Wetland Identification in Seasonally Flooded Forest Soils: Soil Morphology and Redox Dynamics

J. P. Megonigal,* W. H. Patrick, Jr., and S. P. Faulkner

ABSTRACT

Soil morphology provides a long-term record of hydroperiod and soil aeration and is widely used to identify wetlands. This study was conducted to: (i) investigate the influence of soil texture on redox processes, (ii) determine the quantitative relationships between morphology-based hydric soil indicators, redox potential, O_2 content, and water table depth, and (iii) evaluate the use of hydromorphic soils to identify wetlands. Transects were established across a floodplain of the Savannah River, South Carolina, and a third-order tributary. Ten plots were monitored for water table depth, redox potential, and soil O_2 content at depths of 15, 30, 60, and 90 cm during a 2-yr period. Six plots met the criteria for hydric soils. Redox potential, O_2 content, and chroma were strongly correlated when averaged across annual time scales (2 yr). In all cases, anaerobic and reducing conditions near the soil surface were caused by soil saturation. A clay soil in this study, however, was poorly aerated at depths $\geq$60 cm even in a drained condition. Our data provide empirical support for using soil morphology to infer periods of soil saturation and reduction in southeastern wetland forests. Field indicators (mottling, gleying, and histic epipedons) were accurate surrogates for more detailed measurements of redox potential, O_2 content, and water table depth on all sites. Contrary to assumptions in the criteria for hydric soils, temperatures were always $\geq$5 °C at 50 cm during the non-growing season. Our results suggest anaerobic conditions can develop during the winter months. Because southeastern swamp forests are saturated mainly during the winter or spring, growing-season criteria for hydric soils may require further evaluation.

DELINEATING WETLAND AREAS is a major concern of the federal and state regulatory agencies charged with implementing Section 404 of the Clean Water Act (Public Law 92-500, 33 U.S. Congress 1251). Although the task is straightforward on sites that are continuously or regularly flooded, many wetlands experience only short periods of saturation, and some may never flood. Delineating these drier areas through direct observations of saturation or flooding is inconvenient and expensive. As a result, regulatory personnel rely heavily on soil profile and plant community characteristics for indirect evidence of the flooding regime. Measurements of hydrology, vegetation, and soils constitute the three-parameter approach that is currently favored by the federal government for delineating wetlands (Federal Interagency Committee for Wetland Delineation, 1989).

A jurisdictional wetland (i.e., a wetland protected by law) must meet the criteria for hydric soils (Table 1). The most accurate methods for demonstrating hydric conditions involve monitoring soil moisture, water table fluctuations, soil O_2 content, reduction–oxidation (redox) potential, or Fe^{+2} activity (Vepraskas and Wilding, 1983; Faulkner et al., 1989). Because these methods are impractical for routine wetland identification, hydric soils are commonly identified by the presence of one or more field indicators, including a low-chroma matrix or a surface horizon high in organic matter. To satisfy hydric soil criteria, the matrix chroma of a mineral horizon in the top 30 cm must

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Abbreviations: SCS, Soil Conservation Service, ANOVA, analysis of variance; CV, coefficient of variation; CI, chroma index.

Table 1. Criteria for hydric soils.†

1. All Histosols except Folists.
2. Soils that are frequently‡ ponded or flooded ≥7 consecutive days during the growing season.
3. Soils in the Aquic or Albolls suborders, Aquic subgroups, Salorthids great group, Pell great groups of Vertisols, Pachic subgroups, or Cumulic subgroups that are:
   a. somewhat poorly drained and have a frequently occurring water table within 15 cm of the surface for a significant period§ during the growing season, or
   b. poorly drained or very poorly drained and have either:
      (i) a frequently occurring water table within 15 cm of the surface for a significant period during the growing season if textures are coarse sand, sand, or fine sand in all layers within 50 cm, or for soils with other textures,
      (ii) a frequently occurring water table within 30 cm of the surface for a significant period during the growing season if permeability is ≥15 cm h^{-1} in all layers within 50 cm, or
      (iii) a frequently occurring water table within 45 cm the surface for a significant period during the growing season if permeability ≤15 cm h^{-1} in any layer within 50 cm.

† From the Hydric Soils list (Soil Conservation Service, 1991).
‡ *Frequently* is defined as occurring in 50 out of 100 yr.
§ A significant period is usually >2 wk.

be ≤1 when mottles are absent or ≤2 when mottles are present.

The use of field indicators to determine moisture regimes assumes that strong correlations exist between redox potential, O_2 content, water table depth, and physical features such as chroma. These relationships, however, will break down if microbial activity is limited by pH, temperature, or low organic matter (Bouma, 1983). It is important to verify that hydromorphic features are quantitatively related to redox processes and soil saturation, given their widespread use for wetland identification.

Floodplain forests comprise ≈13 million ha in 10 states of the southeastern USA (Hefner and Brown, 1985). Because surface saturation in many of these forests is infrequent, field personnel depend heavily on field indicators to identify hydric soils and predict hydroperiod. We examined the accuracy of morphology-based hydric soil indicators in 10 southeastern floodplain soils. The objectives of the study were to: (i) investigate the influence of soil texture on redox processes; (ii) determine if quantitative relationships exist between soil color, soil O_2 content, redox potential, and water table depth in southeastern wetland forests; and (iii) evaluate the use of common hydric soil indicators to infer flooding regime and delineate jurisdictional wetlands.

MATERIALS AND METHODS

The soils in this study are located on the Department of Energy's Savannah River Site, Aiken County, South Carolina (Fig. 1). Ten plots were established along transects crossing the floodplains of the Savannah River and a tributary, Meyers Branch. The five plots on the Savannah River floodplain extended over a distance of ≈4 km, with dry sites on slightly raised terraces and wet sites in depressions. The Meyers Branch transect was a toposequence of five plots separated by a total distance of 75 m; topographic relief was ≈3 m between the driest and the wettest plot. Average annual precipitation in Aiken County is 1230 mm, there are 210 d in the growing season, and the temperature regime is thermic (Rogers, 1985).

Study plots (3 by 0.5 m) were established perpendicular to topographic gradients on each transect. Pits were excavated within 1.5 m of the study plots and soils were classified by USDA-SCS personnel using standard SCS procedures (Table 2). Soil samples were collected from each profile for particle-size and chemical analyses.

Particle-size and chemical analyses were performed by the University of Georgia Soils Testing Laboratory according to

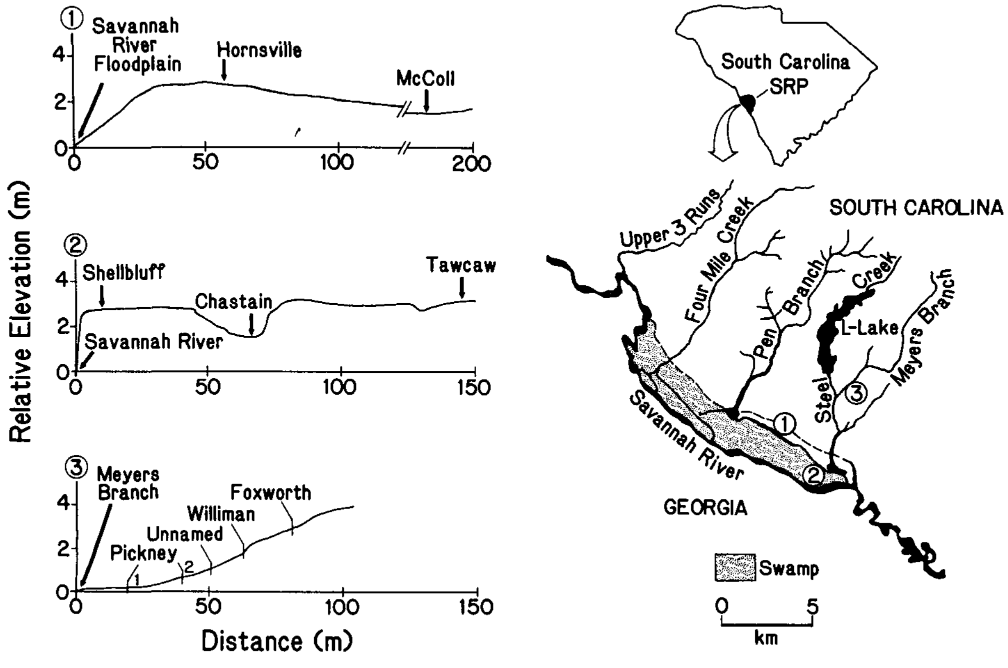

Fig. 1. Location and relative elevations of ten study soils in relation to the Savannah River and Meyers Branch, South Carolina.

Table 2. Taxonomic and hydric classification of 10 soils in South Carolina.

Pedon	Soil series	Family classification	Hydric classification†
MB-1	Pickney	Sandy, siliceous, thermic Cumulic Humaquept	Hydric
MB-2	Pickney	Sandy, siliceous, thermic Cumulic Humaquept	Hydric
MB-3	unnamed	Sandy, siliceous, thermic Histic Humaquept	—
MB-4	Williman	Loamy, siliceous, thermic Arenic Ochraquult	Hydric
MB-5	Foxworth	Thermic, coated Typic Quartzipsamment	Nonhydric
SR-1	Chastain	Fine, mixed, acid, thermic Typic Fluvaquent	Hydric
SR-2	Tawcaw	Fine, kaolinitic, thermic Fluvaquentic Dystrochrept	‡
SR-3	Shellbluff	Fine-silty, mixed, thermic Fluventic Dystrochrept	Nonhydric
SR-4	McColl§	Clayey, kaolinitic, thermic Typic fragiaquult	Hydric
SR-5	Hornsville	Clayey, kaolinitic, thermic Aquic Hapludult	Nonhydric

† According to the Hydric Soils list (Soil Conversation Service, 1991).
‡ Depends on flooding frequency.
§ Taxadjunct to McColl. Contains all the features of a fragipan but polygonal networks in the lower B horizons.

standard methods. Sieved, air-dried samples were extracted using a double-acid Mehlich procedure (Mehlich, 1938) and analyzed for K, Ca, Mg, and Na on a Jarrell-Ash inductively coupled plasma spectrophotometer (Model 955, Thermo-Jarrell-Ash, Waltham, MA). Exchangeable acidity was estimated with the Adams–Evans method (Adams and Evans, 1962; McLean, 1982). Organic matter content, determined by the Walkley–Black method (Walkley and Black, 1934), was multiplied by 0.58 to estimate organic C content. The hydrometer method (Gee and Bauder, 1986) was used for particle-size analysis and soil pH was determined on a 1:1 mixture of air-dried soil and deionized water.

Three redox electrodes and two O_2 diffusion chambers were installed on each plot at depths of 15, 30, 60, and 90 cm as described by Faulkner et al. (1989). Redox potentials were measured with a calomel reference electrode and adjusted to the H_2 electrode standard by adding 224 mV (Garrels and Christ, 1965). Redox potentials are often adjusted to a common pH in order to facilitate comparisons between different soils (Bohn, 1971). We corrected our initial redox measurements to pH 5 and the H_2 electrode standard with the following equation:

$$\text{redox}_5 = \text{redox}_i + [(\text{pH} - 5)59] + 244$$

where redox_i is the uncorrected potential. We accounted for course-scale differences in soil pH between sites and horizons using data in Table 3. Soil solution pH differs from soil pH, however, and both can vary seasonally. A more accurate correction would have required monthly measurements of pH in soil solutions. The pH correction also assumes thermodynamic equilibrium and a slope of 59 mV per pH unit (Bohn, 1971). The primary purpose of the correction was to make redox potentials in the Btg2 horizon of the McColl soil (pH 7.2) comparable to the other soils in our study (pH near 5).

Oxygen content was determined in gas samples from the O_2 diffusion chambers (Faulkner et al., 1989). The method assumed that the gas trapped in an inverted chamber was in equilibrium with a large (but unknown) volume of soil pore space nearby. We report molecular O_2 concentrations in mole percent with a maximum of 21%, the atmospheric level. At 18 °C (mean temperature at the 50-cm depth), a value of 21% is $\approx$9.9 mg O_2 L^{-1} and 5% is 2.4 mg O_2 L^{-1}.

In discussions of the wetland identification issue, we assumed that soils were effectively anaerobic at 5% O_2, based on comparisons of O_2 content and redox_5 data such as those in Table 4. This value is consistent with studies by Callebaut et al. (1982) in which O_2 diffusion rates reached zero as O_2 content approached 5%. The redox potential at which molecular O_2 has been reduced to H_2O (i.e., the onset of anaerobic conditions) varies, but in soil solutions values often range from 200 to 400 mV (Turner and Patrick, 1968). We assumed that redox_5 potentials $\leq$300 mV indicated an Fe-reduction zone. Although we did not measure dissolved Fe^{+2} to verify this assumption, Fe-stability diagrams suggested 300 mV is a conservative value for the onset of Fe reduction at pH 5 (Ponnamperuma et al., 1972).

Water table depth was determined with differential piezometers. Unperforated metal pipes were driven into undisturbed soil to depths of 30, 60, or 90 cm, then cleared of soil with a screw auger to 30 cm below the bottom of the pipe. This design allowed detection of a perched water table but did not necessarily indicate the depth of the free-water surface. A water table well was installed on each study plot in April 1987. Wells were 6-cm-i.d. by 120-cm-long polyvinyl chloride pipe perforated at 2-cm intervals on four sides from the well bottom to the soil surface (90 cm total). Wells were wrapped with 1-mm-mesh nylon screen to prevent back-filling. The outside of each well was lined with pea gravel, and the surface was packed with subsoil from the site. Water table positions prior to April 1987 were estimated from the piezometer wells and a nearby bore hole.

All measurements were made at monthly intervals from January 1986 to November 1987, emphasizing seasonal variations in soil wetness parameters. While monthly measurements did not capture short-term fluctuations of the water table, considering the drainage and permeability characteristics of the hydric soils (Table 5), our data should reasonably reflect seasonal patterns of hydroperiod. More frequent samples, however, would have been useful.

Statistical analyses were performed with SAS (SAS Institute, 1987) using the correlation procedure (Pearsons' test) and the generalized linear models procedure. Coefficients of variation were tested for normality ($P \leq 0.05$) before ANOVA.

RESULTS AND DISCUSSION

Four plots on the Meyers Branch transect (Pickney 1 and 2, Williman, and an unnamed Histic Humaquept) and two plots on the Savannah River transect (Chastain and McColl) met the criteria for hydric soils (Tables 1 and 2). Four of the plots did not meet the criteria (Foxworth, Shellbluff, Tawcaw, and Hornsville). The McColl soil is actually an unnamed taxadjunct to the McColl series. This soil meets most of the criteria for a McColl series (including a fragic-like layer that is dense, brittle, and hard), but lacks well-defined polygonal networks in the lower B horizon.

The soils have a wide range of organic C content and texture (Table 3). Meyers Branch soils are more organic and sandy than Savannah River soils, reflecting differences in flooding energy and upstream sources of sediment. Except for the Foxworth, all the soils experienced periods of saturation or flooding above the 30-cm depth during the study (Fig. 2).

Measurement Variability

Analysis of variance on the CV for replicate sets of redox probes and O_2 chambers showed that Eh (average CV = 126%) was a more variable parameter than O_2 content (average CV = 29%, $P < 0.0001$). Nonhydric soils were less variable than hydric soils ($P < 0.0001$) because redox potentials were usually dominated by O_2.

Table 3. Properties by horizon for 10 soil pedons on the South Carolina Upper Coastal Plain.

Horizon	Depth	Matrix color	Mottles		OC‡	Sand	Clay	Texture	Structure§	pH	BS¶
			Color	Pattern†							
	cm				%						%
Pickney (MB-1)											
A	0–20	10YR 3/2	—	—	11.6	68	11	sandy loam	1fgr	5.2	40
Cg1	20–46	N2/	—	—	3.8	90	2	sand	0	4.9	34
Cg2	46–127	10YR 2/1	—	—	2.3	94	2	sand	0	4.9	10
Pickney (MB-2)											
A	0–33	10YR 2/1	—	—	10.7	92	0	sand	m	4.3	14
Cg1	33–102	10YR 2/1	—	—	2.8	90	4	sand	m	4.5	7
Cg2	102–165	10YR 3/2	—	—	1.3	88	8	loamy sand	m	4.6	9
Unnamed Histic Humaquept#											
Oa1	0–15	10YR 2/2	—	—	19.4	92	0	sand	m	4.5	24
Oa2	15–23	N2/	—	—	19.0	88	1	sand	m	4.4	20
Cg	23–127	10YR 2/1	—	—	3.0	88	4	sand	m	4.6	10
Williman											
A	0–13	10YR 2/1	—	—	3.0	90	1	sand	1fgr	4.1	25
E1	13–20	10YR 5/2	7.5YR 4/4	M2P	0.3	91	3	sand	1fgr	4.9	12
E2	20–33	10YR 5/2	7.5YR 4/4	M2P	0.3	90	4	sand	1fgr	4.9	21
E3	33–61	10YR 7/2	—	—	0.1	87	7	loamy sand	1fgr	4.8	17
Btg1	61–81	10YR 7/1	7.5YR 5/4	F2D	0.1	78	18	sandy loam	2msbk	4.8	8
Btg2	81–102	10YR 7/1	7.5YR 5/4	F2D	0.1	76	24	sandy clay loam	1msbk	4.8	8
Cg	102–122	10YR 8/1	—	—	0.1	97	2	sand	0	5.2	46
Foxworth											
A	0–10	10YR 4/2	—	—	2.2	94	1	sand	1fgr	4.8	19
C1	10–25	10YR 5/3	—	—	0.5	94	1	sand	1fgr	4.9	13
C2	25–86	10YR 6/6	—	—	0.1	93	2	sand	sgr	5.2	16
C3	86–152	10YR 7/2	10YR 6/3	M3D	0.1	95	1	sand	sgr	5.1	38
C4	152–165	10YR 8/2	10YR 5/6	F1P	0.1	100	0	sand	sgr	5.8	100
C5	165–203	10YR 8/2	—	—	0.1	100	0	sand	sgr	6.0	100
Chastain											
A	0–8	10YR 5/6	10YR 5/2	M2D	1.9	12	62	clay	1msbk	4.8	34
Bg1	8–28	10YR 6/2 5YR 5/6	2.5YR 4/4	M2P	1.2	4	82	clay	1msbk	5.1	31
Bg2	28–86	10YR 5/1 2.5YR 3/6	10YR 5/6	C2P	1.9	4	78	clay	1csbk	4.7	25
Bg3	86–122	5B 4/1	—	—	0.8	16	46	clay	m	4.8	22
Tawcaw											
A	0–8	7.5YR 4/4	—	—	2.4	32	44	clay	1fgr	4.7	26
Bw1	8–20	7.5YR 5/6	—	—	1.1	24	58	clay	1msbk	4.9	23
Bw2	20–38	7.5YR 5/4	10YR 6/4	F1D	1.1	22	56	clay	2msbk	5.1	27
Bw3	38–165	7.5YR 5/4	10YR 6/2	C2D	0.4	45	24	loam	1msbk	5.1	19
Shellbluff											
A	0–13	5YR 4/3	—	—	1.6	32	30	clay loam	1fgr	4.6	30
Bw1	13–46	5YR 4/6	—	—	0.9	15	48	clay	2msbk	5.0	27
Bw2	46–94	5YR 6/3	5YR 4/6	F1D	1.6	25	30	clay loam	2msbk	4.9	37
Bw3	94–137	5YR 6/4	10YR 4/4	M1D	0.8	29	28	clay loam	1msbk	5.4	40
McColl††											
A	0–13	10YR 4/3	—	—	2.8	41	38	clay loam		4.6	26
Btg1	13–60	10YR 5/1	10YR 7/1	F2D	0.5	27	46	clay	3csbk	4.7	52
Btg2	60–94	2.5Y 5/2	—	—	0.1	22	44	clay	2csbk	7.2	89
Btxg1	94–127	2.5Y 6/2	10YR 5/6	F2D	0.1	38	20	loam	1csbk	7.6	89
Btxg2	127–140	2.5Y 6/2 —	10YR 5/6 7.5YR 5/6	M3D M3D	0.1	52	8	sandy loam	1csbk	7.7	90
Hornsville											
A	0–8	7.5YR 4/4	—	—	2.4	48	16	loam	2mgr	4.7	23
BE	8–18	10YR 5/6	—	—	0.9	42	18	loam	2msbk	5.0	24
Bt1	18–30	7.5YR 5/6	10YR 5/6	F1D	0.4	36	30	clay loam	3msbk	4.7	12
Bt2	30–66	7.5YR 5/6	10YR 7/2	F1D	0.4	22	60	clay	3msbk	4.8	13
Bt3	66–102	7.5YR 5/6 — —	10YR 6/4 10YR 7/2 5YR 5/6	M3P F2P C2P	0.2	30	52	clay	1csbk	4.8	8
Bt4	102–132	7.5YR 5/6 10YR 5/8 10YR 7/2	—	—	0.1	46	26	sandy clay loam	1csbk	4.7	32

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† The first letter denotes abundance (few, common, or many); the center number denotes size (1 = fine, 2 = medium, 3 = course); the second letter denotes contrast (distinct or prominent).

‡ Organic C = [organic matter] × 0.58.

§ Abbreviations denote grade (1 = weak, 2 = moderate, 3 = strong), size (f = fine, m = medium, c = course), and shape (gr = granular, sbk = subangular blocky). 0 = structurless and m = massive.

¶ Base saturation.

Classified as sandy, siliceous, thermic Histic Humaquept.

†† Taxijunct to McColl. The Btxg1 and Btxg2 horizons lack the polygonal networks of a fragipan.

Table 4. Minimum and maximum O_2 content and redox potential during a 6-mo period when the water table was ≤87 cm below the surface on the Chastian soil.

Depth	O_2 Min.	O_2 Max.	Redox† Min.	Redox† Max.
cm	%		mV	
15	18	19	604	667
30	16	18	600	750
60	11	14	335	673
90	4	6	−60	−97

† Adjusted to pH 5.

Variability can be attributed to spatial heterogeneity in texture, structure, organic matter, aeration, and moisture (McKenzie and Erickson, 1954; Meek and Grass, 1975). With three replicate probes, the CV was ≤30% in 70% of the redox readings. Meek and Grass (1975) reported a CV of 27% for 140 redox electrodes in a flooded field. Despite high variability, many researchers have recognized that redox potentials are useful for characterizing soil drainage conditions in the field (Flühler et al., 1976). Oxygen chambers are less variable because they sample a relatively large soil volume. In addition, soil O_2 is governed by relatively few soil variables (Howeler and Bouldin, 1971; Bohn, 1971). Many researchers prefer redox electrodes because they offer rapid response to a rising water table, microsite-level measurements, and information on redox couples other than O_2–H_2O.

Effects of Soil Texture

The texture and relative positions of soil horizons can influence soil-forming processes. Oxygen content and $redox_5$ potential generally decreased with depth on hydric soils (Fig. 3). An exception to this pattern was the McColl soil, which showed evidence of a perched water table (Fig. 4). The O_2 and $redox_5$ depth profiles reflect flooded periods when the soil was most reduced at the surface and dry periods when it was least reduced at the surface.

The well data suggest that perching occurred between the 30- and 60-cm depth. Base saturation increased from 52% in the Btg1 horizon (13–60 cm) to 89% in the Btg2, Btxg1, and Btxg2 horizons (Table 3). The Btg2 surface at 60 cm appeared to slow percolation and perch water. A horizon at 94 cm with most of the properties of a fragipan (but lacking well defined polygonal networks) coincided with a decrease in clay content from 44 to 20% (Table 3). Fragipan soils generally have <35% clay (Soil Survey Staff, 1975; Ransom et al., 1987). This layer was probably not the direct cause of perched water and hydromorphic features near the surface of the McColl soil.

On nonhydric soils, O_2 content and $redox_5$ potential were generally high and relatively constant with increasing depth (Fig. 3). In the absence of saturation in these soils, O_2 diffusion rates were rapid enough to balance soil respiration to depths of ≈1 m. By comparison, the Chastain soil (hydric) was consistently low in O_2 at 60 cm during an unsaturated period that lasted 6 mo (Table 4). Oxygen content decreased from 21 to 13% between the surface and 60 cm during unsaturated conditions. Several studies have shown that O_2 diffusion rates fall abruptly to zero near 10% air-filled pore space (Wesseling, 1962; Grable, 1966; Grable and Siemer, 1968). Clay soils may approach 10% air-filled pore space even at field capacity due to an abundance of micropores (Rawls et al., 1991). We propose that the high clay content in the Chastain soil reduced O_2 diffusion rates relative to soil respiration, causing sub-atmospheric O_2 levels even when the soil was unsaturated. Reduced rates of O_2 diffusion during unsaturated periods may help maintain mottled and gleyed horizons in some soils, particularly clayey soils subject to periodic flooding. Texture had relatively little effect on O_2 content at depths ≤30 cm, the section of interest to wetland regulators.

Correlations among Soil Wetness Indicators

We examined the relationship between Munsell soil colors and indicators of soil wetness using the chroma index of Evans and Franzmeier (1988). Chroma index values were calculated as follows:

$$CI = (A_{\text{matrix}} \times C_{\text{matrix}}) + (A_{\text{mottles}} \times C_{\text{mottles}})$$

where A = abundance (few = 0.01, common = 0.11, many = 0.35) and C = chroma. The total abundance of mottles was subtracted from one to give the abundance of the matrix. When there were two dominant matrix chromas (Chastain), the matrix abundance was divided equally between them. In this index, the chroma of each color in a horizon is weighted by its relative surface area;

Table 5. Measurements of hydrology and redox potential compared with the presence or absence of common hydric soil field indicators at 0-30 cm.

Series	Drainage class†	Permeability†	Surface Saturation	15 cm Sat.	15 cm Ana.	15 cm Red.	30 cm Sat.	30 cm Ana.	30 cm Red.	Chroma 1	Chroma ≤2 & mottles	Histic epipedon
		cm h^{-1}	% of growing season‡									
Pickney 1	VP	≥15	18	59	59	76	94	71	94	Y	—	N
Pickney 2	VP	≥15	6	53	24	59	88	71	100	Y	—	N
Unnamed§	—	—	0	29	29	71	76	59	88	Y	—	Y
Williman	P	<15	0	12	18	29	35	29	29	N	Y	N
Chastain	P	<15	25	31	38	25	38	31	25	Y	Y	N
McColl	P	<15	24	35	29	29	41	18	35	Y	Y	N
Tawcaw	SP	<15	6	6	0	0	12	0	0	N	N	N

† Data from the Hydric Soils List (Soil Conservation Service, 1991). VP = very poor, P = poor, and SP = somewhat poor drainage.

‡ Percentages are based on the number of growing season sample dates a soil was saturated (Sat.), anaerobic (Ana., ≤5% O_2), or reduced (Red., ≤300 mV, pH 5).

§ Classified as a sandy, siliceous, thermic Histic Humaquept.

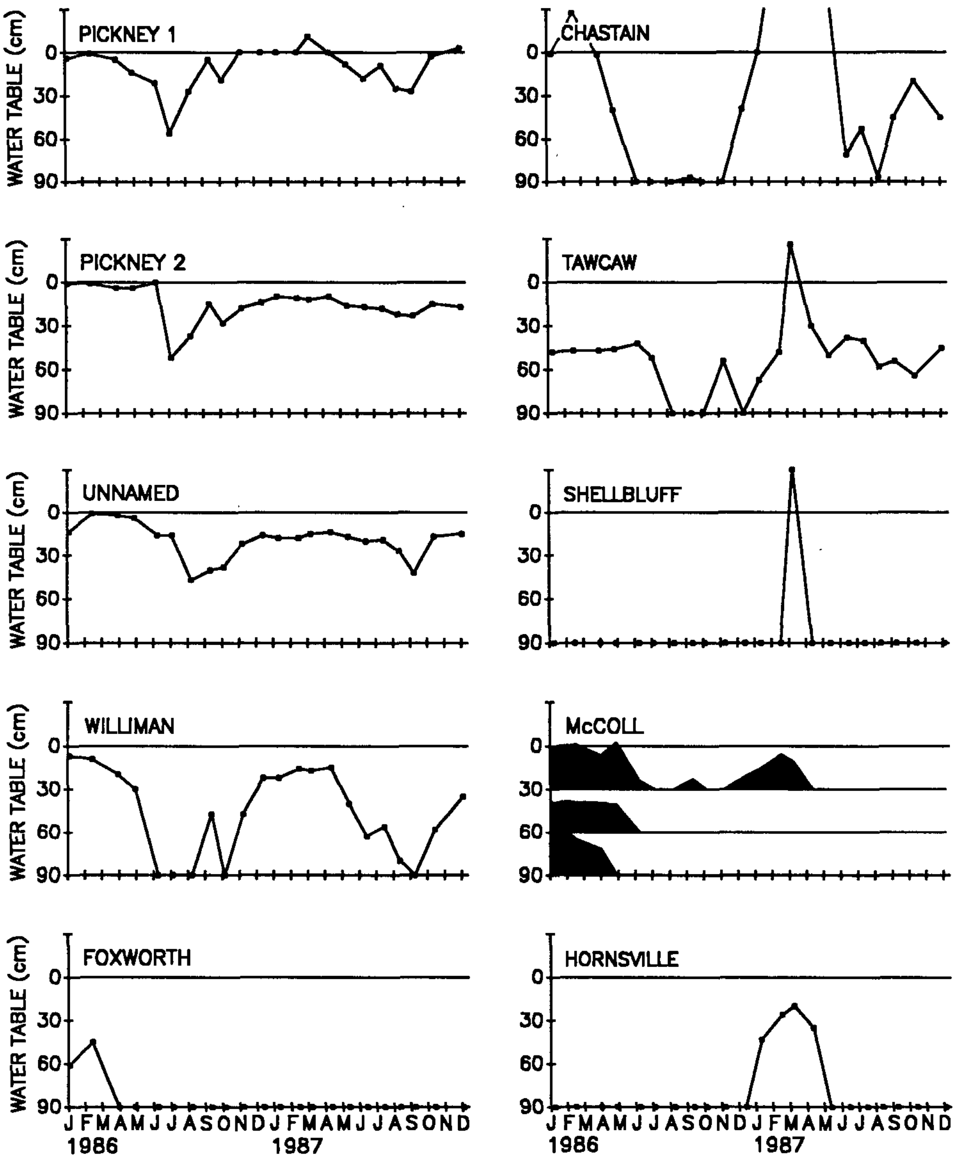

Fig. 2. Water table levels on ten soils in the upper coastal plain of South Carolina. Because of a perched water table, the McColl figure shows measurements from piezometer wells at 30-, 60-, and 90-cm depths.

a low value indicates the soil was dominated by low chromas.

The CI was most strongly related to the number of days the soils were saturated ($r^2 = 0.77$, $P \leq 0.0005$) or reduced ($r^2 = 0.73$, $P \leq 0.0009$) at 30 cm (Fig. 5). Evans and Franzmeier (1988) found that chromas were best correlated with soil saturation at depths of 30 to 60 cm, presumably because dissolved organic C is most abundant near the surface. The McColl soil had a CI lower than predicted for its flooding regime (Fig. 5). This pedon occurred behind a ridge on the upland edge of the Savannah River floodplain (Fig. 1), and thus was relatively protected from flooding. A flood in March 1987 inundated plots near the river channel, but not the McColl or Hornsville plots (Fig. 2). It is likely that the McColl soil floods more frequently in years of normal rainfall (160 mm below normal in 1986, 100 mm below normal in 1987).

When averaged across the entire study period, there was a strong positive correlation between redox$_5$ potential and O_2 content ($r^2 = 0.94$, $P \leq 0.0001$) (Fig. 6). Water table depth was inversely correlated to O_2 content ($r^2 = 0.86$, $P \leq 0.0001$) and redox$_5$ potential ($r^2 = 0.87$, $P \leq 0.0001$).

While there is often a strong seasonal correspondence between water table depth, O_2 content, and redox$_5$ potential in graphical presentations of data (McKeague, 1965; Faulkner et al., 1989; Josselyn et al., 1990), statistical correlations are usually weak or insignificant (e.g., Ransom and Smeck, 1986). Ransom and Smeck (1986) attributed a weak correlation between dissolved O_2 and redox in soil solutions to nonequilibrium conditions. A fluctuating water table is likely to cause nonequilibrium conditions by maintaining relatively reduced microsites (e.g., ped interiors) and oxidized macrosites (large pore spaces). In floodplain forests, hydrologic inputs of O,

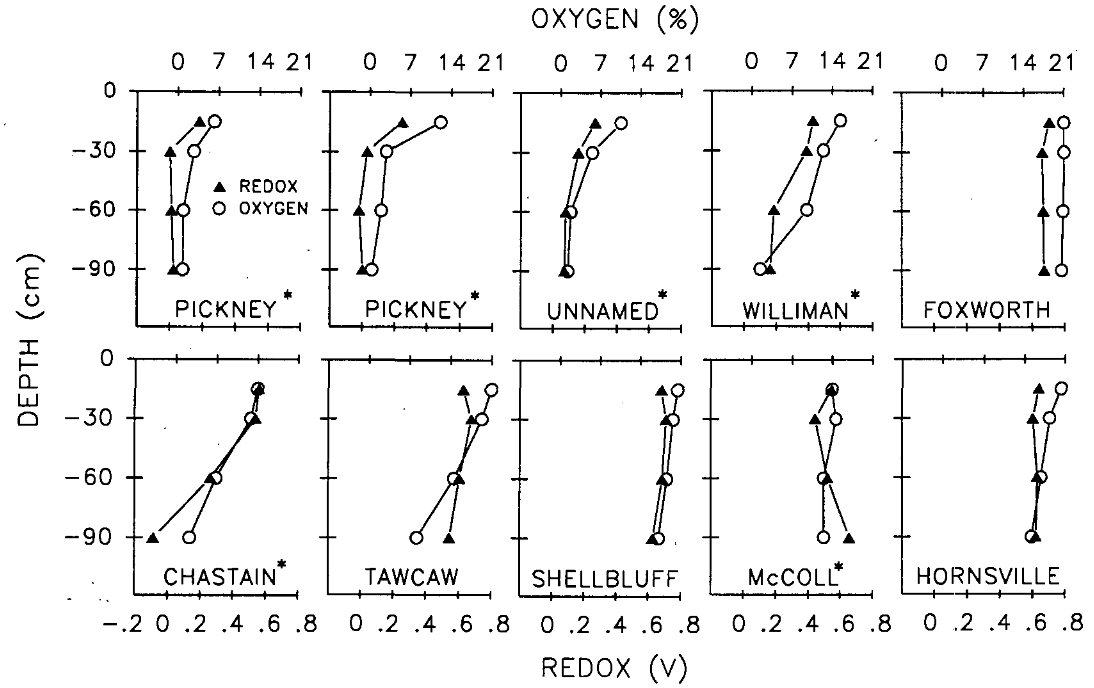

Fig. 3. Oxygen content and redox potential by depth for eight southeastern soils. The soils in the top row were on the Meyers Branch transect, those on the bottom were on the Savannah River transect. Hydric soils are marked with an asterisk. Values are the average of 22 monthly samples.

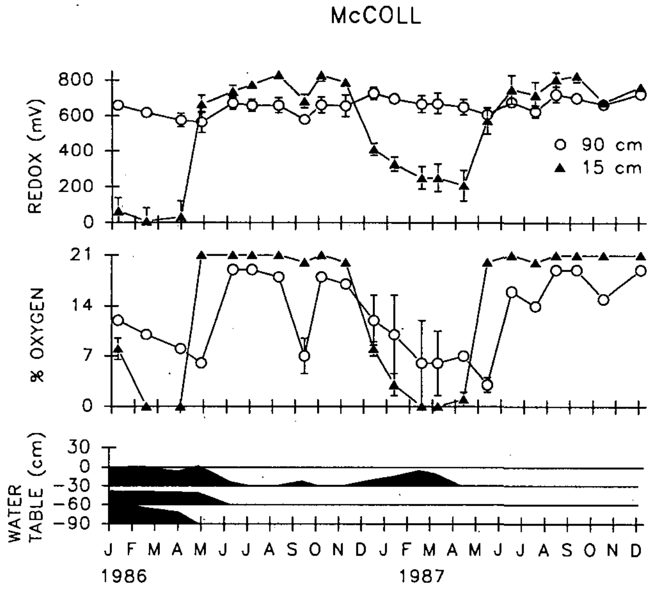

Fig. 4. Relationships between redox, O_2 content, and piezometer well depth at 15 and 90 cm in the McColl soil. Oxygen and redox data are means ±1 SE. Horizontal lines on the water table graph represent the bottom of three piezometer wells (30, 60, and 90 cm).

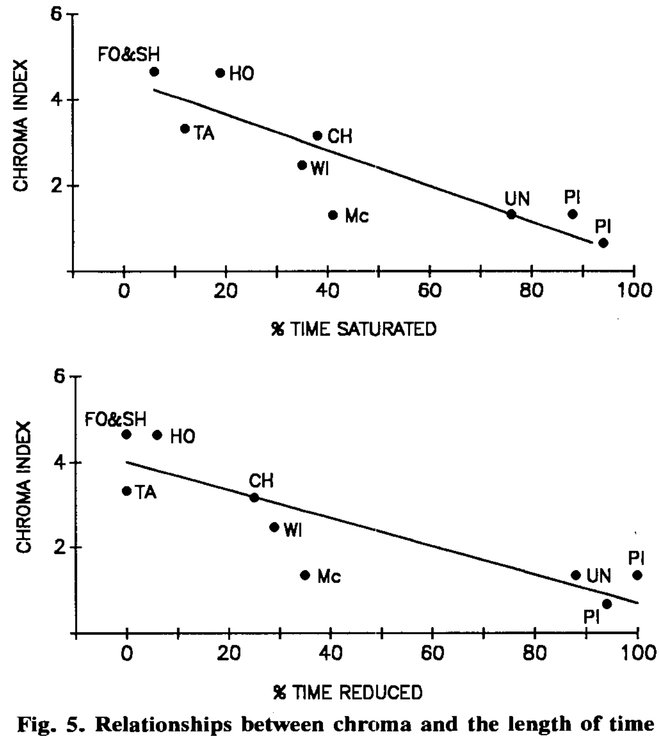

Fig. 5. Relationships between chroma and the length of time a soil was saturated or reduced (≤300 mV, pH 5). Abbreviations are the first two letters of the soil series name.

N, Mn, and Fe or outputs of soluble metals through leaching may also prevent short-term thermodynamic equilibrium. Our data suggest that these effects average out with time; on an annual time scale, redox$_5$ potentials strongly reflected average O_2 content.

The strength of the correlations between water table depth, redox$_5$ potential, and chroma provides a sound empirical basis for using soil profile characteristics to delineate southeastern wetland forests. These relation-

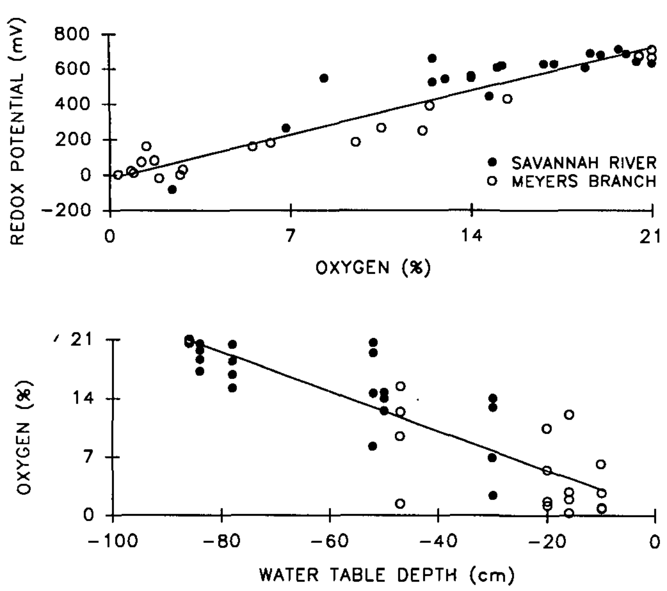

Fig. 6. Relationships between redox potential (pH 5), O_2 content, and water table depth. Each point is an average of 22 monthly collections at each depth (n = 4) in each plot (n = 10).

ships are unlikely to break down as long as conditions remain favorable for microbial activity (Vepraskas and Wilding, 1983; Pickering and Veneman, 1984; Couto et al., 1985).

Wetland Identification

Hydric soils are used by regulatory personnel as a surrogate for long-term records of flooding and soil aeration in seasonally wet forests. Hydric soils can be identified by the presence of gley colors; a low-chroma matrix ($\leq$2) with mottles below the A horizon; a significant accumulation of organic matter on the surface (e.g., a histic epipedon); Fe–Mn concretions; H_2S gas; or numerous oxidized root channels (Federal Interagency Committee for Wetland Delineation, 1989). We evaluated some commonly used field indicators of hydric soils with measurements of redox$_5$ potential, O_2 content, and water table depth for the soils in this study (Table 5). Because all sites had >50% dominance by facultative, facultative wetland, and obligate wetland plants species (Megonigal, unpublished data, 1988), vegetation data were not useful in discriminating between the wetland and nonwetland forests.

The Pickney and unnamed Histic Humaquept soils were saturated within 15 cm of the surface for roughly 30 to 60% of the growing season and reduced for 60 to 80% of the same period (Fig. 2, Table 5). Extensive saturation is consistent with gley colors below the A horizon (Daniels et al., 1971) and the presence of histic and cumulic epipedons. Such features are caused by leaching of soluble metals and retarded decomposition rates under anaerobic conditions. A surface horizon of 19% organic C in the Histic Humaquept soil would seem at odds with 0 d of surface saturation based on the well data (Table 5), even in years with below-normal rainfall. Inundation probably occurred more frequently than we found with monthly samples. The high organic C content of the A and O horizons on these soils may cause significant periods of surface saturation due to a capillary fringe. These data do not support a recent proposal that requires evidence of ponding or flooding to classify a site as a wetland.

The Williman, Chastain, and McColl soils were saturated, anaerobic, and reduced above 30 cm for periods exceeding 30 d (Table 5) and meet the 1989 requirements of a jurisdictional wetland (Environmental Laboratory, 1987; Federal Interagency Committee for Wetland Delineation, 1989). Hydric soil indicators would have correctly identified the Pickney, Williman, Chastain, McColl, and Histic Humaquept soils as hydric soils. Diagnostic field indicators correctly classified 18 of 24 pedons in the Mississippi River valley (Faulkner and Patrick, 1992); errors favored neither a hydric nor a nonhydric classification.

Tawcaw mapping units have both hydric and nonhydric inclusions (Soil Conservation Service, 1991). The water table, redox$_5$, and O_2 data are consistent with a low-chroma matrix and mottles at 38 cm (Fig. 2; Table 5). The site can be correctly identified as nonhydric by diagnostic field indicators. Redox$_5$ potential and O_2 content did not respond to ≈7 d of flooding in March 1987 (Fig. 2), perhaps because of low temperatures.

Growing Season Criteria

Based on evidence that microbial respiration (O_2 consumption) is negligible below 5 °C (Pickering and Veneman, 1984; Evans and Franzmeier, 1988), hydric soil criteria require that saturation or flooding occur during the growing season (Table 1). The Soil Conservation Service (Soil Survey Staff, 1975) assumes the growing season in a thermic temperature regime is from February to October. Soil temperatures on our sites varied from 7 to 13 °C at 15 cm during the nongrowing season, and rarely fell below 5 °C (Table 6). We observed declines in O_2 content during the winter months on flooded sites. Reinke et al. (1981) measured positive rates of soil respiration in a longleaf pine (*Pinus palustris* Miller) forest on the Savannah River Site during the winter (3 g CO_2 m^{-2} d^{-1}). These data suggest that temperatures during the nongrowing season are favorable for microbial activity in our soils. In central Massachusetts, Pickering and Veneman (1984) found that winter temperatures were

Table 6. Minimum, maximum, and mean soil temperatures for November through February 1986 and 1987.

Month	Depth	Temperature		
		Min.	Max.	Mean
	cm	°C		
November	15	8	19	15.4
	30	9	19	16.1
	50	13	20	16.3
December	15	11	14	12.0
	30	12	16	13.9
	50	13	16	14.7
January	15	7	13	10.3
	30	4	14	10.6
	50	8	15	11.6
February	15	7	13	9.7
	30	9	15	10.8
	50	8	14	11.8

warm enough for biological activity and significant reduction in a Scarboro soil. We question the use of temperature regimes to determine the length of the growing season, at least for the purpose of wetland identification.

CONCLUSIONS

Our data provide quantitative in situ evidence of a strong association between hydromorphic characters, redox potential, and O_2 content in wetland forest soils. These relationships are primarily the result of soil saturation. In an unsaturated soil with 82% clay, however, poor aeration at depths $\geq$60 cm was apparently related to texture. The data provide a sound empirical basis for using soil profile characteristics to delineate wetland forests.

In the soils we studied, hydric soil indicators were an accurate surrogate for direct measurements of hydrology; if a soil had the appropriate hydromorphic characteristics within 30 cm of the surface, the pedon was saturated for $\geq$30 d at 15 cm (Table 5). A soil that lacked these characters (the Tawcaw) was inundated only once in 2 yr for a brief period. It is likely that southeastern floodplain soils develop hydromorphic characteristics with fewer than 30 d of saturation, but such a conclusion is beyond the resolution of our data.

One aspect of the criteria for wetland soils and wetland hydrology was not supported; the data suggest anaerobic and reducing conditions may develop during the nongrowing season (as defined by the SCS). Because palustrine forests in the southeastern USA are flooded mainly during the winter and spring months, this criterion deserves further evaluation.

It is important to note that flooding (and associated wetland functions such as floodwater storage) can occur without the development of mottles or other hydromorphic features, as illustrated by the Tawcaw and Shellbluff soils. Conversely, hydromorphic features may indicate a history of flooding that no longer exists (Faulkner and Patrick, 1992). Thus, while hydromorphic features accurately indicate a history of soil saturation, proper management of wetlands depends on current and accurate hydrologic data.

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