The current definition for a hydric soil requires 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 redox reactions that consume O₂ 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 O₂ 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 O₂ content (depths of 10, 30, 60, and 90 cm) with diffusion chambers and a modified Yellow Springs Model 51B O₂ 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 O₂ concentration in the South Carolina, Louisiana, and Mississippi soils to estimate...
rates of O₂ consumption. Monotonic decreases in O₂ content during periods when the O₂ diffusion chambers were continuously submerged (judging from monthly water table data) were used to calculate rates of O₂ 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 O₂ 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 E1TH 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 growing season (February-October) 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. (Fig. 1). To be conservative in our analyses of temperature and O₂ consumption rates, we grouped February with the nongrowing season months November through January.

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.)
and Mississippi soils). Thus, the microbial activity season months assigned to Thermic temperature regime soils were wrong in 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 O2 and sources of CO2 during winter. Rates of O2 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 O2 consumption in soils can also be estimated from data on soil CO2 emissions. Soil emissions of CO2 originate from both root and microbial respiration, but it is likely that most O2 consumption in soil pore spaces is due to microbes — root respiration may be supported entirely by O2 transported from the atmosphere via air spaces in the stem (Armstrong, 1964; Grosse et al., 1992). Consider a soil with a winter CO2 emission rate of 4.0 g m\(^{-2}\) d\(^{-1}\) (Bridgham and Richardson, 1992; Pulliam, 1993) and 50% pore space filled with O2-saturated water (10 mg O2 L\(^{-1}\)). Even if we assume that microbial respiration is just 40% of the measured CO2 emission rate (Pulliam, 1993), a 1-m\(^3\) soil profile would require just 4 d to become anoxic. Thus, both the O2 and CO2 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 O2 consumption and soil respiration.

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 Vene-

man, 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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