# Steel Rod Oxidation as a Hydrologic Indicator in Wetland Soils

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## ABSTRACT

**Depth of rusting on steel rods has been proposed as an inexpensive means of determining depth to the water table and the reducing zone in wetland soils. The suitability of steel-rod oxidation as a hydrologic indicator in wetland soils was tested in a series of laboratory and field experiments in both Histosols and a mineral soil (Typic Fluvaquent). In laboratory microcosms, the steel-rod rusting depth exactly matched water-table levels under both permanently flooded and drained conditions. But under a rapidly fluctuating hydrology, once heavy rust formed on the rods it did not dissolve upon partial reflooding. Field experiments showed a good correspondence between steel-rod rusting depth and water-table depth under both relatively constant and seasonally changing hydrology in Histosols ($r^2 = 0.80$, slope = 0.81). In the Typic Fluvaquent, a close correspondence between steel-rod rusting depth and water-table depth occurred under relatively constant hydrological conditions but, with a rapidly dropping water table, rod oxidation showed a lag period in response. We conclude that the steel-rod technique is valuable as a hydrologic indicator of the reducing zone in basic science studies. We recommend frequent sampling (monthly) and the use of other hydrological measures to ensure unambiguous results. The technique is unsuitable for jurisdictional delineation in areas with a fluctuating hydrology due to prolonged lag periods in rod oxidation under some conditions and the inability of previously formed rust to dissolve upon reflooding.**

HYDROLOGY is the main forcing function and energy signature of wetlands (Odum, 1983; Mitsch and Gosselink, 1986). Many ecosystem processes in wetlands are controlled to a large extent by the availability of electron acceptors (i.e., soil oxidation/reduction potential), which is itself largely determined by hydrology (Faulkner and Richardson, 1989). Wetland scientists are, therefore, continually faced with the problem of quantifying hydrology. While several techniques are available to measure soil and hydrologic parameters (Faulkner et al., 1989), they are often more extensive and time consuming than desired for routine determinations.

Hydrology is also central to wetland identification and delineation. Despite the sometimes conflicting nature of several legal and scientific definitions (i.e., Section 404 of the Clean Water Act, Food Security Act of 1985, U.S. Fish and Wildlife Service classification system), all incorporate hydrology, vegetation, and soils as critical components of wetlands. The presence of wetland hydrology, hydrophytic vegetation, and hydric soils are the mandatory technical criteria for identifying wetland areas (Federal Interagency Committee for Wetland Delineation, 1989).

Obvious and definitive hydrologic indicators are not always available in many wetland environments, or are present only seasonally, and must thus be inferred from secondary observations. Wetland hydrology is often *the* determining factor in jurisdictional wetland delineation of bottomland hardwoods, riparian systems, and southern peat bogs, since nonwetland areas in these ecosystems often meet the hydrophytic vegetation and hydric soil criteria.

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**Abbreviations:** DP, drained pocosins; GS, gum swamps; SP, short pocosins; TP, tall pocosins; Eh, redox potential; SE, standard error.

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Based on the redox attributes of Fe, McKee (1978) proposed using uncoated steel welding rods to measure time-integrated water-table depth. Iron forms rust in the oxidized $Fe^{3+}$ state, but is reduced under anaerobic conditions to $Fe^{2+}$. The boundary between these two conditions is often approximated by the water table. Ferrous iron does not have the characteristic reddish-orange color of $Fe^{3+}$. These Fe redox attributes are also responsible for soil gleying and mottling used as morphological wetness indicators in soils (Environmental Laboratory, 1987).

McKee (1978) found a strong correlation ($r = 0.87$) between water-table depth and steel-rod rusting depth in several well to poorly drained loamy soils in South Carolina. He recommended leaving the rods in the soil for 3 to 4 mo during the period of highest water table. Hook et al. (1987) used the steel-rod technique to assess the relationship between red alder (*Alnus rubra* Bong.) height growth and water table. They reported a significant relationship ($r = 0.62$) and concluded that the technique was an accurate measure of water-table depth; however, no independent water-table measurements were made.

Carnell and Anderson (1986) measured the steel-rod rusting depth in water, sand, and a natural soil (stagnopodzol). They determined that the maximum rust depth correlated well with both water level and rooting depth of Sitka spruce (*Picea sitchensis* [Bong.] Carr.). McKee (1978) and Hook et al. (1987) gave few details on criteria for determining the rusting depth; however, Carnell and Anderson (1986) specified the lower level of brown/orange corrosion on the metal.

We initiated this study to determine the suitability of steel-rod oxidation as a routine hydrologic indicator of the reducing zone in wetland soils. Water-table depth approximates the boundary of low redox potential necessary for Fe reduction in wetlands with a seasonal hydroperiod (Buol et al., 1980; Faulkner et al., 1989). Because of the procedural difficulties in measuring redox potential throughout a depth profile in many sites, water-table depth was used as a surrogate to determine the reducing zone. Redox electrodes were placed at 5 and 30 cm to verify the relationship between water table and redox potential.

## DESCRIPTION OF STUDY AREAS

Histosols were located in the Croatan National Forest in the lower Coastal Plain of North Carolina. Four replicate plots of three community types occurring on Histosols were established as part of a larger study of C and nutrient dynamics in pocosins. Short pocosins occupy the ombrotrophic center of the bog complex and are characterized by stunted ($<2$ m tall), evergreen to semideciduous, broad-leaf shrubs such as *Cyrilla racemiflora* L., *Lyonia lucida* (Lam.) K. Koch, and *Zenobia pulverulenta* (Bartram) Pollard, and pond pine (*Pinus serotina* Michaux). Depth to water table is generally $<35$ cm except during extreme drought, and the organic horizon is 1 to 3 m thick (Richardson et al., 1981; Richardson, 1983). The soil series is Dare, a dysic, thermic Typic Medisaprist. Tall pocosins are characterized by a species mixture similar to SP but of taller stature, a more variable seasonal hydrology with depth to water table ranging from 0 to $>100$ cm, and an organic horizon generally $<1$ m thick. The soil series is Croatan, a loamy, siliceous, dysic, thermic Terric Medisaprist. Gum swamps occur along the outflows of lakes and along streams with vegetation typical of southeastern bottomland hardwoods (black gum [*Nyssa sylvatica* Marshall], sweetgum [*Liquidambar styraciflua* L.], red maple [*Acer rubrum* L.] and bald cypress [*Taxodium distichum* (L.) Richard]). They have a seasonally variable hydrology with depth to water table ranging from 0 to $>100$ cm and an organic horizon $<1$ m thick. The soil series is Dorovan, a dysic, thermic Typic Medisaprist. Additionally, four DP sites were established within 10 m of drainage ditches on a Dare soil series. All peats are very acidic (pH $\leq 4$).

Mineral sites were in a narrow bottomland hardwood forest (sweetgum, hickories [*Carya* spp.], and black gum) along a small, intermittent stream in Duke Forest in the North Carolina Piedmont. Two sites were established: a lower, wetter site (DF1) and an adjacent, slightly higher site (DF2). These sites are part of the Wehadkee soil series, a fine-loamy, mixed, nonacid, thermic Typic Fluvaquent with a pH of 5.5.

## MATERIALS AND METHODS

### *Laboratory Equipment*

We conducted a laboratory experiment to attain maximum control over the hydrologic regime. Intact blocks of Dare and Wehadkee soils were taken from the Croatan and Duke Forest sites, respectively, and put in large plastic buckets. Steel rods were cut to reach from the bottom of the buckets to $\approx 10$ cm above the soil surface. Three treatments were established in the Histosol and mineral soils: (i) continuously flooded, (ii) nonflooded, but with the soil periodically moistened, and (iii) flooded/drained, with 4 wk of flooding to the soil surface, followed by 4 wk of drainage, and finally 4 wk of flooding to $-8$ cm. All treatments were duplicated.

### *Field Methods*

Uncoated, mild steel welding rods, 91-cm long, were cleaned with steel wool and inserted in the soils to 80 cm. Rods were left in the Histosols in the Croatan National Forest for approximately 1 mo (avg. = 33.4 d, minimum = 12 d, maximum = 49 d, all incubation times except initial and final dates $\geq 29$ d). Readings were taken from September 1988 through December 1989. In a long-term experiment, all rods were placed in the soil at one time and pulled sequentially during a 14-wk span (at 2, 4, 8, and 14 wk) in two SP sites. In the Wehadkee mineral soil in Duke Forest, rods were incubated both monthly (avg. = 36.0 d, minimum = 18 d, maximum = 63 d, 7 of 9 dates between 31 and 40 d) and long-term (all rods placed simultaneously in the soil and pulled sequentially at monthly intervals) from December 1988 through September 1989. Rods were gently cleaned of adhering soil with a cloth, and the depth of rusting measured from the soil surface. Rust was often discontinuous, even in the zone of heavy formation, and small specks of rust would occasionally occur further down on the rod. We chose the lowest point of the obvious, heavy rust zone as the steel-rod rust depth. Two of the authors measured rusting depth on all rods and calibrated readings to ensure consistency of results.

Water-table wells were constructed from 7.5-cm polyvinyl chloride (PVC) pipe that had closely spaced holes drilled along the entire length. They were sunk in a preaugered hole to 1 m and capped. Steel rods were placed in the immediate vicinity of the wells. Welded Pt redox electrodes were constructed following Faulkner et al. (1989). Electrodes were permanently installed at 5- and 30-cm depths in the two Duke Forest sites and in two SP sites in the Croatan National Forest. Redox potentials have been corrected (+244 mV) for the saturated calomel electrode (Faulkner et al., 1989). Water-table and redox readings were taken when steel rods were pulled and during any additional visits to a site.

Differences between the steel-rod rusting depth and water-table depth were analyzed as a sign difference (steel-rod rusting depth minus water-table depth) and an absolute difference (the absolute value of the sign difference). For example, if the steel-rod rusting depth is −10 cm and the water table depth −8 cm, the sign difference is −2 and the absolute difference is 2. The sign difference determines if the steel-rod rusting depth over- or underestimates the water-table depth, while the absolute difference determines the magnitude of the variation.

## RESULTS

### Laboratory Experiment

An exact correspondence between steel-rod rusting depth and water-table depth was found under the two constant hydrologic regimes, nonflooded and continuously flooded, in both the Histosol and Typic Fluvaquent (Table 1). But under a fluctuating hydrologic regime, with alternating flooded, drained, and partially reflooded conditions (to −8 cm), the steel rods overestimated depth to the water table upon reflooding in both the peat and mineral soils. Two zones of rust were evident on the rods, a reddish-orange zone above −8 cm and a black zone below −8 cm. Iron was probably mobilized during the initial flooded period, accounting for particularly heavy, continuous rust formation during the following nonflooded period. It was apparent that the heavy rust zone formed on the rods during nonflooded conditions did not dissolve during partial reflooding in the alternating hydrologic regime.

**Table 1. A comparison of steel-rod rusting depth and water-table depth under three hydrologic regimes in both mineral and Histosol soil laboratory microcosms. The flooded/drained treatment was flooded for 4 wk, drained for 4 wk, and flooded again to −8 cm for 4 wk. Each steel-rod value is the average of two replicates.**

| Hydrologic regime | Soil type | Water table | Steel rod |
|---|---|---|---|
| | | cm | |
| Nonflooded | Typic Fluvaquent | −17 | −17 |
| | Typic Medisaprist | −17 | −17 |
| Continuously flooded | Typic Fluvaquent | 0 | 0 |
| | Typic Medisaprist | 0 | 0 |
| Alternating flooded/drained | Typic Fluvaquent | −8 | −17 |
| | Typic Medisaprist | −8 | −17 |

**Table 2. A comparison of different incubation times for steel rods in a Histosol. Rods were either placed in the soil simultaneously and removed sequentially from 2 to 14 wk later (long-term), or a fresh set of rods was placed in the soil at approximately monthly intervals (1-mo). The 4-wk rods were the same for both the long-term and 1-mo treatments. Each Fe rod value is the average of two replicates.**

| Site† | Time | Steel rod | | Water table |
|---|---|---|---|---|
| | | Long-term | 1-mo | |
| | wk | cm | | |
| SP2 | 2 | −13.5 | | −13.0 |
| | 4 | −14.8 | −14.8 | −16.0 |
| | 8 | −11.5 | −12.0 | −9.0 |
| | 14 | −8.5 | −7.0 | −7.5 |
| SP17 | 2 | −9.5 | | −14.5 |
| | 4 | −10.5 | −10.5 | −18.5 |
| | 8 | −16.5 | −10.0 | −12.0 |
| | 14 | −6.75 | −9.0 | −9.0 |

† Two short pocosin sites in a Dare soil series, a Typic Medisaprist, in Croatan National Forest.

A fresh set of steel rods were also put into the alternating flooded/drained treatments upon partial refloodng to −8 cm. Rods pulled after 2 wk did not show adequate rust formation to predict the water-table level, but after ≈4 wk of incubation the rusting depth was −7.25 cm in the peat soil and −7.75 cm in the mineral soil.

### Croatan National Forest—Histosols

An additional test was made of the most appropriate length of incubation for steel rods in the field. A long-term set of rods was placed in two SP sites (SP2 and SP17), with all rods placed in the soil simultaneously and pulled sequentially at regular intervals from 2 to 14 wk. New rods were also put into the soil and incubated for approximately monthly intervals during the same period. During this period, the water table was relatively constant (Table 2), so no major differences occurred between the long-term and monthly rods. Also, the 2-wk rods (in the long-term sequence) relatively accurately predicted the water table (within 5 cm), as opposed to the laboratory test. We used monthly incubations for the remainder of the time in the Croatan.

**Table 3. Mean difference between steel-rod rusting depth and water-table depth. Sign difference is steel-rod rusting depth minus water-table depth, and absolute difference is the absolute value of the sign difference.**

| Site† | Sign difference | Absolute difference |
|---|---|---|
| | cm | |
| | Croatan National Forest—Histosol | |
| SP2 | | 2.8 (2.2)‡ |
| SP5 | | 3.0 (3.1) |
| SP12 | | 4.2 (4.1) |
| SP17 | | 4.8 (4.3) |
| All SP | −0.1 (5.1) | 3.7 (3.5) |
| TP4 | | 7.7 (5.2) |
| TP5 | | 3.3 (3.1) |
| TP6 | | 3.8 (4.0) |
| TP7 | | 12.7 (7.8) |
| All TP | 1.0 (9.0) | 6.5 (6.2) |
| DP1 | | 8.6 (5.7) |
| DP2 | | 5.4 (4.1) |
| DP3 | | 4.3 (3.9) |
| DP4 | | 3.0 (2.1) |
| All DP | 2.9 (6.4) | 5.3 (4.6) |
| GS1 | | 7.8 (6.5) |
| GS2 | | 9.6 (10.1) |
| GS3 | | 6.9 (7.2) |
| GS4 | | 10.5 (7.5) |
| All GS | −0.4 (11.7) | 8.7 (7.7) |
| All Histosols | 0.8 (8.4) | 6.0 (5.9) |
| | Duke Forest—Typic Fluvaquent | |
| DF1 | | |
| 1-mo rods | 16.6 (23.3) | 18.3 (21.8) |
| Long-term rods | 5.9 (19.1) | 10.3 (16.9) |
| DF2 | | |
| 1-mo rods | 9.1 (16.6) | 13.3 (12.9) |
| Long-term rods | 2.6 (11.5) | 8.6 (7.5) |

† SP = short pocosin; TP = tall pocosin; DP = drained pocosin; GS = gum swamp; DF1 = Duke Forest lower; DF2 = Duke Forest upper.
‡ Standard deviation.

Short pocosins (Dare soil series) have a stable hydrologic regime with a water table generally within 35 cm of the surface throughout the year (Fig. 1). Because of these optimal conditions, the steel rods accurately predicted the water table (Table 3). The average absolute deviation between the rods and the water table for all SP readings was only 3.7 cm. Redox potential was relatively constant from +200 to +300 mV at −30 cm (data available from authors), indicating reducing conditions for Fe (pH = 4). Redox potential was quite variable at −5 cm as the water table approached and receded from the surface.

Both TP (Croatan soil series) and GS (Dorovan soil series) (Fig. 2) experienced a much greater drop in the water table during dry conditions than SP. Drained pocosin sites never had the water table approach the surface. With a more widely fluctuating hydrology, the absolute deviations between steel-rod rusting depth and water-table depth were larger, on average ranging from 5.3 to 8.7 cm (Table 3). The GS4 site had one of the largest average differences between the steel-rod rusting depth and water-table depth, but the rods still relatively accurately tracked the water table (Fig. 2), with rod measurements often intermediate between the previous and current water-table readings. This would be an expected response if depth of rod oxidation is a time-integrated measure of the reducing zone. A widely fluctuating hydrology would necessarily give divergent responses between point measurements of steel-rod rusting depth and water-table depth.

The sign difference between the steel-rod rusting depth and water-table depth is not significantly different from zero for any plot (two-tailed *t* test, $P > 0.05$), indicating that rods do not consistently over- or underestimate the water table (Table 3). Two reduced data sets were also considered, where the water table had risen or fallen since the last measurement by >5 cm. Again, rods had no consistent bias in estimating the water table (data available from authors).

A linear regression between the steel-rod rusting depth and water-table depth for all Croatan values (Fig. 3A) is highly significant ($P < 0.0001$). Water-table depth explained 80% of the variation in the steel-rod rusting depth. The slope of 0.81 (SE = 0.03) is significantly less than one (two-tailed *t* test, $P > 0.05$).

Steel rods were duplicated at each site for the long-term experiment. The variation between rods within a site was small, with an average standard deviation of 2.1 cm.

### Duke Forest—Typic Fluvaquents

Both monthly and long-term (sequential) rods were measured in the two Duke Forest sites throughout the 9-mo experimental period. Under conditions of relatively constant hydrology, the Duke Forest sites showed a close correspondence between steel-rod rusting depth and water-table depth (Fig. 4). Once the water table began a rapid decrease during the summer of 1989, rod oxidation appeared to have a large lag in response. Even after several months of a lowered water table, the 1-mo rods showed little increase in depth of

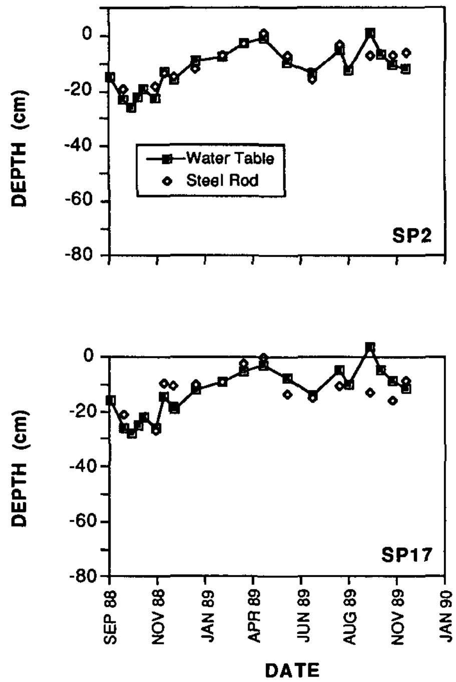

Fig. 1. Steel-rod rusting depth and water-table depth for two short pocosin sites with an organic horizon >1 m deep (Dare soil series) in Croatan National Forest.

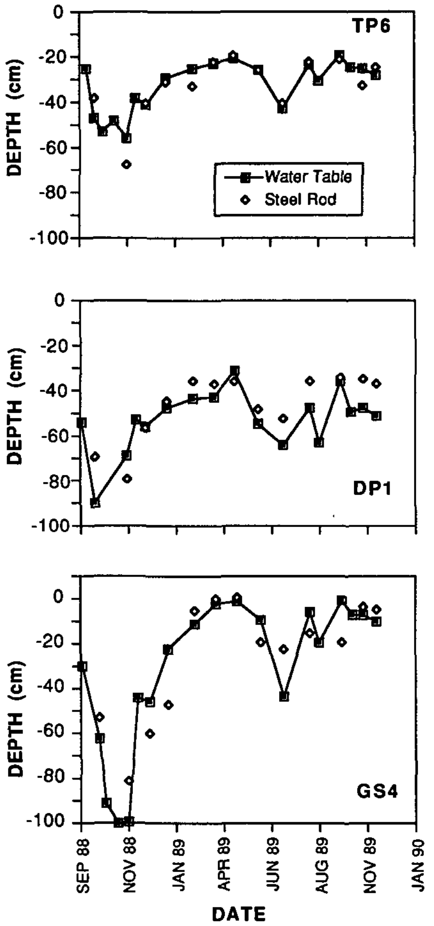

Fig. 2. Steel-rod rusting depth and water-table depth for two sites with shallow organic horizons (<1 m) (TP = tall pocosin, Croatan soil series; GS = gum swamp, Dorovan soil series) and a drained short pocosin (DP, Dare soil series) in Croatan National Forest. Note that the minimum measured depth for Fe rods was −80 cm and −100 cm for the water table.

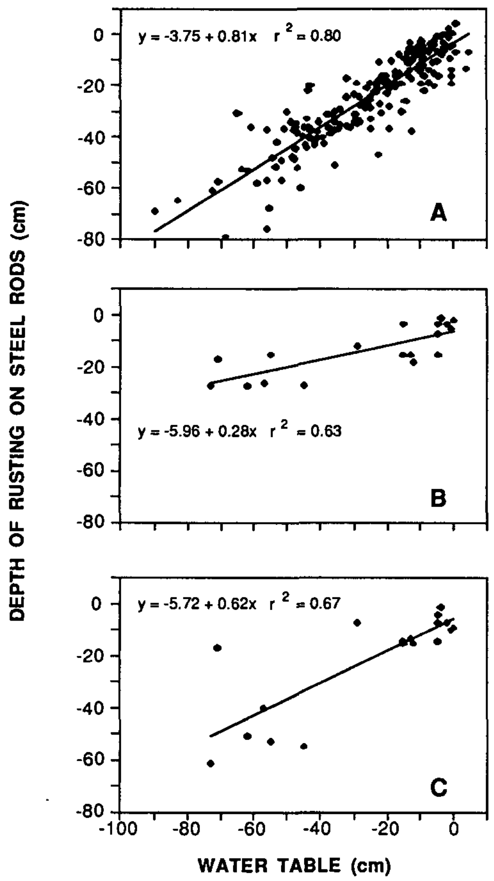

Fig. 3. Regressions of steel-rod rusting depth vs. water-table depth (A) for all Histosols in Croatan National Forest, (B) for 1-mo steel-rod incubations in a Typic Fluvaquent in Duke Forest, and (C) for long-term (sequential) rod incubations in the same Duke Forest sites.

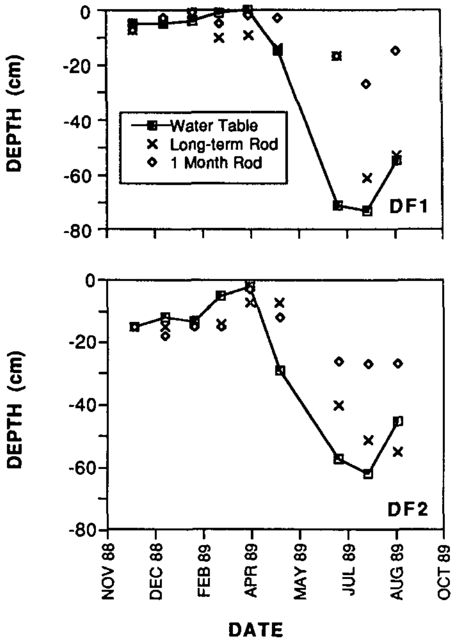

Fig. 4. Steel-rod rusting depth and water-table depth for two sites in a bottomland hardwood forest on a Typic Fluvaquent in Duke Forest. One set of steel rods was placed in the soil in December 1988 and pulled sequentially at monthly intervals (long-term rods), while another set of fresh rods was placed in the soil each month (1-mo rods).

rusting. The long-term rods showed a lag period in oxidation of 1 to 2 mo in the spring with a falling water table but, by the end of the summer, more closely predicted the water table.

The absolute deviations between the steel-rod rusting depth and water-table depth were large for both the 1-mo and long-term rods in DF1 and DF2, with an average range of 8.6 to 18.3 cm (Table 3). The sign difference between steel-rod rusting depth and water-table depth was not significantly different from zero (two-tailed *t* test, $P > 0.05$), but this is probably due to the very large standard deviations.

The redox profile at DF1 (pH = 5.5) indicated reducing conditions at −30 cm throughout the winter and spring of 1988 and 1989, with an increase in Eh corresponding to a drop in water table below −30 cm in the summer (data available from authors). The Eh was oxidizing relative to Fe at −5 cm in DF1 except for a brief period in April 1989. Although the water table exceeded −30 cm from December 1988 to May 1989 in DF2 (Fig. 4), duplicate redox electrodes indicated an Eh favoring formation of $Fe^{3+}$ at −30 cm throughout the 9-mo period. In fact, the Eh at −30 cm closely paralleled that at −5 cm. Nevertheless, the steel rods indicated reducing conditions below −20 cm from December 1988 through May 1989 at DF2. This discrepancy between a mixed redox potential in the field and a directly measured redox couple ($Fe^{2+}$/$Fe^{3+}$) indicates the difficulty in interpreting redox data under field conditions (Ponnamperuma, 1972) and the information gained from simultaneously measuring several hydrologic parameters.

Water-table depth accounted for 63% of the variation in 1-mo steel-rod rusting depths in the Duke Forest sites (Fig. 3B) and was highly significant ($P < 0.0001$), but the slope was only 0.28 (SE = 0.05), indicating the large lag in the 1-mo steel-rod oxidation response to a rapidly falling water table. Water-table depth accounted for a slightly higher percentage of the variation in long-term steel-rod rusting depth (67%) (Fig. 3C), and the slope was much higher (0.62, SE = 0.11, $P < 0.0001$).

## DISCUSSION

The laboratory microcosm experiment determined that steel-rod rust depth accurately predicted water-table depth under conditions of constant hydrology in both a Histosol and a Typic Fluvaquent. But under a rapidly fluctuating water table, partial reflooding did not dissolve the heavy rust that had formed on the steel rods, leaving a black oxide below the water table. In the field, rods did not always show the heavy, continuous zone of rust found in the alternating flooded/drained treatment. The nonflooded treatments were periodically moistened, but were much drier and had a spottier development of rust with much unadulterated, shiny metal surface remaining. The heavier rust formation on the rods in the alternating flooded/drained treatment than in the nonflooded treatment underscores the fact that, although one of the attractions of the steel-rod technique is its seeming simplicity, the rods are reacting to a very complicated suite of soil chemical variables. Also, the noncontinuous rust formation on the rods in the nonflooded treatment often occurred in rods in the field, which requires interpretation in reading and is a major source of error in the method. McKee (1978) found no correlation with the quantity of oxidized Fe formed on the rods with water-table depth, and our results here may indicate why no such relationship would exist in the field. The rods in the continually flooded treatment had a greyish sheen throughout their length, as did rods under reducing conditions in the field.

Carnell and Anderson (1986) described four potential colors of steel rods due to different soil conditions, all of which we observed in our laboratory and field experiments: bright unadulterated metal, matt grey under constant reducing conditions, black oxide under a rapidly oscillating water table, and reddish-orange rust under oxidizing conditions. However, steel-rod color will probably be an unreliable indicator of the reducing zone in wetland soils. For example, the reddish-orange rust formed under oxidizing conditions may be indistinct and discontinuous, especially in very dry soils such as the nonflooded treatment in the laboratory experiment. Also, organic matter may adhere to rust particles, making all appear to be black oxides, which was normally the case in Histosols.

Extensive field experiments in both Histosols and a mineral soil indicated also that steel-rod rust depth closely corresponded to water-table depth under conditions of relatively constant hydrology. Yet when hydrology was rapidly changing, the discrepancy between the steel-rod rusting depth and water-table depth could be large. The steel-rod technique worked relatively well with monthly incubations in Histosols, even with large seasonal changes in water table. In the Typic Fluvaquent though, even after several months of a lowered water table, rods incubated at 1-mo intervals showed a significant lag response in oxidation. Long-term (sequential) rods had an initial lag period but did eventually respond to large seasonal changes in water table in a mineral soil. The very dry soil conditions, limiting Fe mobility, in the summer in Duke Forest may explain the difference in behavior between the monthly and long-term rods.

The average absolute difference between the steel-rod rusting depth and water-table depth was 6.0 cm in Histosols, 15.8 cm in the Typic Fluvaquent using a 1-mo incubation, and 9.5 cm in the Typic Fluvaquent using a long-term (sequential) incubation. The regression analyses reinforce the conclusion that the steel-rod technique worked better in Histosols and poorly in the mineral soil with a 1-mo incubation of fresh rods (Fig. 3). McKee (1978), in his study of steel-rod rusting in mineral soils, did a similar regression with a slope of 1.13 and an $r^2$ of 0.75. Carnell and Anderson (1986) also found a slope of $\approx 1$ in their regression of water-table depth against steel-rod rusting depth and, although no correlation coefficient was reported, the visual fit was excellent.

We found it to be extremely difficult to determine a maximum depth of rusting on some steel rods. Other investigators who have used this method have communicated the same difficulties to us. Such a large degree of interpretation can add significant bias between investigators within a study and between studies. Careful practice in calibrating results and care in consistency of reading the steel rods is necessary.

A frequent sampling schedule (approximately monthly) is optimal so that short-term changes in hydrology may be measured. Shorter incubations may not allow adequate time for development of rust, and longer incubations may mask shorter term hydrologic fluctuations. Carnell and Anderson (1986) similarly found about 1 to 3 mo an optimal steel-rod incubation time. A long-term incubation with all rods simultaneously placed in the soil and sequentially removed at monthly intervals seems superior to placing fresh rods in the soil each month, at least in mineral soils. Rapidly changing hydrologic regimes are the most difficult to measure, and under these circumstances the steel-rod technique gave the least accurate results.

We conclude that the steel-rod technique has potential to be a useful hydrologic indicator of reducing conditions in many freshwater wetland soils in basic science studies, as long as frequent samples and concurrent measurement of other hydrologic and soil parameters are taken in order to provide the least ambiguous information. Steel rods are cheap and directly measure a redox couple of considerable ecological importance ($Fe^{2+}/Fe^{3+}$). But in jurisdictional delineation of transitional wetland areas experiencing short-term hydrologic events, the steel-rod technique is inadequate and can provide erroneous answers. The major sources of error are prolonged lag periods in rod oxidation under some conditions and the inability of previously formed rust to dissolve upon refloodng. In such situations, only frequent sampling of several hydrologic variables, most importantly the water table, will provide accurate answers (Faulkner et al., 1989).

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## REFERENCES

Buol, S.W., F.D. Hole, and R.J. McCracken. 1980. Soil genesis and classification. 2nd ed. Iowa State Univ. Press, Ames.

Carnell, R., and M.A. Anderson. 1986. A technique for extensive field measurement of soil anaerobism by rusting on steel rods. Forestry 59:129–140.

Environmental Laboratory. 1987. Corps of Engineers wetlands delineation manual. Tech. Rep. Y-87-1. U.S. Army Engineer Waterways Exp. Stn., Vicksburg, MS.

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

Faulkner, S.P., and C.J. Richardson. 1989. Physical and chemical characteristics of freshwater wetland soils. p. 41–72. *In* D.A. Hammer (ed.) Constructed wetlands for wastewater treatment: Municipal, industrial and agricultural. Lewis Publ., Chelsea, MI.

Federal Interagency Committee for Wetland Delineation. 1989. Federal manual for identifying and delineating jurisdictional wetlands. U.S. Gov. Print. Office, Washington, DC.

Hook, D.D., M.M. Murray, D.S. DeBell, and B.C. Wilson. 1987. Variation in growth of red alder families in relation to shallow water table levels. For. Sci. 33:224–229.

McKee, W.H., Jr. 1978. Rust on iron rods indicates depth of soil water tables. p. 286–291. *In* W.E. Balmer (ed.) Soil moisture–site productivity symposium, Myrtle Beach, SC. 1–3 Nov. 1977. USDA, Washington, DC.

Mitsch, W.J., and J.G. Gosselink. 1986. Wetlands. Van Nostrand Reinhold, New York.

Odum, H.T. 1983. Systems ecology, an introduction. Wiley-Interscience, New York.

Ponnamperuma, F.N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29–96.

Richardson, C.J. 1983. Pocosins: Vanishing wastelands or valuable wetlands? BioScience 33:626–633.

Richardson, C.J., R. Evans, and D. Carr. 1981. Pocosins: An ecosystem in transition. p. 3–19. *In* C.J. Richardson (ed.) Pocosin wetlands: An integrated analysis of Coastal Plain freshwater bogs in North Carolina. Hutchinson Ross, Stroudsburg, PA.