DIVISION S-10—WETLAND SOILS

The Microbial Activity Season in Southeastern Hydric Soils

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ABSTRACT

The growing season requirement is an often overlooked part of the definition for hydric soils. The current technical definition for a hydric soil states that flooding or soil saturation must occur during the portion of the year when soil temperature at 50 cm is >5°C. In this study, we defined the portion of year when soils were >5°C at 50 cm as the *microbial activity season* and reserved the term *growing season* for plant activity. In the technical criteria for hydric soils, specific microbial activity season months have been assigned to each of the soil temperature regimes. Our objectives were to determine the portion of the year when southeastern U.S. hydric soils are <5°C at 50 cm and to estimate rates of microbial activity during winter flooding. We found that 34 bottomland hardwood forest soils in South Carolina, Louisiana, and Mississippi were never <5°C at 50 cm during a period of 2 to 3 yr. Also, winter rates of soil respiration and O_2 consumption (1.6 mL O_2 L^{-1} air d^{-1}) are apparently sufficient to cause anoxia in saturated soils. Based on the available data, we recommend a 12-mo microbial activity season for southeastern bottomland hardwood forests. Additional data will be necessary to determine the relationships between temperature, soil saturation, and development of redoximorphic features in southeastern soils.

THE CURRENT DEFINITION for a hydric soil requires saturation during the growing season, defined as the portion of the year when soil temperatures at 50 cm are above 5°C (Soil Conservation Service, 1991). The temperature threshold is based on evidence that microbial activity is negligible below 5°C (microbial zero). Temperatures <5°C inhibit microbially mediated reduction–oxidation reactions that consume O_2 and reduce Fe and Mn compounds (Pickering and Veneman, 1984; Evans and Franzmeier, 1988). These redox processes provide the necessary conditions for the formation of soil redoximorphic features such as Fe concentrations and depletions. Temperature measurements are made at 50 cm because this depth is below the influence of diurnal variations in air temperature (Soil Survey Staff, 1975). A single temperature measurement at 50 cm is equivalent to averaging diurnal air temperature measurements during a period of several days.

Because soil temperature data are not readily available for most sites, specific growing season months are assigned to each soil temperature regime (Soil Conservation Service, 1991). Soil temperature regimes are in turn defined by the mean annual soil temperature and, in some cases, the variation around an annual mean. Soils with thermic temperature regimes, such as those in southeastern USA, have mean annual soil temperatures ranging from 15 to 19.9°C with annual fluctuations >5°C at 50 cm (Soil Conservation Service, 1991). The assumed growing season period for hydric soils with thermic temperature regimes is February to October. In addition, some regulatory guidances for identifying wetlands use frost-free days to estimate the growing season (Environmental Laboratory, 1987). It appears that the technical definition of growing season is open to much interpretation in practice (Williams, 1992).

The growing season concept was originally used in soil surveys to indicate the types of crops a soil would support, and it is questionable if the concept can be extended to soil microbial processes. We will use the term *microbial activity season* to distinguish the annual period of significant soil microbial activity from the annual period of significant plant growth.

We used temperature and soil oxygen data from a large number of soils in South Carolina, Louisiana, Mississippi, and Georgia to evaluate the microbial activity season in southeastern U.S. hydric soils. Our objectives were to (i) determine the period of the year that hydric soils are <5°C, (ii) estimate the period of significant microbial activity in these soils, and (iii) evaluate the results in terms of the scientific issues surrounding the current definition of wetlands.

METHODS

Most of our data on soil O_2 content, temperature, and water table depth were collected during two studies on redox processes in bottomland hardwood forest soils (Faulkner and Patrick, 1992; Megonigal et al., 1993). We located elevational transects in South Carolina (n = 2), Louisiana (n = 4), and Mississippi (n = 1) with aerial photography, soil surveys, and ground reconnaissance. The transects were selected to encompass much of the local variability in alluvial soil types (Table 1). Within each transect, we established plots on four to six soils that ranged from locally well drained to poorly drained. Measurements were made on a total of 34 Gulf and Atlantic Coastal Plain soils at monthly intervals for periods of 2 to 3 yr.

We measured soil O_2 content (depths of 10, 30, 60, and 90 cm) with diffusion chambers and a modified Yellow Springs Model 51B O_2 meter (Yellow Springs Instrument Co., Yellow Springs, OH). Soil temperature was determined with a Cole-Palmer portable meter (Model H-08110-20) and thermistors (Cole-Palmer Instrument Company, Niles, IL). Water table depth was measured in wells made of perforated polyvinyl chloride (PVC) pipe (5 to 6 cm i.d. by 120 cm long). The wells were placed in bore holes, lined with pea gravel, and sealed at the soil surface with either concrete or clayey subsoil from the site. Further details on construction, installation, and measurement procedures are available in Faulkner et al. (1989).

We used monthly measurements of O_2 concentration in the South Carolina, Louisiana, and Mississippi soils to estimate

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Table 1. Soil classification and duration of saturation during the growing season (February-October) for bottomland hardwood soils in South Carolina, Louisiana, and Mississippi.

Soil classification			
Soil taxonomy	Hydric or nonhydric†	Saturation Feb. to Oct.‡	Dates studied
		%	
	South Carolina§		
Cumulic Humaquept	hydric	94	1/86 to 12/87
Cumulic Humaquept	hydric	88	"
Histic Humaquept	hydric	76	"
Arenic Endoaquult	hydric	35	"
Typic Quartzipsamment	nonhydric	0	"
Typic Fluvaquent	hydric	38	"
Fluvaquentic Dystrochrept	hydric	12	"
Fluventic Dystrochrept	nonhydric	0	"
Typic Fragiaquult	hydric	41	"
Aquic Hapludult	nonhydric	0	"
	Louisiana and Mississippi¶		
Aeric Fluvaquent	nonhydric	5	9/82 to 4/85
Typic Fluvaquent	hydric	11	"
Typic Fluvaquent	hydric	19	"
Typic Fluvaquent	hydric	63	"
Aquic Hapludalf	nonhydric	0	"
Vertic Endoaqualf	nonhydric	0	"
Vertic Haplaquept	hydric	20	"
Vertic Haplaquept	hydric	21	"
Vertic Haplaquept	hydric	37	"
Typic Fluvaquent	hydric	100	"
Aeric Endoaqualf	nonhydric	0	"
Vertic Haplaquept	hydric	25	"
Vertic Haplaquept	hydric	19	"
Vertic Haplaquept	hydric	37	"
Typic Fluvaquent	hydric	55	"
Typic Udifluvent	nonhydric	0	"
Typic Udifluvent	nonhydric	0	"
Vertic Hapludoll	hydric	100	"
Typic Fluvaquent	hydric	100	"
Vertic Endoaqualf	nonhydric	17	"
Vertic Endoaqualf	hydric	17	"
Vertic Haplaquept	hydric	41	"
Typic Fluvaquent	hydric	89	"

† From the Hydric Soils list (Soil Conservation Service, 1991).
‡ Presence of the water table within 30 cm of the soil surface.
§ From Megonigal et al. (1993).
¶ From Faulkner and Patrick (1992).

rates of O_2 consumption. Monotonic decreases in O_2 content during periods when the O_2 diffusion chambers were continuously submerged (judging from monthly water table data) were used to calculate rates of O_2 consumption during two periods: November through February and March through October. The rates are conservative because of the high ratio of air volume to soil surface area in our chambers compared with undisturbed soil air spaces (Faulkner et al., 1989). We tested the null hypothesis that O_2 consumption rates were greater in summer months than winter months with a one tailed *t* test using tables published in Naiman et al. (1977).

The North Carolina site was located in a tidal freshwater reach of the White Oak River (Kelley et al., 1995), where soils are mapped as Typic Medisaprists (Barnhill, 1992). We measured soil temperature (10-cm depth) at 30-min intervals for nearly 1 yr using a CR10 logger and a Model 107 thermistor (Campbell Scientific, Inc., Logan, UT). Soil temperature was also measured in 1994 at a bottomland hardwood site near Alpharetta, GA, with an ElTH Electronic Thermometer (Ben Meadows Company, Atlanta, GA) inserted to a depth of 15 cm.

The temperature regime of all these soils is thermic, and they are supposed to have a growing season beginning in February and ending in October (Soil Conservation Service, 1991). However, February is one of the coldest months of the year in southeastern USA. (Fig. 1). To be conservative in our analyses of temperature and O_2 consumption rates, we grouped February with the nongrowing season months November through January.

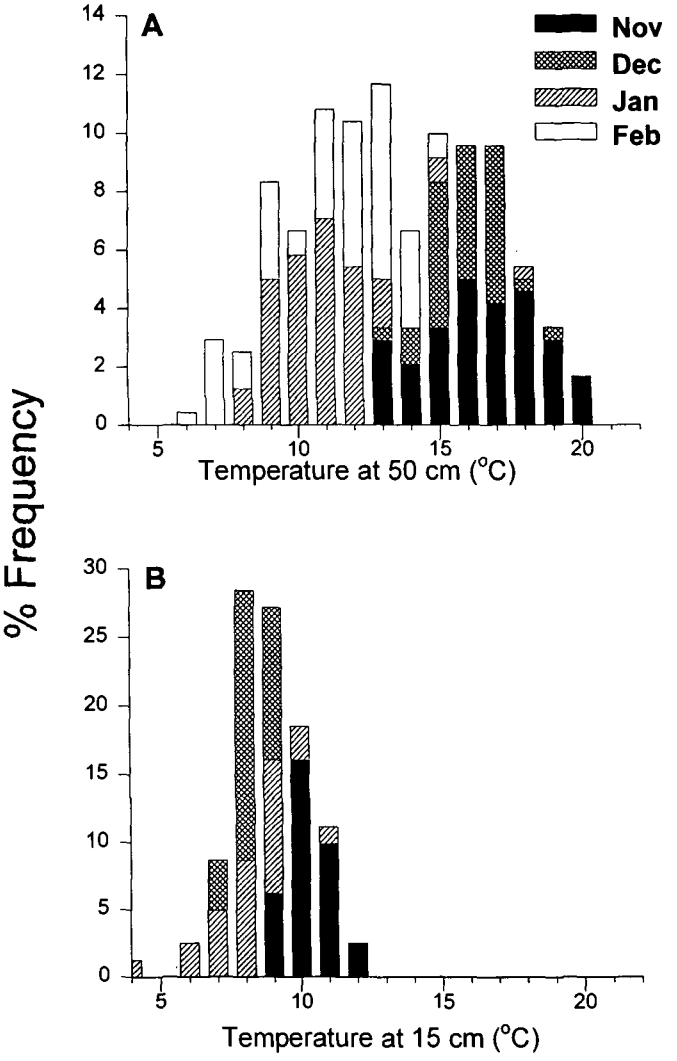

Fig. 1. Frequency distributions of soil temperature for bottomland hardwood forests during the four coldest months of the year (November through February). (A) 240 observations of temperature at 50-cm depth from study soils located in South Carolina (*n* = 10), Louisiana (*n* = 19), and Mississippi (*n* = 5). (B) soil temperature frequencies for 81 observations at a single site in northern Georgia during 1994 (15-cm depth). February data were not available.

RESULTS AND DISCUSSION

Soil temperatures at the 50-cm depth were well above 5°C from November through January in all of the 34 soils we studied, and many soils were >10°C at 50 cm (Fig. 1). Temperatures should have been <5°C during this period, according to the technical definition of hydric soils (Soil Conservation Service, 1991). We can eliminate the possibility that the temperature regime in our soils was misclassified since annual averages and ranges at 50-cm depth conform to the definition of Thermic soils (mean = 17.6°C and range = 22°C in South Carolina soils; mean = 18.3°C and range = 21°C in Louisiana

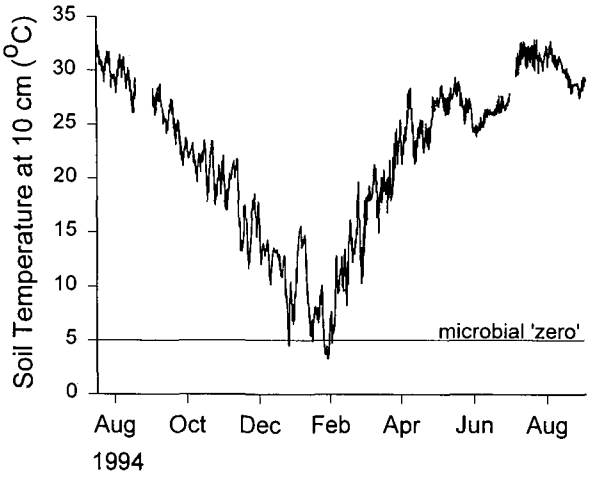

Fig. 2. Soil temperature at 10-cm depth recorded at 30-min intervals in a North Carolina muck. The horizontal line at 5°C indicates the temperature threshold that is commonly assumed for significant microbial activity in temperate soils.

and Mississippi soils). Thus, the microbial activity season months assigned to Thermic temperature regime soils were wrong in the all the cases we studied.

Measurements at depths <50 cm are indicative of conditions near the soil surface where much of the microbial activity occurs in forest soils. Continuous measurement of soil temperature at 10-cm depth showed that a North Carolina muck nearly always exceeded 5°C from August 1994 to September 1995 (Fig. 2). Similar results were observed during daylight hours at 15-cm depth in a bottomland hardwood forest in northern Georgia – just one measurement, during December, was <5°C (Fig. 1). Considering the geographic range of our sites, we believe that southeastern bottomland hardwood forests have a 12-mo microbial activity season.

Evidence of Biological Activity in Winter

Our temperature data indicate that southeastern bottomland hardwood forest soils should permit year-round microbial respiration. If so, soils should be sinks for O_2 and sources of CO_2 during winter. Rates of O_2 consumption were similar in South Carolina, Louisiana, and Mississippi, and cold-season rates were not significantly different from warm-season rates ($P < 0.01$, Table 2). Our data suggest that soil saturation may cause anaerobic conditions to develop as rapidly in the winter as in the summer.

Rates of O_2 consumption in soils can also be estimated from data on soil CO_2 emissions. Soil emissions of CO_2 originate from both root and microbial respiration, but it is likely that most O_2 consumption in soil pore spaces is due to microbes – root respiration may be supported entirely by O_2 transported from the atmosphere via air spaces in the stem (Armstrong, 1964; Grosse et al., 1992). Consider a soil with a winter CO_2 emission rate of 4.0 g m^{-2} d^{-1} (Bridgham and Richardson, 1992; Pulliam, 1993) and 50% pore space filled with O_2-saturated water (10 mg O_2 L^{-1}). Even if we assume that microbial respiration is just 40% of the measured CO_2 emission rate (Pulliam, 1993), a 1-m^3 soil profile would require just 4 d to become anoxic. Thus, both the O_2 and CO_2 flux data suggest that soils in southeastern wetlands have the capacity to function as hydric soils following relatively short periods of winter saturation. In addition, our data lend support to a 5°C threshold for delineating the microbial activity season – our sites were always warmer than 5°C at 50 cm and showed evidence of year-round O_2 consumption and soil respiration.

Table 2. Rates of O_2 disappearance from O_2-diffusion chambers during periods of continuous submergence.

Site/season	Mean	SD†	*n*	Min.	Max.
	mL O_2 L^{-1} air d^{-1}				
		South Carolina			
Mar.-Oct.	1.77	0.86	46	0.65	4.29
Nov.-Feb.	1.69	0.62	11	0.97	3.04
		Louisiana			
Mar.-Oct.	1.32	0.88	18	0.09	3.33
Nov.-Feb.	1.49	1.24	28	0.19	4.62

† SD = standard deviation.

Despite the occurrence of significant microbial activity during the winter in our soils, we know that many wetland biogeochemical processes are temperature dependent and we expect changes in rates with the seasons. However, there are very few data to support the premise that longer periods of saturation are necessary to develop hydric soils during the winter months than the summer months in southeastern bottomland forests. In addition, we are not aware of any data that quantify the relationships between soil temperature, duration of saturation, and the development of redoximorphic features in hydric soils.

There is currently a need for work on the temperature-response characteristics of key wetland biogeochemical processes, both in the field and in the lab. As an example, denitrification mitigates N pollution of water by converting NO_3 to N_2 gas. Lockaby et al. (1994) estimated in situ rates of denitrification in a bottomland hardwood forest in Alabama and found that December and August rates were equivalent. They suggested that high winter rates were due to a lack of competition for NO_3^- between denitrifiers and trees (Groffman and Tiedje, 1989). The coincidence of flooded soils and high rates of denitrification during the winter suggests that a significant portion of annual N gas loss from bottomland hardwood forest soils may occur during the winter.

Wetland Identification Issues

Growing season criteria are used in the legal definition of a wetland to exclude certain plant species that can survive soil saturation only when it occurs during winter dormancy (Environmental Laboratory, 1987). In addition, many biogeochemical processes proceed at rates that are temperature dependent, particularly those that produce redoximorphic features (Pickering and Veneman, 1984). Because the current definitions for hydric soils and wetlands were adapted from a system intended for agricultural application, their use in wetland identification is problematic and must be reconsidered.

Each of the three major parameters that define wetland

ecosystems – soils, vegetation, and hydrology – is affected differently by temperature and must be considered independently in terms of growing season activity. Soil temperature regulates microbial processes and some plant processes such as root growth. In contrast, shoot growth is most responsive to air temperature. Certain biotic activities, such as habitat use by fish (Leitman et al., 1991) and seed dispersal (Schneider and Sharitz, 1988), are linked to the hydrologic regime that operates independently of temperature. Additional discussion on the application of growing season criteria to wetland vegetation is provided by Bedford et al. (1992).

Floodwater storage and sediment removal are particularly important processes in wetland forests and are not temperature dependent. Sediments are a major sink for N, P, trace metals, and water-borne pollutants (Craft and Richardson, 1993; Puckett et al., 1993; Leigh, 1994). The hydrologic cycle in bottomland hardwood forests dictates that much of the annual sediment deposition will occur during the winter (Baumann et al., 1984). As an example, sediment retention by forested wetlands along the Cache River in Arkansas occurred primarily in the period November through February (Kleiss, 1996).

Establishing appropriate microbial activity season criteria will require input from both scientists and regulatory personnel. Scientists must provide temperature response curves for important wetland functions, such as denitrification, and quantify the significance of these processes in particular landscapes. At present, very few such data exist. Regulatory agencies must decide on the wetland functions that will be protected and at what levels. We believe that sound scientific data can and should be used to develop technical standards for accurately identifying wetland systems.

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REFERENCES

Armstrong, W. 1964. Oxygen diffusion from the roots of some British bog plants. Nature (London) 204:801–802.

Barnhill, W.L. 1992. Soil survey of Onslow County, North Carolina. USDA-SCS. U.S. Gov. Print. Office, Washington, DC.

Baumann, R.H., J.W. Day, Jr., and C.A. Miller. 1984. Mississippi deltaic wetland survival: Sedimentation versus coastal submergence. Science (Washington, DC) 224:1093–1095.

Bedford, B.L., M. Brinson, R. Sharitz, A. van der Valk, and J. Zedler. 1992. Evaluation of proposed revisions to the 1989 "Federal Manual for Identifying and Delineating Jurisdictional Wetlands." Bull. Ecol. Soc. Am. 73:14–23.

Bridgham, S.D., and C.J. Richardson. 1992. Mechanisms controlling soil respiration (CO_2 and CH_4) in southern peatlands. Soil Biol. Biochem. 24:1089–1099.

Craft, C.B., and C.J. Richardson. 1993. Peat accretion and N, P, and organic C accumulation in nutrient-enriched and unenriched Everglades peatlands. Ecol. Applic. 3:446–458.

Environmental Laboratory. 1987. Corps or Engineers wetlands delineation manual. Tech. Rep. Y-87-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Evans, C.V., and D.P. Franzmeier. 1988. Color index values to represent wetness and aeration in some Indiana soils. Geoderma 41:353–368.

Faulkner, S.P., and W.H. Patrick, Jr. 1992. Redox processes and diagnostic wetland soil indicators in bottomland hardwood forests. Soil Sci. Soc. Am. J. 56:856–865.

Faulkner, S.P., W.H. Patrick, and R.P. Gambrell. 1989. Field techniques for measuring wetland soil parameters. Soil Sci. Soc. Am. J. 53:883–890.

Groffman, P.M., and J.M. Tiedje. 1989. Denitrification in north temperate forest soils: Spatial and temporal patterns at the landscape and seasonal scales. Soil Biol. Biochem. 21:613–620.

Grosse, W., J. Frye, and S. Lattermann. 1992. Root aeration in wetland trees by pressurized gas transport. Tree Physiol. 10:285–295.

Kelley, C.A., C.S. Martens, and W. Ussler. 1995. Methane dynamics across a tidally flooded riverbank margin. Limnol. Oceanogr. 40: 1112–1129.

Kleiss, B.A. 1996. Sediment retention in an eastern Arkansas bottomland hardwood wetland. Wetlands (in press).

Leigh, D.S. 1994. Mercury contamination and floodplain sedimentation from gold mines in North Georgia. Water Resour. Bull. 30: 739–748.

Leitman, H.M., M.R. Darst, and J.J. Nordhaus. 1991. Fishes in the forested floodplain of the Ochlockonee River, Florida, during flood and drought. Water Resour. Invest. Rep. 90-4202, U.S. Geol. Surv., Tallahassee, FL.

Lockaby, B.G., F.C. Thornton, R.H. Jones, and R.G. Clawson. 1994. Ecological responses of an oligotrophic floodplain forest to harvesting. J. Environ. Qual. 23:901–906.

Megonigal, J.P., W.H. Patrick, Jr., and S.P. Faulkner. 1993. Wetland identification in seasonally flooded forest soils: Soil morphology and redox dynamics. Soil Sci. Soc. Am. J. 57:140–149.

Naiman, A., R. Rosenfeld, and G. Zirkel. 1977. Understanding statistics. 2nd ed. McGraw-Hill Book Co., New York.

Pickering, E.W., and P.L.M. Veneman. 1984. Moisture regimes and morphological characteristics in a hydrosequence in central Massachusettes. Soil Sci. Soc. Am. J. 48:113–118.

Puckett, L.J., M.D. Woodside, B. Libby, and M.R. Schening. 1993. Sinks for trace metals, nutrients, and sediments in wetlands of the Chickahominy River near Richmond, Virginia. Wetlands 13:105–114.

Pulliam, W.M. 1993. Carbon dioxide and methane exports from a southeastern floodplain swamp. Ecol. Monogr. 63: 29–53.

Schneider, R.L., and R.R. Sharitz. 1988. Hydrochory and regeneration in a bald cypress-water tupelo swamp forest. Ecology 69: 1055–1063.

Soil Conservation Service. 1991. Hydric soils of the United States 1991. USDA-SCS. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA-SCS Agric. Handbk. 436. U.S. Gov. Print. Office, Washington, DC.

Williams, A.E. 1992. Clarification and interpretation of the 1987 manual. U.S. Army Corps of Engineers CECE-OR memorandum.