productivity Index (PI) model to express forest productivity based on soil properties, topography, and climate. Further development of the PI model led to the characterization of pedogenic horizons rather than depth increments (Gale and others 1991, Pierce and others 1984). Models that describe soil layers by horizon are compatible with the U.S. Natural Resources Conservation Service (NRCS) Soil Interpretation Record (SIR) database, which is readily available and includes extensive information from actual measurements.

Pertinent soil physical characteristics affect root proliferation and function on the Gulf Coastal Plain. These include the seasonal dynamics of soil aeration and strength that impede root growth, soil structural attributes that facilitate vertical root elongation, and plant-available water defined as soil water between field capacity and wilting point. Da Silva and others (1994) selected similar soil

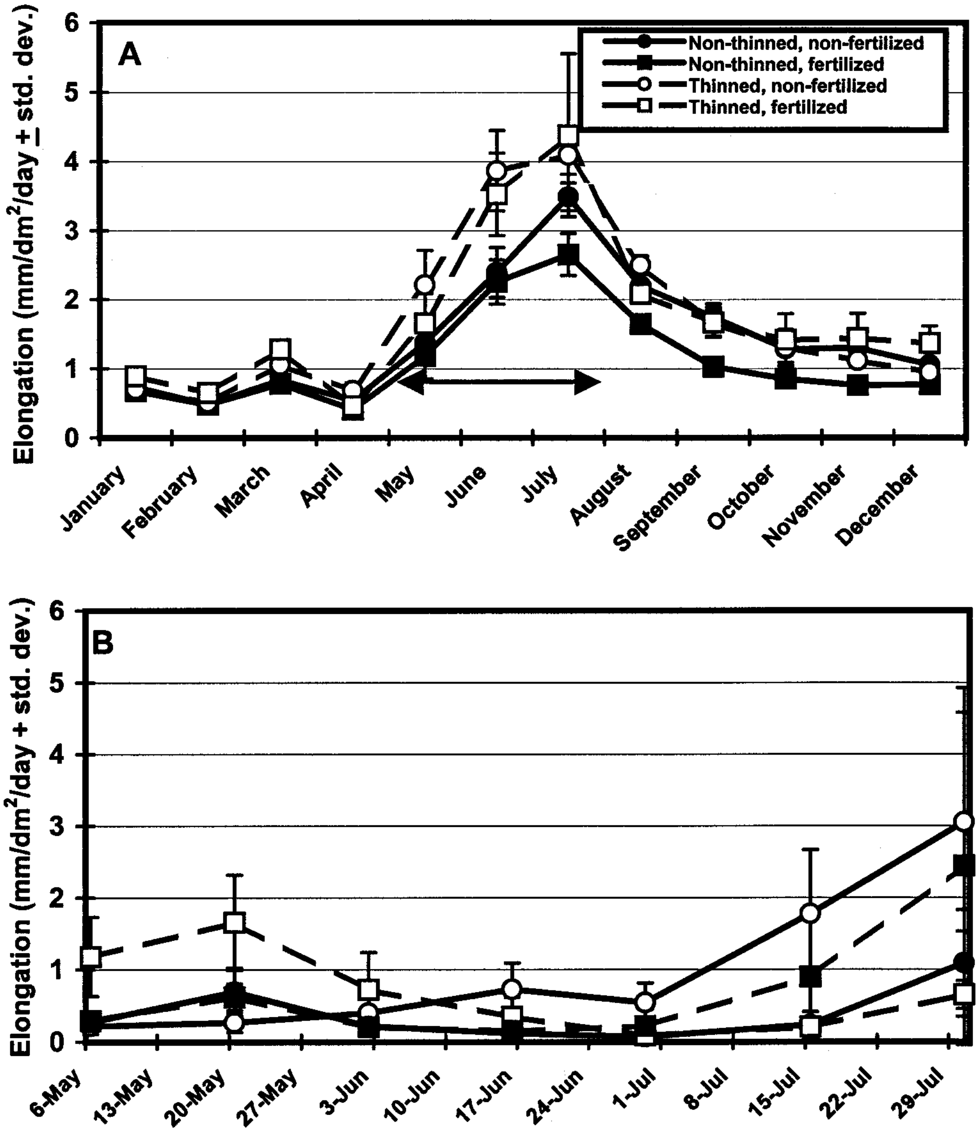

Figure 5—Average monthly net lateral root elongation by treatment in the 0- to 30-cm depth, during 1993 through 1997 (A), and in 1998 (B). The arrow in (A) represents the measurement period in (B).

physical properties to model the least limiting water range (LLWR) or amount of soil available to agricultural crops. They predicted the LLWR over a range of bulk densities as a function of air-filled porosity, soil strength, and plant-available water.

The NRCS soil series descriptions contain information on the color of the soil matrix, as well as the frequency, size, and color of redox depletions and vertical streaks by horizon (Soil Survey Staff 1998). In 17 plots each on 3 topographically different Gulf Coastal Plain sites, Sprecker and others (1999) placed redox sensors in each horizon to a 50-cm depth. They found high correlations between Munsell color, water table depth, and redox potential. Furthermore, with information from aquic soils in Louisiana, Daigle and others (1996) expressed the association between the volume of soil with redoximorphic features and Eh. We hypothesize that the relationship between Eh and NRCS color can be used to predict soil aeration limitations to root processes. Once relationships between NRCS soil color and root

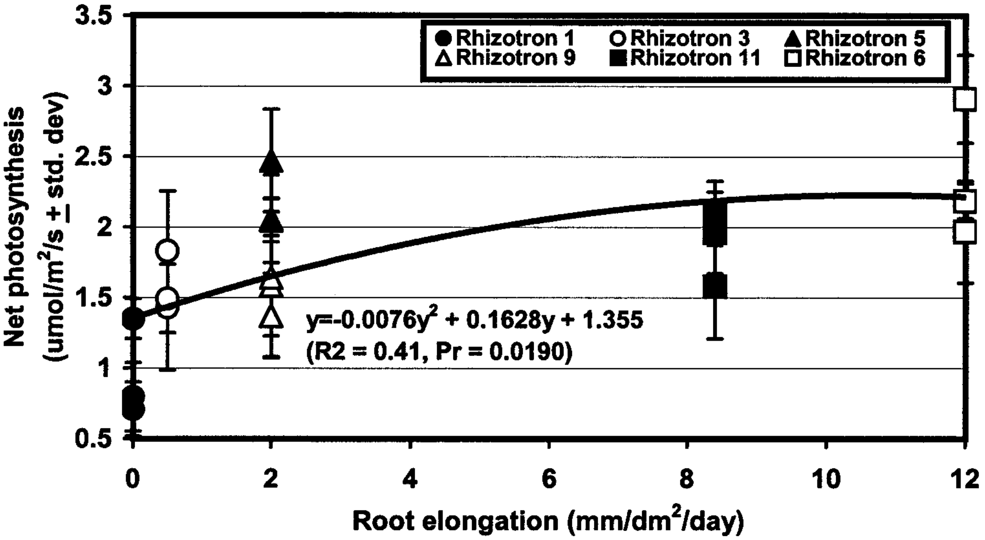

Figure 6—Relationship between net photosynthesis and net root elongation of six 17-year-old loblolly pine trees in July 1998 on a Beauregard soil in the Kisatchie National Forest, Louisiana. We present the mean and standard deviation of measurements taken at 1100, 1300, and 1500 hours.

survival and growth are established, the color of the soil matrix and the spatial distribution of redox depletions in each horizon of a soil series will reflect the volume of soil that is and is not favorable for root proliferation.

Water content and bulk density are the primary factors that control soil strength (Smith and others 1997). The NRCS primary characterization data and SIR database convey water retention and bulk density by horizon for all soil series. In the root zone submodel, it may be possible to predict seasonal soil strength as a function of bulk density, plant-available water, and seasonal soil water content. Before including soil strength in a root zone submodel, however, we should determine the range of soil strength that inhibits loblolly pine root elongation. Furthermore, we must consider that soil strengths that mechanically impede root elongation may not completely limit vertical and horizontal expansion of the root system if well-developed interped spaces, soil fractures, or old root channels are common. The NRCS soil survey descriptions of soil structure provide information on the occurrence of interped spaces. Management history and stand age may also help determine the prevalence of soil fractures and old root channels.

Conclusions

Our conceptual submodel of the root zone calculates the volume of plant-available soil in each horizon as a function of soil aeration, soil strength, and plant-available water. Initial calculations by horizon assume that physical restrictions are absent. As soil aeration and strength reach levels that reduce root survival or elongation, or plant-available water becomes limiting to root function, the unrestricted soil volume is decreased accordingly. We sum horizon values to give the amount of soil available for water and mineral nutrient uptake. Once we calculate the volume of plant-available soil, we can determine values of potential root zone water storage and plant-available water that reflect root zone limitations and apply them in physiological process models.

This approach to modeling plant-available water and the potential for root proliferation on the Gulf Coastal Plain is promising. Preliminary research is needed, however, to define limiting values of soil aeration and strength associated with *in situ* loblolly pine root survival and elongation. For soil physical limitations to root survival and elongation, a root zone submodel should rely on data from the NRCS National Soil Survey program, which is the only source of extensive information on forest soils collected by standardized methods. The NRCS SIR database is available by soil association in the readily accessible State Soil Geographic database (Soil Survey Staff 1995). This resource allows application of our conceptual root zone submodel in process model predictions of forest productivity at the regional scale.

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We combined published information and our own experimental results from the Gulf Coastal Plain to evaluate how soil aeration and strength interact with loblolly pine root growth. Our results demonstrate that soil aeration and strength differ by soil series and year and are subject to vertical and horizontal spatial variation. Comparison of loblolly pine root phenology and seasonal redox potential indicates that oxygen is frequently limiting to new root growth. The strength of these soils may also restrict loblolly pine root growth. Physiological process models that predict southern pine productivity should apply accurate calculations of plant-available soil in simulations of potential root zone water storage and plant-available water. We propose a conceptual root zone submodel that predicts the volume of plant-available soil with soil aeration, strength, and water retention by horizon. Model parameters are components of the Natural Resources Conservation Service (NRCS) Soil Interpretation Record (SIR) database collected across the United States.

Keywords: Soil aeration, soil strength, spatial variation, redox potential, root phenology, root zone sub-model.