Hydrol. Earth Syst. Sci. Discuss., 6, 3637–3668, 2009
www.hydrol-earth-syst-sci-discuss.net/6/3637/2009/

Hydrology and Earth System Sciences Discussions

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Hydropedological assessment of a vertisol climosequence on the Gulf Coast Prairie Land Resource Area of Texas

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Received: 31 March 2009 – Accepted: 5 April 2009 – Published: 30 April 2009

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Vertisols contain slickensides and wedge-shaped aggregates formed by shrink-swell processes during wet-dry cycles in seasonal climates. The dynamic distribution of macro- and microvoids as a by-product of this unique process, accompanied by microtopographic lows and highs, mitigate our ability to make accurate and precise interpretations of aquic and hydric conditions in these problematic soils. We studied Vertisols across a subhumid to humid climosequence to assess the formation of redoximorphic features on planar landscape positions in response to varying levels of rainfall. Approximately 1000 mm of MAP is required to form soft iron masses that then increase in abundance, and to shallower depths, with increasing rainfall. More than 1200 mm of MAP is needed to form iron pore linings, regardless of microlow or microhigh topographic position. Soft iron masses with diffuse boundaries become more abundant with higher rainfall in microlows, whereas masses with nondiffuse boundaries are more common in microhighs. Iron depletions do not correlate with rainfall in terms of abundance or depth of occurrence. Most soft iron masses form in oxygenated ped interiors as water tends to first saturate and reduce voids where iron depletions form. The quantity of crayfish burrows is strongly correlated with rainfall and first appears coincidentally with soft iron masses in microlows near 1000 mm of MAP. Dithionite-citrate extractable and ammonium-oxalate extractable iron oxides increase systematically with rainfall indicating frequent episodes of iron reduction and precipitation into pedogenic forms. It appears that Vertisols forming in these landscapes with MAP greater than 1200 mm should classify as Aquerts because of the presence of aquic conditions. These same soils may also meet the definition of hydric as one criterion for the identification of Federally protected wetlands. However, there is a considerable disjunct between protracted periods of saturation and limited periods of reduction in these soils. Non-Darcian bypass flow appears to be the principle mechanism governing the flux of water through these cracking soils where water first accumulates and then persists in microlow bowls.

1 Introduction

Vertisols cover approximately 132 000 km^2 of land area in the coterminous USA (Guo et al., 2006) where seasonal wetness regulates the shrink-swell processes critical to their formation (Wilding and Tessier, 1988). These unique properties present numerous agricultural and engineering problems worldwide (Dudal and Eswaran, 1988; Coloumbe et al., 1996; Nordt et al., 2004). Determining when saturation is sufficient to undergo anaerobiosis to the extent that land use problems emerge has been controversial, leading to the identification of Vertisols as one of the problem soils for making aquic and hydric interpretations (Comerma, 1985; Griffin, 1991; Jacob et al., 1997). First, by definition, Vertisols are seasonally wet because they must desiccate during at least some part of the year in order for cracks to form from shrinkage forces. Defining soil moisture regimes and hydric conditions is notoriously difficult for seasonally wet soils and often depends on qualitative assessment of iron redoximorphic features. Second, there is uncertainty as to whether soft iron masses are relict or contemporaneous, and whether their occurrence is related to the modern soil hydroperiod. Third, Vertisols possess a spatial and temporal dynamic distribution of micropores and macropores often contributing to water flux in non-Darcian terms. This is expressed as bypass flow where water is transported under positive pressure along macropores adjacent to unsaturated ped interiors. These factors often can lead to disequilibrium between periods of saturation and reduction when using elemental iron as a proxy for oxygen deficiencies. Fourth, because of microtopographic cyclicity (gilgai and subsurface waviness) it is difficult determining when both the microlow and microhigh are saturated and anaerobic or how much of the pedon cycle must meet these conditions for the soil to be considered aquic or hydric.

One of the most widespread regions in the world containing Vertisols is along the Gulf Coast Prairie of Texas where they are mapped on shallow, planar slopes, and to a lesser extent in depressional landscape positions. Much of the region has been cultivated for decades and is now being encroached upon by urbanization (Griffin, 1991;

Nordt and Wilding, 2009). Knowledge of wetness conditions of Vertisols in this region has been gained from casual observation of morphological features during soil survey mapping, or from water table monitoring of one or more random locations (see Griffin, 1991; Jacob et al., 1997). As such there has been much confusion in the classification and mapping of Vertisols regarding wetness conditions, compounded by a lack of understanding of the genesis of wetness features in these soils.

The purpose of this paper is to systematically evaluate field and laboratory properties diagnostic of wetness in microtopographic lows and highs across a subhumid to humid Vertisol climosequence in the Gulf Coast Prairie Land Resource Area of Texas. We then analyze saturation and reduction data from two previous water table monitoring studies in the region to assess whether aquic and hydric conditions exist, and if present, to assess where these conditions begin along the climosequence. We close by providing a qualitative hydropedological model of Vertisol formation.

2 Setting and methods

The study area covers the Beaumont Formation, a coastwise fluvial-deltaic terrace as part of the Gulf Coast Prairie Major Land Resource Area of Texas (Fig. 1). Mean annual precipitation (MAP) ranges from approximately 700 to 1450 mm and traverses the Ustic to Udic soil moisture boundary (~900 mm) within a hyperthermic (>22°C) soil temperature regime (see Soil Survey Staff, 1999). Vegetation is prairie and dominated by warm season grasses (USDA-SCS, 1981). The Beaumont Formation is dominated (95%) by nearly level, co-linear surfaces with isolated depressions as evidenced by numerous county soil surveys (e.g. Miller, 1997) and other geologic maps (e.g. Barnes, 1987). The interdistributary floodbasins are mapped as Vertisols with Alfisols and Mollisols on adjacent meander ridges. Soils on the Beaumont are late Pleistocene in age (Blum and Price, 1994).

We studied twelve pedons located in nondepressional landscape positions on the Beaumont, with three in the Ustic soil moisture regime (Victoria series), and nine in the Udic soil moisture regime (three each in the Laewest, Lake Charles, and League series) (Fig. 1; Table 1). The Victoria series is classified as a Sodic Haplustert, the Laewest and Lake Charles as Typic Hapluderts, and the League as an Oxyaquic Hapludert. Two previous water table monitoring sites are located along the climosequence: one within the area of the Laewest series near the Ustic to Udic boundary and the other within the area of the League series on the eastern boundary of the study area (Fig. 1). All of these soils classify as fine, smectitic, hyperthermic at the Family taxonomic level. These Vertisols have A-Bss(g)-Bssk(g) profiles dominated by mollic epipedons and cambic or calcic subsurface diagnostic horizons (Soil Survey Staff 2008, http://ssldata.nrcs.usda.gov). However, microlows tend to have thicker sola and mollic epipedons and greater depth to carbonate than microhighs (Fig. 2a and b). Percentage organic carbon in the microlows of surface horizons ranges from approximately 1.6 to 3.4%, whereas in the microhighs organic carbon content ranges from 1.4 to 2.9%. Reaction is slightly acidic in surface horizons of microlows above 1200 mm of MAP. All subsoils at varying depths are alkaline (Nordt et al., 2006).

Each of the twelve soil pits was excavated with a backhoe to dimensions of 4 to 6 m long, 2 m wide, and 2 to 4 m deep. In each pit, all horizons from a microlow and microhigh pedon were described and sampled according to standard procedures (Soil Survey Division Staff, 1993). Each sampled horizon was characterized for standard physical and chemical properties at the Soil Survey Laboratory in Lincoln, Nebraska (Soil Survey Staff, 1994; USDA-NRCS, 1995). Surface relief produces the microlow and microhigh topography and gilgai expression, which ranges from approximately 10 to 30 cm. The distance between microhighs commonly ranges from 2 to 3 m, which also tracks the degree of subsurface waviness (see Fig. 2a and b).

For this investigation, we assessed field morphological and laboratory data related to wetness across the climosequence. From field descriptions we focused on redoximorphic features in the form of iron concentrations (concretions, soft masses, pore linings) and iron depletions (soft masses and pores) in relation to matrix colors. The compiled information included abundance (%), location (matrix versus void), color (Munsell

chart), and boundary (diffuse versus nondiffuse). In terms of boundary we combined clear and abrupt into the category of nondiffuse, to differentiate from diffuse. Additionally, crayfish burrows were documented with regard to location and depth as a marker for wetness conditions. Dithionite-citrate extractable (Fe_d) and ammonium-oxalate extractable (Fe_o) iron oxides were evaluated from the characterization data because the oxidation state of iron is the principal contributor to the formation of redoximorphic features. These chemical data were cross-checked with matrix colors and abundance of redoximorphic features described in the profiles. The entirety of the characterization data were used to help taxonomically classify the Vertisols. For methods describing water table monitoring for the two localities in the study area, see Griffin (1991). It is important to note that whereas the Griffin study defines saturation as water that can be measured in a piezometer, others believe that it is best described as "free water" because of the difficulty of completely saturating ped interiors in Vertisols (Wes Miller, personal communication, 2009).

3 Matrix colors

Matrix colors of surface horizons meet the requirement of a mollic epipedon (Soil Survey Staff, 1999) in most microlows and microhighs across the climosequence reflecting the importance of belowground biomass production from the associated grassland community. When the thickness requirement is not met, it is by only a few cm, in part an artifact of profile selection within each of the pit excavations. There is a wide range of color hues of B horizons in the study area, even though gray matrixes (value $\geq$4, chroma $\leq$2) dominate the profiles in the upper 1 m of the climosequence. The depths at which chromas of three are first encountered increases with increasing rainfall in both the microlow and microhigh (Fig. 3).

4 Redoximorphic features

4.1 Iron concentrations

Most forms of iron manganese in the study area are present as concretions with abrupt boundaries, which show no relationship to climate in terms of abundance, depth, size, or color. This suggests that these redoximorphic features are relict and not actively forming today (Vepraskas 1994, 2001). A few ped coats and pore linings deep in some profiles indicate periodic reduction and re-precipitation of iron manganese.

In microlows, soft iron masses with nondiffuse boundaries first occur at approximately 900 mm of MAP and not until 1075 mm of MAP for those with diffuse boundaries (Fig. 4a). These redoximorphic-rainfall relationships generally hold for the microhighs (Fig. 4b). Further, cm of the solum containing soft iron masses increases in the both the microlow and microhigh with increasing rainfall, although there is considerable variability to this trend. These data also indicate that soft iron masses in the microlow are of equal importance in terms of boundary (diffuse versus nondiffuse) and location (void versus matrix). In microhighs, however, nearly all of the soft iron masses have nondiffuse boundaries, but as with microlows, they can still occur in either the matrix or along voids. The depth to the first soft iron masses, whether with diffuse or nondiffuse boundaries, systematically decreases with increasing rainfall in both the microlow and microhigh (Fig. 4c and d). Once encountered, the presence of soft iron masses generally persists to the bottom of the solum in both topographic positions. Color hues of soft iron masses in the microlows do not relate to rainfall, nor to whether the boundaries of the masses are diffuse or nondiffuse, nor to whether they occur in the matrix or along voids (Fig. 4e). There is no correlation of these properties to rainfall in the microhighs either, even though most soft iron masses have nondiffuse boundaries in the matrix (Fig. 4f).

Iron pore linings appear in surface horizons of both microlows and microhighs when 1250 mm of MAP is exceeded, but with the thickness of the zone containing these features greater in microlows (Fig. 5a). All iron pore linings have a relatively uniform dis-

tribution of diffuse and nondiffuse boundaries in microlows, but with nondiffuse boundaries in microhighs (Fig. 5b). Color hues show little preference to any particular pore lining regardless of its boundary, and range from 2.5 Y to 5YR.

4.2 Iron depletions

Iron, as in depleted soft masses do not appear until approximately 1000 mm of MAP in microlows where they occur exclusively along voids but with either diffuse or nondiffuse boundaries (Fig. 6a). In microhighs, depleted soft masses first appear near 1100 mm of MAP and are dominated by nondiffuse boundaries that occur equally between the matrix and voids (Fig. 6b). In terms of depth to iron depleted masses and pores, there is no correlation to MAP in either the microlow or microhigh (Fig. 6c and d). Regardless of boundary condition, depleted masses in microlows have equal proportions of gleyed and nongleyed colors (Fig. 6e). In microhighs, the few nondiffuse boundaries that occur are all nongleyed and along voids (Fig. 6f). However, depleted masses with nondiffuse boundaries are somewhat equally represented between gleyed and nongleyed and between voids and the matrix.

Iron depleted pores dominate the microlows, and as with depleted soft masses, first appear near 1000 mm of MAP (Fig. 7a). They increase somewhat in abundance as rainfall increases. Depleted pores all have gleyed, diffuse boundaries in microlows, but those with nondiffuse boundaries can be either gleyed or nongleyed (Fig. 7b). All depleted pores in microhighs have nondiffuse boundaries, but interestingly are all gleyed.

4.3 Crayfish burrows

We classify crayfish burrows (krotovina) as a redoximorphic feature because of their influence on water flux and because these fauna require water-logged habitats. The crayfish in our study area are probably those with complex burrows that begin near the ground surface above the water table that branch downward to the water table, consistent with seasonally wet soils (Hasiotis and Mitchell, 1993; Stone, 1993). In our climosequence on shallow, planar slopes (nondepressional), crayfish burrows do not appear until MAP is slightly greater than 1000 mm (Fig. 8), which roughly coincides with the Ustic/Udic soil moisture regime boundary and the first appearance of iron redoximorphic features. Notably, there is a strong correlation between the depth of these features and MAP as the burrows come closer to the surface with greater rainfall. Crayfish burrows do not appear in microhighs until approximately 1400 mm of MAP, however.

The length and thickness of individual crayfish burrows revealed no particular pattern along the climosequence. Further, the material used to line the walls of the burrows appears to reflect the source material, typically consisting of an array of red, gray, brown and yellow colors. Even with prolonged saturation, the colors of the lined walls exhibit variegated colors probably because individual burrows do not persist long enough for sufficient iron reduction to form dominantly gray colors.

On the dry end of the climosequence burrows are concentrated at a depth of 1 to 1.5 m in the microlow coinciding with the greatest abundance of soft iron masses. On the wet end of the spectrum, burrows and iron concentrations are distributed throughout a greater part of the profile.

4.4 Fe_o and Fe_d

The quantity of extractable Fe_d and Fe_o iron oxides in the surface horizons of the climosequence increases systematically with rainfall in both microlows and microhighs (Fig. 9a and b). Quantities between microlows and microhighs in surface horizons are nearly identical confirming field observations of similar matrix colors and abundances of iron oxide features. The difference is that a greater proportion of these features may be relict in the microhighs because of their nondiffuse boundaries. We also plotted Fe_d and Fe_o data at a depth of 100 cm and discovered a similar trend as with Fe_d as in the surface horizon, but that the overall concentration of Fe_o decreased as it forms a curvilinear trend with rainfall (Fig. 9c and d). The Fe_o trend is both subtle and difficult to explain, however.

5 Comparison to monitoring stations

We compared our field and laboratory observations to two other Vertisols in the study area that had been hydromorphically monitored from 1989–1990 (Griffin, 1991). The first of these pedons was described and sampled as the Beaumont series (88TX 245-1), but later correlated to the League series. The other was described and sampled as the Lake Charles Series (88TX 469-1), but later correlated to the Laewest series. Saturation was measured with piezometers and tensiometers at the surface and at depths of 25, 50, and 100 cm with reduction determinations at the same depth intervals with alpha, alpha′-dipyridil. The Laewest monitoring station (microlow) in Victoria County near the city of Victoria, Texas receives approximately 950 mm of MAP and is compared to morphological and chemical data from our nearby LAW 469-1 (99TX 469-1) pedon from the same area (Fig. 1; Table 1; Fig. 2a). The monitoring site has never been cultivated and is in native rangeland. During the monitoring period average rainfall slightly exceeded the 30-year mean. The League monitoring station (transitional microlow to microhigh) in Jefferson County near the city of Beaumont, Texas was compared to results of our nearby LEG 245-1 (01TX 245-1) pedon from the same area (Fig. 1; Table 1; Fig. 2b). The Jefferson County site was under cultivation, but not irrigated. Its MAP is approximately 1400 mm with the average during the monitoring period slightly exceeding the 30-year mean.

At the Laewest site (Fig. 10a) the interval of saturation during the monitoring period increased from 5% at the surface to 31% at a depth of 100 cm according to piezometers, but in the absence of iron reduction as measured by alpha, alpha′-dipyridil (Fig. 10a). Tensiometers exhibit somewhat less saturation at depth than do the piezometers perhaps indicating that ped interior take longer to wet. At both the monitoring station and in our study area neither soft iron masses or pore linings were described within the upper 100 cm (Table 2), consistent with the absence of chemically-detected reduced iron. This is supported by our data showing that the most kinetically active forms of iron, as measured by Fe_o, is $<0.1\%$ in the surface horizon (see Fig. 9).

Thus, whereas this soil is saturated for up to 31% of the time within the upper 100 cm, it is an expression of oxyaquic rather than aquic conditions.

Monitoring data from the League site (Fig. 10b) differs because saturation increases from 29% of the monitoring period at a depth of 25 cm to nearly 100% of the monitoring period at a depth of 100 cm according to piezometers (Fig. 10b). In turn, a saturation threshold is crossed whereby iron reduction was initiated near the surface (<5 cm depth) for approximately 25% of the monitoring period before decreasing to 2% at depths of 25 and 50 cm, and followed by an increase to 8% at a depth of 100 cm. However, only 8% of the time was the entire soil mass reduced according to alpha, alpha′-dipyridil. Thus, saturation persists about 14 times longer than reduction at a depth of 25 cm and about 12 times longer at a depth of 100 cm. Griffin (1991) described few to common soft iron masses throughout the upper 100 cm of the monitored League soil. Our observations of LEG 245-1 revealed 9% iron pore linings in the surface horizon with few to common soft iron masses beginning at a depth of approximately 100 cm and extending to the bottom of the profile (Table 2). The presence of these features with diffuse boundaries confirms significant intervals of contemporaneous iron reduction.

6 Taxonomic and hydric classification

Aquic conditions occur with coincidence of saturation and reduction in the presence of redoximorphic features. According to the USDA Soil Taxonomy (Soil Survey Staff, 1999) aquic conditions at the suborder level of Vertisols must occur within a depth of 50 cm for an unspecified period. For the subgroup level, aquic conditions must occur within the upper 100 cm. Oxyaquic conditions, or saturation without reduction, must occur throughout the upper 100 cm for 20 days consecutively or 30 days cumulatively during an annual cycle. Oxyaquic conditions can only be inferred from water table monitoring data.

With these definitions the Laewest soils, and by extension the Victoria soils to the

southwest (Fig. 1), do not classify as aquic at either the suborder or subgroup taxonomic levels because of the absence of iron concentrations within the upper 100 cm. Further, the upper 100 cm according to water table monitoring data is not saturated for sufficient duration for the taxonomic placement of oxyaquic. Thus, the Laewest taxonomy of Typic Hapludert and the Victoria taxonomy of Sodic Haplustert are verified in terms of soil moisture regime (Table 1).

Classification of the League soils, however, is problematic. These soils have sufficient quantities of iron concentrations within the prescribed depth to classify as aquic at the suborder level, especially when accompanied by positive reaction with alpha, alpha′-dipyridil for an undetermined duration over an unspecified area of soil mass. Accordingly, the League and some Lake Charles soils will classify as Aquerts and not Uderts (Table 1), or more specifically as Endoaquerts at the great group level because of a continuous saturated and reduced column within the solum. The rationale for the original classification of oxyaquic at the subgroup level for the League soils was the extended period of saturation accompanied by only short periods of reduction (Griffin, 1991; Jacob et al., 1997).

Another view of wetness conditions for the League is a determination of whether the soils are hydric in terms of Federally protected jurisdictional wetlands (Environmental Laboratory, 1987). Because of the association of high color values with low chromas, iron pore linings within the upper 30 cm, and a positive reaction to alpha, alpha′-dipyridil these soils would indeed qualify as hydric in the F3 category of Redox Dark Surface in the microlows (USDA-NRCS, 1996). We cannot determine with certainty if the microhighs of these pedons are hydric because reaction to alpha, alpha′-dipyridil was not performed in prior studies. However, iron pore linings are in sufficient quantity that the microhighs would also classify as hydric, but in the F6 category of Depleted Matrix (USDA-NRCS, 1996). Further complicating these interpretations is that the three League pedons are in improved pasture preventing an assessment of potential hydrophytic vegetation.

7 Hydropedological formation of Vertisols

Redoximorphic features indicative of periodic saturation and reduction first appear in the Laewest soils near 1000 mm of MAP and reach their maximum expression within the League soils on the eastern end of the climosequence. As a consequence, we examine in more detail a topographic microlow and microhigh for a typical Laewest pedon (LAW469-1, Fig. 2a, Table 2) and League pedon (LEG245-1; Fig. 2b, Table 2) to better understand the formation of redoximorphic features and aquic and hydric conditions of these problematic soils. These two pedons are also closest to the monitoring stations of Griffin (1991; see Fig. 1).

Along the climosequence, the Laewest and League soils formed from parent materials containing high chroma colors, yet both have gray matrix colors in the upper part (Table 2). Analysis of documented periods of saturation and reduction according to nearby monitoring data, however, makes it unclear whether the dominance of gray matrix colors is contemporaneous or relict. One interpretation is that with greater rainfall more iron is reduced, mobilized, and either transported to greater depths and re-precipitated, or leached, as confirmed qualitatively by Driese et al. (2005). Mass balance calculations for Fe_d and Fe_o for one of the League (001TX 245-1, Table 1) and one of the Lake Charles (99TX 157-1, Table 1) soils confirms this interpretation in both the microlow and microhigh (Driese, 2004). Thus, we proceed under the assumption that the gray matrixes are, at least in part, the consequence of current periods of saturation and reduction of iron. The difficulty of documenting pedogenic versus inherited soil color and its confounding influence on interpretations of wetness conditions is not uncommon (Rabenhorst and Parikh, 2000; Jacobs et al., 2002).

The upper part of the well structured Laewest soil rarely saturates as evidenced by the absence of redoximorphic features (Table 2) and presence of deep water tables (Fig. 10a). Macrovoid development is from pedality, surface cracks, slickensides, and roots. The upper part of the League soil also has well expressed structural properties, enhanced by crayfish burrows, pedality, root channels, and slickensides (Table 2)

but in the presence of higher water tables (Fig. 10b). Well expressed macrovoid development leads to bypass flow where precipitation exceeds the infiltration capacity of surface horizons when the matrixes rarely saturate (Blake et al., 1973; Anderson and Bouma, 1977a,b; Bouma et al., 1977; Bouma and Lovejoy, 1988), compounded by greater macroporosity development from protracted periods of drying and cracking (Lin et al., 1999). Bypass flow can penetrate to depths of greater than 2 m in a matter of days without saturating overlying zones even in subhumid to humid Vertisols (Blake et al., 1973; Lin et al., 1995). This is consistent with recent work showing that 77% of the water is carried by only 3% of the porosity defined as >0.5 mm diameter in some Vertisols (Lin et al., 1997). Recent work by Amidu et al. (2007) on a central Texas Vertisol confirms that water collection is preferential in the bottom of bowls of microlows that rapidly fill with water from bypass flow during rainfall events.

These observations support our interpretations that microlow bowls in both the Laewest and League soils serve as the initial zone of saturation (or free water as documented in piezometers) with the depth of the soft iron masses approximating the average depth of the perched water table (Veneman et al., 1998). In fact, the depth of occurrence of redoximorphic features in the Laewest (~1 m) approximates the depth having the longest period of saturation according to monitoring data (Fig. 10a). Redoximorphic features occur throughout much of the solum of the League soils where intervals of saturation and reduction greatly exceed that of the Laewest (Fig. 10b). This suggests that the saturated column extends to near the surface of the League soils during significant parts of the year.

Once microlow bowls begin to fill with water and reach a state of semi-equilibrium, water begins to stack in overlying macrovoids forming iron depletions with the reduced iron diffusing into oxygenated ped interiors where they form soft masses. Iron depletions often form below the microlow bowls, and below microhighs at similar depths, along macrovoids that serve as water conduits leading to soft iron masses forming mainly in ped interiors by diffusion. Here, iron depleted macrovoids are more widely spaced because of the increase in size and decrease in strength of structural aggregates, accompanied by a decrease in rooting (Table 2). The process of capillary flow upward and downward from the perched water table in the microlows helps explain the presence of some gray ped interiors and soft iron masses on ped exteriors in the both the Laewest and League soils. Soft iron masses with nondiffuse boundaries in the microlow of the Laewest, and in the microhigh of both the Laewest and League, suggest that these features did not form in their current position with respect to the distribution of macrovoids (Vepraskas, 2001). Lateral shifting of soft iron masses from the microlow to microhigh during shrink-swell processes may have reworked the boundaries of these features from diffuse to nondiffuse.

Iron pore linings in the League soils support the interpretation of saturation in surface horizons from a rising water table as microlow bowls fill, with anaerobic conditions persisting long enough to allow for hydrophytic plant growth. Iron pore linings even form in surface horizons of microhighs in the League soils seemingly after microlows fill with water causing saturation in the surface of the microhighs. These iron concentrations are perhaps the most reliable indicator of contemporary anaerobic conditions and the presence of hydrophytic plants (Chen et al., 1980; Mendelssohn et al., 1995).

Regarding extractable forms of iron oxides, the Fe_d phase is in greater abundance and should include crystalline iron oxide species that based on color of the existing soft iron masses and pore linings is likely goethite and lepidocrocite (Schwertmann, 1993). Extractable Fe_o probably tracks short-order ferrihydrite, although the color of some pore lining colors suggests that goethite is an important mineralogical component. Thus, the increase in both Fe_d and Fe_o is probably a result of measuring some disseminated iron oxides in the soil matrix, but more so the total quantity of the various visible iron oxide forms captured in the bulk samples.

Minimal formation of iron redoximorphic features in the Laewest soils apparently arises from: high pH that increases the period of saturation needed for iron reduction, low organic carbon (<0.2%) for microbial respiration, and limited periods of saturation (see Genther et al., 1998; West et al., 1988; Vepraskas, 2001). These conditions in the League soils are more favorable for iron reduction because of acidic conditions.

Further, Fe_o levels are considerably higher in the upper part of the League (>0.2%) than the Laewest soils (<0.1%), confirming the greater abundance of low-order iron oxides such as ferrihydrite and possible goethite.

8 Conclusions

Many redoximorphic features exhibit a strong correlation to rainfall across a subhumid to humid Vertisol climosequence in the Coast Prairie Land Resource Area of Texas. With their first appearance near 1000 mm of MAP, soft iron masses, crayfish burrows, and Fe_o and Fe_d extractable iron oxides increase in abundance with increasing rainfall with iron pore linings appearing near 1200 mm of MAP. However, the results of this study, accompanied by an assessment of nearby water table monitoring stations, confirm that Vertisols are indeed difficult to interpret regarding the presence of aquic and hydric conditions. As such, further water table monitoring studies associated with redox potentials and iron reduction dyes, need to be systematically performed on Vertisol microlows and microhighs in the coast prairie of Texas. Detailed three-dimensional mapping of redoximorphic features in both microlows and microhighs should accompany these studies to better model water flow, saturation, and reduction in the complex landscapes.

Acknowledgements. The authors are grateful for many fruitful discussions regarding the hydropedology of Vertisols with J. Wiedenfeld and W. Miller, currently and formerly, employees of the USDA-NRCS. We also thank H. Lin for his leadership in the field of hydropedology and for organizing the recent critical zone hydropedology conference at Penn State University. We also acknowledge the USDA-NRCS National Soil Survey Laboratory in Lincoln, Nebraska for assistance with soil characterization, as well as the support of the National Science Foundation through grant EAR-9814607 awarded to the authors, which funded initial Texas Coast Prairie Vertisol climosequence research.

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Table 1. Soil characteristics of the Vertisol climosequence in the Gulf Coast Prairie Land Resource area of Texas.

Soil series[a]	Pedon ID[b]	County	Lat/Long (°)	MAP[c] (mm)	MAT[c] (°C)	Slope (%)	Vegetation	Profile	Classification[d]
Victoria	01TX 355-2	Nueces	27.56 97.55	755	22.0	0-1	Rangeland	A-Bw-Bss-Bssk	fine, smectitic, hyperthermic Sodic Haplustert
Victoria	01TX 355-1	Nueces	27.81 97.72	788	22.0	0-1	Rangeland	A-Bw-Bss-Bssk	fine, smectitic, hyperthermic Sodic Haplustert
Victoria	01TX 409-3	San Patricio	28.11 97.35	894	22.0	0-1	Rangeland	A-Bw-Bss-Bssk	fine, smectitic, hyperthermic Sodic Haplustert
Laewest	99TX 391-1	Refugio	28.47 97.12	924	21.6	0-1	Rangeland	A-Bss-Bssk	fine, smectitic, hyperthermic Typic Hapludert
Laewest	99TX 469-1	Victoria	28.72 97.76	1000	21.3	0-1	Rangeland	A-Bss-Bssk	fine, smectitic, hyperthermic Typic Hapludert
Laewest	99TX 239-1	Jackson	28.88 96.40	1066	21.1	0-1	Rangeland	A-Bss-Bssk	fine, smectitic, hyperthermic Typic Hapludert
Lake Charles	99TX 481-1	Wharton	29.43 96.08	1124	20.3	0-1	Pasture	A-Bss-Bssk	fine, smectitic, hyperthermic Typic Hapludert
Lake Charles	99TX 157-1	Fort Bend	29.60 95.88	1170	20.4	0-1	Pasture	A-Bss-Bssk	fine, smectitic, hyperthermic Typic Hapludert
Lake Charles	99TX 201-1	Harris	29.59 95.07	1321	20.7	0-1	Rangeland	A-Bss-Bssk	fine, smectitic, hyperthermic Typic Hapludert
League	001TX 071-1	Jefferson	29.80 94.56	1331	20.3	0-1	Pasture	A-Bssg-Bssk	fine, smectitic, hyperthermic Oxyaquic Dystrudert
League	001TX 245-2	Jefferson	29.87 94.32	1411	20.2	0-1	Pasture	A-Bssg-Bssk	fine, smectitic, hyperthermic Oxyaquic Dystrudert
League	001TX 245-1	Jefferson	30.04 94.19	1437	20.2	0-1	Pasture	A-Bssg-Bssk	fine, smectitic, hyperthermic Oxyaquic Dystrudert

[a] See Fig. 1 for pedon localities.
[b] Pedon data taken from Soil Survey Staff, 2008 (http://ssldata.nrcs.usda.gov).
[c] Rainfall data taken from http://www.worldclimate.com/ (1961–1990).
[d] See Soil Survey Staff, 1999.

Table 2. Key properties of a typical Laewest (LAW) and League (LEG) pedon in the study area (see Figs. 1 and 2).

Pedon	Horizon	Depth (cm)	Macrovoids: Structure[a]	Macrovoids: Slicks[b]	Macrovoids: Roots[c]	Crayfish %	Matrix	Iron concentrations: %	Iron concentrations: Loc	Iron concentrations: Bound	Iron concentrations: Color	Iron depletions: %	Iron depletions: Loc	Iron depletions: Bound	Iron depletions: Color	Feo[e]
LAW 469-1							*Microlow*									
	A	0–16	m1/2sbk	–	c1	–	10 YR 2/1	–	–	–	–	–	–	–	–	0.15
	Bss	16–118	m2sbk	mp	c1	–	10 YR 2–3/1	–	–	–	–	–	–	–	–	0.09
	Bssk	118–176	m2/3abk-we	mp	c1	–	10 YR 3–4/1	1	m	n	7.5 YR	2	v	n	2.5 Y	0.06
	B'ss	176–265	m2/3abk	md	f/c1	–	10 YR 6–7/6	1	m	n	5 YR	1	v	n	2.5 Y	0.05
							Microhigh									
	A	0–11	m2sbk	–	c1	–	10 YR 4/1	–	–	–	–	–	–	–	–	0.08
	Bk	11–28	m2abk	–	c1	–	2.5 Y 4/2	–	–	–	–	–	–	–	–	0.09
	Bssk	28–198	m2/3we	md	f1	–	2.5 Y 4–5/2–4	–	–	–	–	–	–	–	–	0.08
	B'ss	198–265	m2/3abk	md	f1	–	10 YR 6–7/6	3	m	n	5–7.5 YR	2	v	n	2.5 Y	0.08
LEG 245-1							*Microlow*									
	Ap	0–16	w1sbk	–	c1	–	2.5 Y 3/1	9	p	d	2.5 Y/5 YR	–	–	–	–	0.37
	Bssg	16–104	w2we-abk	md/p	f/c1	1–2	10 YR 3-5/1	–	–	–	–	–	–	–	–	0.11
	Bssg	104–115	w2we-abk	mp	f1	1	10 YR 5/1	1	m	d	10 YR	–	–	–	–	0.05
	Bsskg	115–252	w2we-abk	md	f1	1	10 YR 5–7/1	5–20	m	d	10 YR–2.5 Y	–	–	–	–	0.06
	Bsskg	252–275	m2/3we-abk	md	f1	1	7.5 YR 5/6	1	m	n	7.5 YR	–	–	–	–	0.09
							Microhigh									
	Ap	0–26	w2sbk	–	c1	–	2.5 Y 3/1	4	p	n	7.5 YR	–	–	–	–	0.32
	A	15–26	w2sbk	–	c1	5	2.5 Y 3/1	20	m	n	2.5 Y	–	–	–	–	0.19
	Bkg	26–46	m1/2abk	–	c1	5	2.5 Y 5/2	4/1	m/p	n	7.5 YR	–	–	–	–	0.09
	Bssk	46–270	m2/3abk	md/p	f1	5–7	2.5 Y 4–7/1	5–25	m	n	2.5 Y–5 YR	–	–	–	–	0.06
	Bss	355–390	m2/3abk	fp	f1	3	7.5 YR 5/6	10	m	n	5 YR	10	m	n	10 YR	0.08

[a] Structure – w=weak, m=moderate; 1=fine, 2=medium, 3=coarse; sbk=subangular blocky, abk=angular blocky, we-wedge
[b] Slickensides – m=many, d=distinct, p=prominent
[c] Roots – f=few, c=common; 1=fine
[d] Redoximorphic properties – m=matrix, v=void, p=pore (location); n=nondiffuse, d=diffuse (boundary)
[e] Feo – ammonium-oxalate extractable

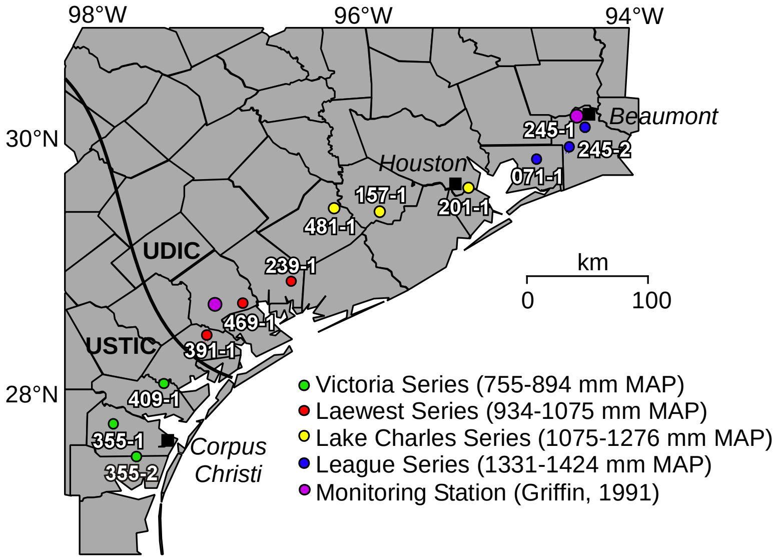

Fig. 1. Map showing the twelve Vertisol pedon localities of this study and the two water table monitoring localities from Griffin (1991), in relation to mean annual precipitation and taxonomic soil moisture regime on the Beaumont Formation of the Gulf Coast Prairie Major Land Resource Area.

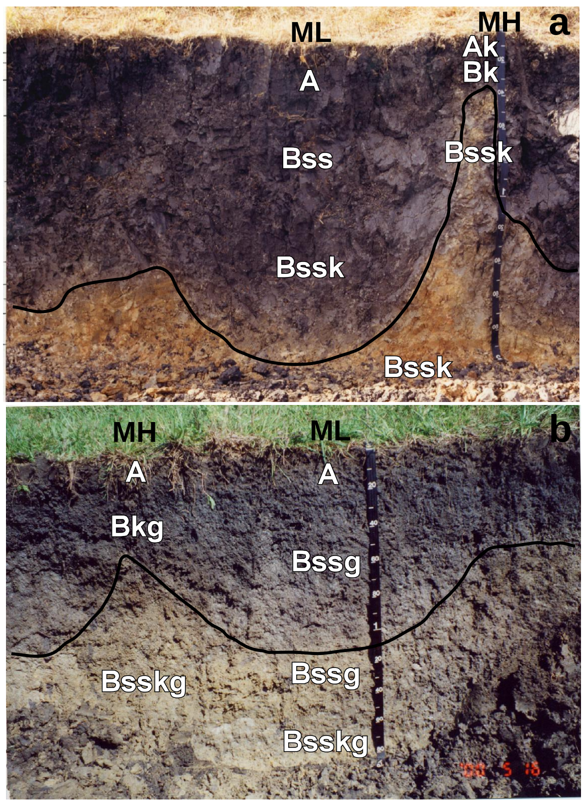

Fig. 2. Photographs of field pit exposures of a Laewest soil (LAW 469-1) and League soil (LEG 245-1) in the study area, exhibiting attributes of microlow (ML) and microhigh (MH) topography.

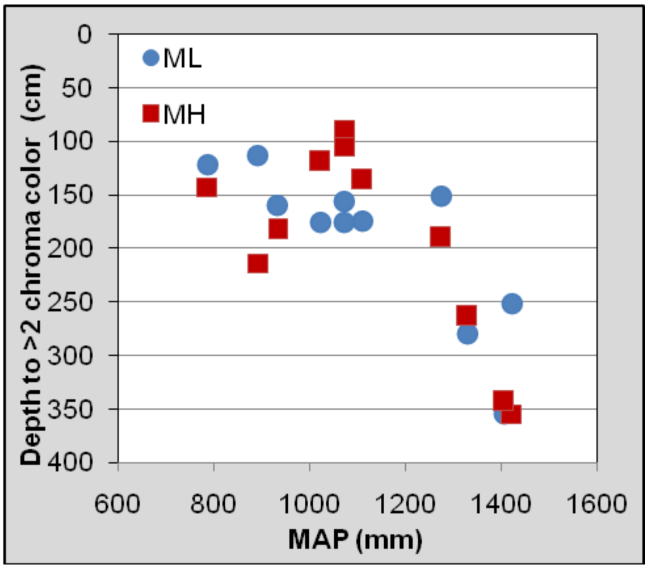

Fig. 3. Depth to matrix color chromas greater than 2 for the microlows and microhighs.

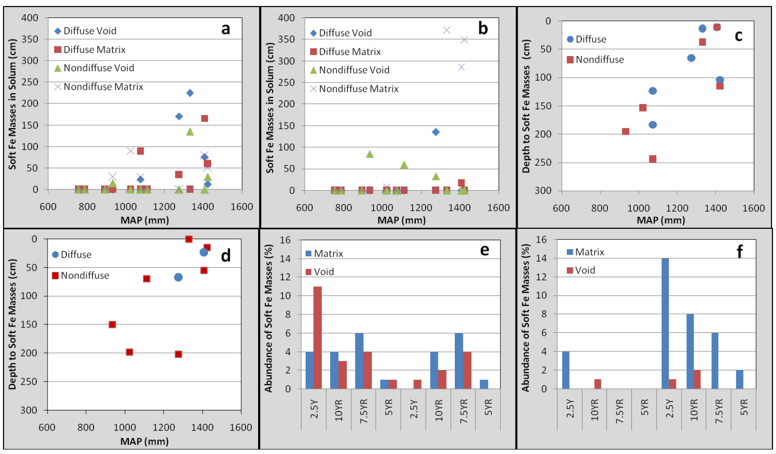

Fig. 4. Proportion of solum containing soft iron masses with diffuse and nondiffuse boundaries in the microlows **(a)** and microhighs **(b)**; depth to first soft iron masses with diffuse and nondiffuse boundaries for microlows **(c)** and microhighs **(d)**; and abundance of color hues of soft iron masses by diffuse and nondiffuse boundary and matrix versus macrovoid in microlows **(e)** and microhighs **(f)**.

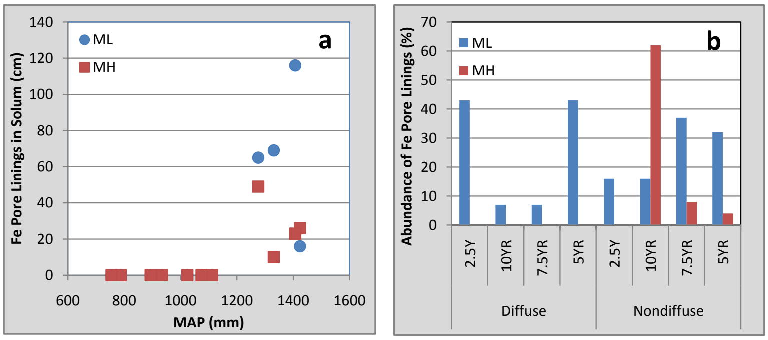

Fig. 5. Proportion **(a)** and color hue abundance by diffuse and nondiffuse boundaries **(b)** of iron pore linings by microlows and microhighs.

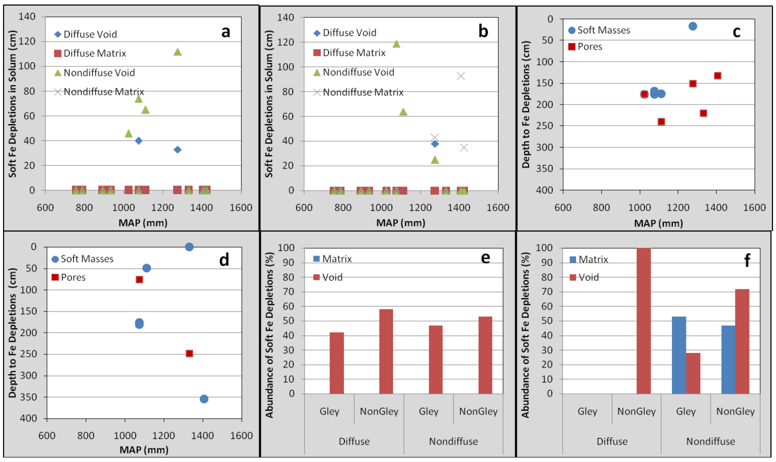

Fig. 6. Proportion of solum containing soft iron depletions with diffuse and nondiffuse boundaries in the microlows **(a)** and microhighs **(b)**; depth to first depleted soft iron masses and pores for microlows **(c)** and microhighs **(d)**; and abundance of color hues of soft iron masses by diffuse and nondiffuse boundary and by matrix versus macrovoid in microlows **(e)** and microhighs **(f)**.

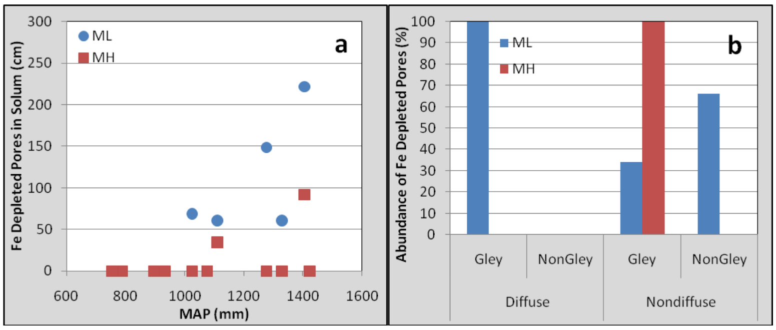

Fig. 7. Proportion **(a)** and color hue abundance by diffuse and nondiffuse boundary **(b)** of iron depleted pores by microlows and microhighs.

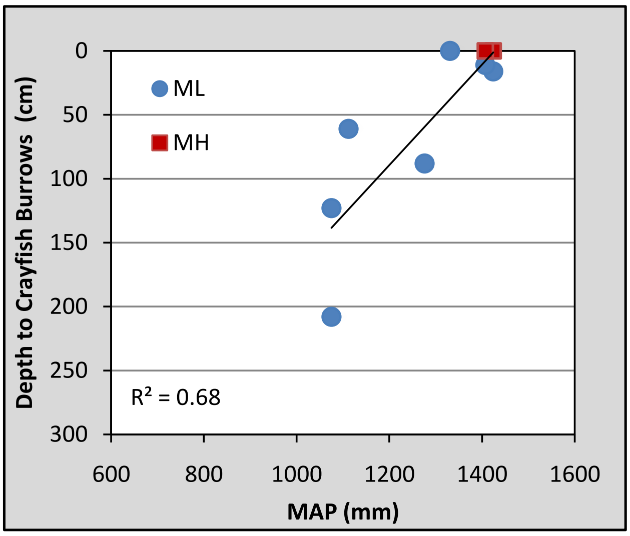

Fig. 8. Depth to first crayfish burrows by microlows and microhighs.

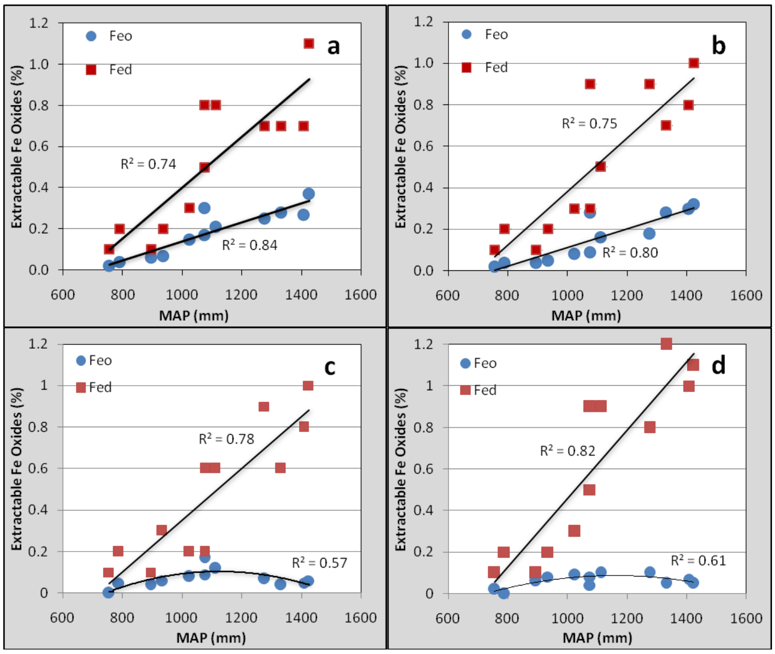

Fig. 9. Weight percentage of Fe_d and Fe_o extractable iron oxides for surface horizons of microlows **(a)** and microhighs **(b)** and for depths of 100 cm for microlows **(c)** and microhighs **(d)**.

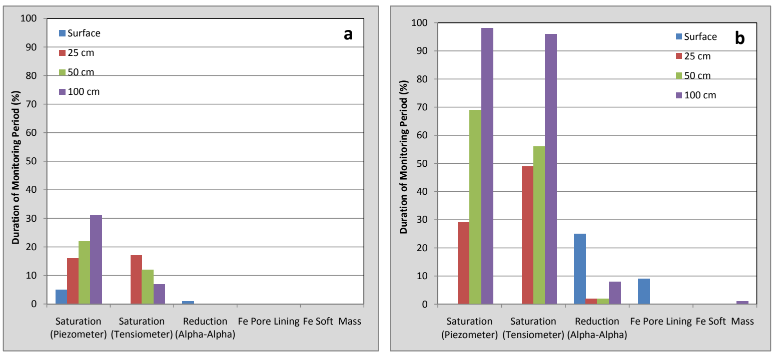

Fig. 10. Water table monitoring data (piezometer and tensiometer for saturation, alpha alpha′-dipyridil for iron reduction) from Giffin (1991) in comparison to redoximorphic features (iron pore linings, iron soft masses) from a nearby Laewest (LAW 469-1) **(a)** and League (LEG 245-1) **(b)** soil from the study area.