Communications in Soil Science and Plant Analysis, 37: 1775–1781, 2006

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1080/00103620600710611

Noncontinuous Development of Reducing Conditions in Wetland Soils

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Abstract: Soil aeration status in relation to water table was analyzed by contour mapping in a forested wetland, an emergent marsh, and an irrigated rice field. Two soil aeration status indicators, oxygen (O_2) and redox potential (Eh), showed a significant correlation ($P < 0.01$). Soil O_2 and Eh levels generally decreased with the water table rise in the forested wetland and marsh, but with a noncontinuous pattern. The results indicate that soil aeration status could be temporally improved at an optimum water table level, probably due to O_2 transport by wetland plants. The soil Eh in the rice fields clearly showed a seasonal pattern regardless of the water tables.

Keywords: Oxygen, redox potential, water table, wetlands

INTRODUCTION

The major stress in wetland ecosystems is anoxia. When a soil is flooded, soil oxygen (O_2) is rapidly depleted through aerobic respiration using O_2 as the terminal electron acceptor. This is because the rate of gaseous O_2 diffusion through water is much slower than through air and normally cannot meet the metabolic demand of the soil organisms. In the absence of O_2, other alternative electron acceptors (nitrate, manganese, iron, sulfate, and carbon dioxide) are progressively reduced with decreasing energy to the microbial community (Patrick and Jugsujinda 1992; Puckett and Cowdery 2002). Consequently, almost all metabolically mediated activities such as decomposition, mineralization, and nutrient absorption are reduced. In some cases, the

Received 16 March 2005, Accepted 15 February 2006
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biological availability of major and trace nutrients become limited, and reduced elements and organic compounds can reach toxic levels (Gambrell and Patrick 1978).

Plants adapt to anoxia by avoiding root anoxia, not by physiological changes in the cell metabolisms. The primary plant strategy is the development of vascular spaces (aerenchyma) in the roots and stems. The plant root porosity of normal mesophytes is about 2 to 7% of its volume, whereas wetland species have pore spaces up to 60% of their volume (Webb and Jackson 1986). The major mechanism of O_2 transport through the plants is gaseous diffusion from the aerial portions of the plants into the roots. Pressurized gas flow, driven by a gradient in temperature and water vapor pressure, was found to be an important mechanism for water-floating plants to obtain O_2 (Dacey 1980, 1981).

Soil O_2 and redox potential (Eh) are two different indicators of soil oxidation-reduction status. In most case studies, soil-reducing conditions are estimated by the water table level, and the reducing intensity is quantified by O_2 and/or Eh measurement at a certain soil depth. Little information is available on the O_2 and Eh status in soil profiles. The objective of this study is to map the soil O_2/Eh status in the soil profiles of three major types of wetland and to explore the pattern of aeration status with the water table rise.

MEASUREMENT AND DATA ANALYSIS

Field measurements in a bottomland hardwood forest, an emergent marsh, and an irrigated rice field were synthesized for this objective. Table 1 summarizes the measurements conducted at these three sites. Large variations in the soil O_2 content and Eh existed among the replicate plots in the forested wetland and marsh. The primary database was sorted by the water table regardless of different season and plots in these two sites. The median of a certain water table interval (normally 3 to 5 cm) was determined, and then the medians of the soil O_2 and Eh within this water table range (e.g., from -28 to -24 cm) were calculated (Excel, Microsoft 2000). The secondary database consisted of the medians of the water table at different range and the soil O_2 and Eh median values at each water table range for the forested wetland and marsh, as well as means of the duplicate Eh measurements in the rice field. Then the simplified secondary database was used for the following analysis. Significance of correlation between two independent variables was tested ($\alpha = 0.05$) using PROC CORR (SAS 8.02, SAS Institute, Inc.).

RESULTS AND DISCUSSION

Oxygen can rapidly diffuse into the soil profiles of well-drained soils (characterized by high O_2 and Eh). In waterlogged soils (characterized by low O_2

Table 1. Measurement at the three wetland sites

Parameter	Forested wetland[a]	Emergent marsh[b]	Irrigated rice[c]
Location	Georgia, USA 31°55′ N, 81°15′ W	California, USA 37°32′ N, 122°00 W	Liaoning, China 41°32′ N, 122°23′ E
Study period	Nov. 91 to Oct. 92	Dec. 97 to Nov. 99	June 99 to Oct. 99
Replication	28	24	2
No. of measurement	10	13	17
Water table (cm)[d]	−41 to 0	−39 to 15	0 and 10
O_2 (%)	0 to 21	0 to 21	N/A
Eh (mV)	−215 to +741	−173 to +733	−267 to +591

Notes: Soil O_2 content and Eh were measured at soil depths of 15, 30, and 60 cm for the forested wetland and the emergent marsh. Soil O_2 content was not measured in the rice field, but Eh was measured at depths of 1, 2, 4, 8, 14, and 22 cm in the soil profile. Description of the technique for O_2 content and Eh measurement in soil profiles is available in Faulkner, Patrick, and Gambrell (1989). Both the forested wetland and emergent marsh sites showed a similar hydrological cycle, with a dry period from May to October and a wet period from November to April.

[a]The forested wetland soil C and N contents are 2.46 and 0.19% on average, respectively. Soil pH is near neutral, and vegetations are dominated by *Acer rubrum* L. and *Fraxinus profunda* Bush.

[b]The marsh soil series is of Reyes clay. Vegetation is dominated by one obligate wetland species, *Salicornia virginica*.

[c]The rice (*Oryza sativa* L.) soil type is locally described as meadow brown. Soil OM content is 2.12% and pH (top 20 cm) fluctuated between 6.4 and 6.7. Water level was controlled by irrigation in the rice field. Detailed description on this study site was previously reported (Yu, Chen, and Patrick, 2004).

[d]Negative values in the water table represent measurements below soil surface.

and Eh), as a result of water table rise, O_2 diffusion is considerably limited, because O_2 diffusion rate in water is about 10^{-4} of that in air (Greenwood 1961). Statistical analysis indicated that a positive correlation between the soil O_2 and Eh was significant ($P < 0.01$) at every soil depth of the forested wetland and marsh sites. Soil O_2 and Eh in these two sites was inversely correlated with the water table with statistical significance ($P < 0.01$).

The results showed a good agreement in the soil O_2 and Eh patterns when the water table rose in the forested wetland (Figure 1) and marsh (Figure 2). However, the development of soil-reducing conditions, as indicated by the decrease of the soil O_2 and Eh levels, showed a noncontinuous characteristic. In the forested wetland, the O_2 level in the soil air at 60 cm deep dropped below 5% when the water table rose to −24 cm and again to −12 cm. The O_2 levels were actually more than 5% at this soil depth in a water table range of −19 to −12 cm. Similarly the Eh values in the soil profile below the water table increased when the water table rose from −26 to −22 cm

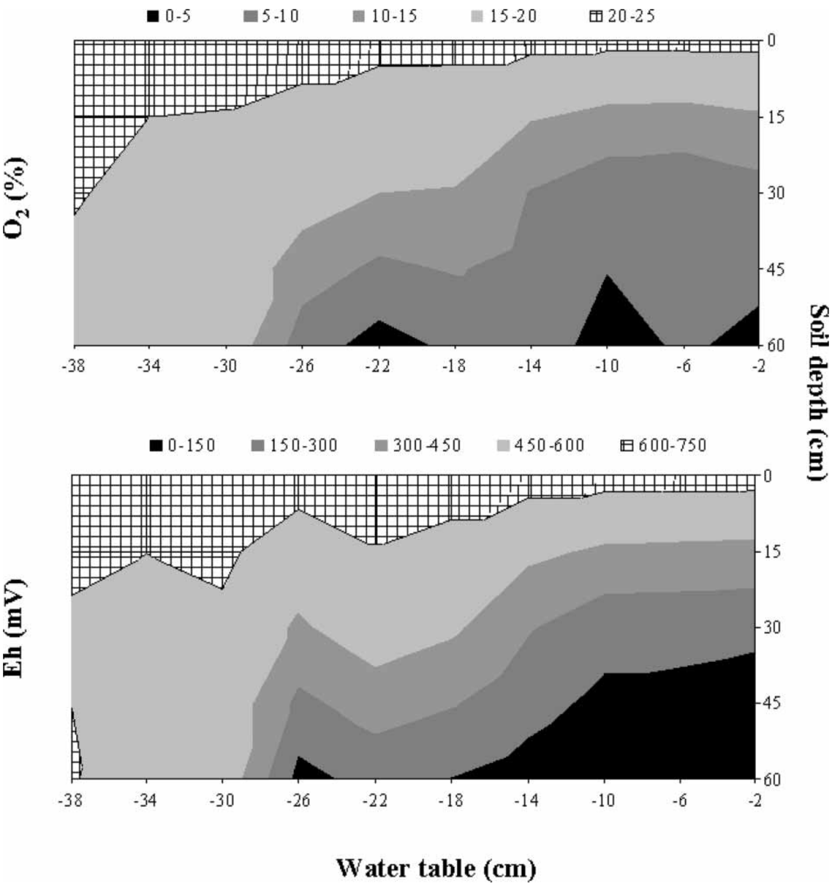

Figure 1. Variation of soil O_2 content and Eh with water table in the forested wetland.

(Figure 1). The same characteristic was more clearly found in the marsh soil where the soil aeration status was significantly improved for the waterlogged part of the soils when the water table was about -12 cm (Figure 2). Wetland plants play a critical role not only for maintaining the root aerobic metabolism, but also for the aeration of the surrounding soils. Transport of atmospheric O_2 through the wetland aerenchyma system can only occur when O_2 deficiency develops in the root zones. The amount of O_2 supply though this mechanism may exceed the demand of plant root. The excess O_2 can diffuse to the surrounding soils, especially the lower depths of the soil where severe anoxia conditions prevail. However, there must be a threshold of a water table where the hydraulic pressure is larger than the O_2 transport potential through the wetland plant, regardless of transport mechanisms. When the water table rises above this threshold level, the soils are at risk of facing severe O_2 deficiency and reducing conditions.

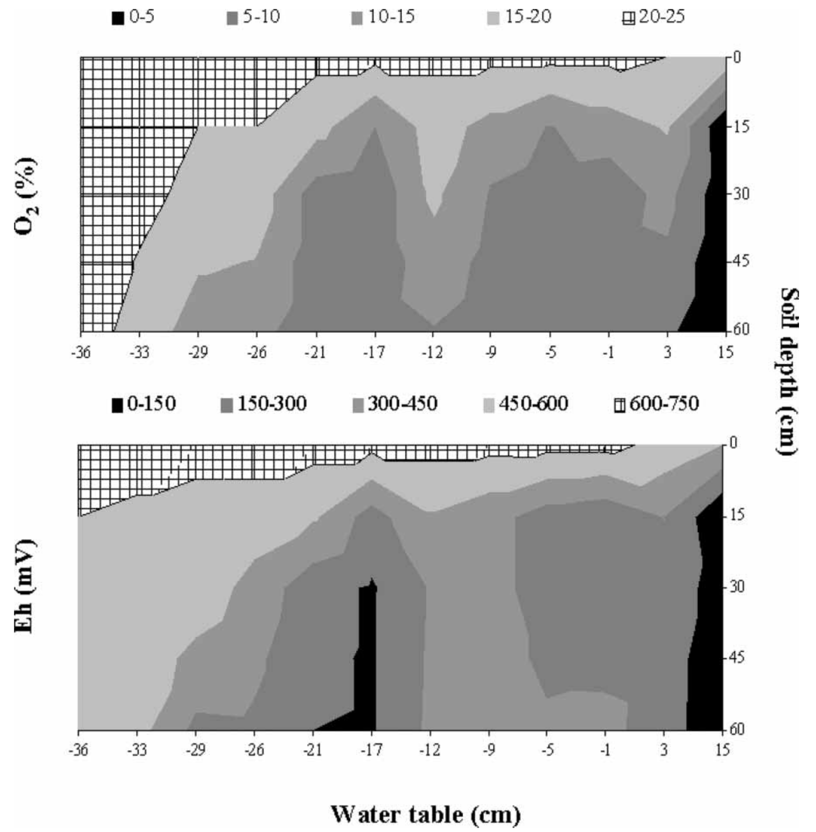

Figure 2. Variation of soil O_2 content and Eh with water table in the emergent marsh.

Rice is an annual crop in that its aerenchyma system develops in each growing season (Kludze, DeLaune, and Patrick, 1993). The soil Eh in the rice fields clearly showed a seasonal pattern, because the water tables were kept almost constant by irrigation control. The soil Eh patterns under the two water levels were quite identical in the rice-growing season, and the soil Eh increased dramatically after drainage (Figure 3). Strictly reducing conditions (Eh < -150 mV) mainly developed in three periods after rice transplanting: day 50 to 60 (early), day 67 to 77 (middle), and day 95 to 105 (late). Soil original organic matter (OM), release of new OM from the root, and degradation of the dead root probably contributed most to the development of the three strictly reducing zones, respectively. Oxygen transport through the rice plant root might play a significant role in elevating the soil aeration status between the three strictly reducing zones (Yu, Chen, and Patrick 2004). Organic matter application and plant root exudates mainly affected the plow layer of the rice field (top 20 cm) where the reducing conditions were the most severe because of high O_2 demand. A lower water

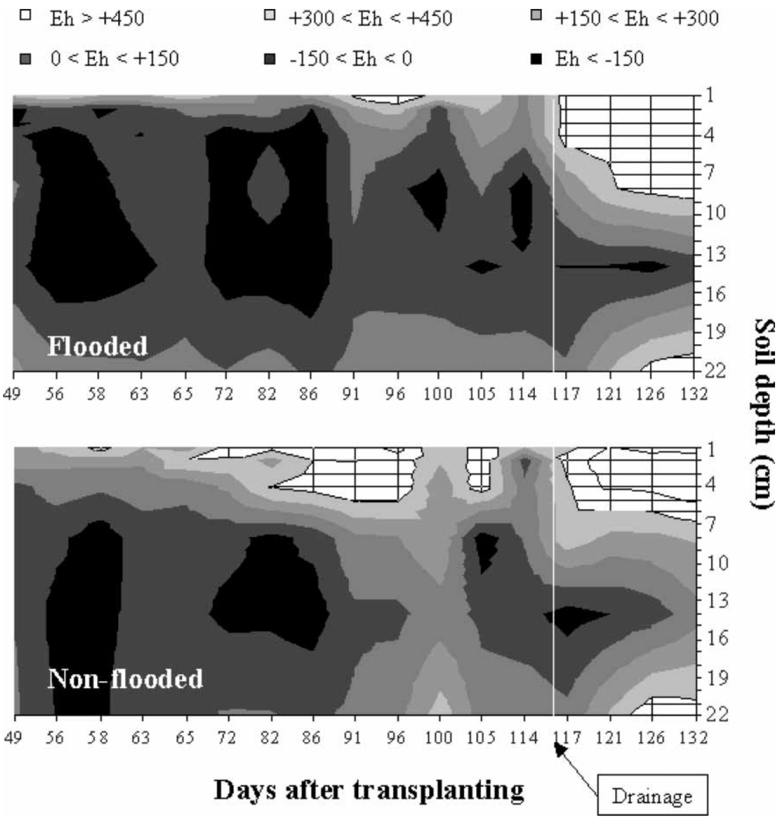

Figure 3. Seasonal variation of soil Eh at different water tables in the irrigated rice fields [modified from Figure 1 in Yu, Chen, and Patrick (2004) with permission].

table (0 cm) showed two important effects: 1) introducing more aeration to the top layers of the rice fields than the fields with higher water table (10 cm), resulting in the strictly reducing zones ($Eh < -150$ mV) being developed 4 or 5 cm deeper; and 2) making the soil Eh generally distribute to a higher level [e.g., the bulk of the soil with $Eh < -150$ mV was decreased from 19% to 13%, and at the same time the bulk of the soil with $Eh > +450$ mV was increased from 6% to 10% (Figure 3)].

The contour mapping of the soil O_2/Eh status in wetland soil profiles can help us better understand the ecosystem's function and sustainability. When soil anoxia is moderate, the magnitude of O_2 diffusion through many wetland roots is large enough not only to meet the root demands but also to aerate the adjacent soils. The oxidized rhizosphere found in many wetland root zones can detoxify the soluble reduced ions produced in the surrounding anoxic soils by reoxidizing them to precipitate in the rhizosphere (Howes et al. 1981; Laanbroek 1990). There should be an optimum water level that could provide the best aeration to the soils. Also, there should be a critical level of water table that is probably unique for each system, above which the O_2 transport through the plants will shut down. Further research is needed to determine these water levels, which can be used as a diagnosis of a wetland ecosystem. In the rice fields, the three periods with strictly reducing conditions developed in the soils corresponded to the major CH_4 (an important greenhouse gas) emission periods, indicating a close relationship between the soil Eh and CH_4 production. Water table management effectively reduced the average CH_4 emission rate from 25.2 (10 cm) to 5.3 (0 cm) mg CH_4 m^{-2} day^{-1} with no change in rice yield observed, providing a feasible approach to mitigate CH_4 emission from rice fields (Yu, Chen, and Patrick 2004).

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