Limitations to Redoximorphic Feature Development in Highly Calcareous Hydric Soils

Wetlands in arid climates are particularly important to understand and conserve given their low spatial extent and high rate of delivering ecosystem services. Hydromorphic soils formed in calcareous geologic materials in western Wyoming present challenges related to wetland delineation. Despite the presence of hydrophytic vegetation and wetland hydrology, these soils have not developed the traditional redoximorphic features required to identify hydric soils. To determine the limiting factor responsible for the lack of redoximorphic feature expression, a mesocosm study was conducted with cores extracted from the field. Fifteen intact soil cores were treated with Fe, organic C (OC), a combination of Fe + OC, or no amendment and inundated for 18 wk. Oxidation–reduction potential and pH were measured weekly and after 18 wk, the barrels were drained, the soil cores were dissected, and the redoximorphic features were described. The mesocosms treated with Fe and Fe + OC generated the greatest amount of redoximorphic features (21.9 and 23.0%, respectively). In contrast, the OC-treated and control mesocosms produced minimal redoximorphic features (0.16 and 0.08%, respectively). According to the results of this study, the addition of Fe and the accompanying acidifying conditions allowed for the development of redoximorphic features and therefore is responsible for their absence in situ. The field identification of carbonatic hydric soils will require the use of an alternative field indicator beyond soil morphological indicators.

Abbreviations: Eh, redox potential; IRIS, Indicator of Reduction in Soils; OC, organic C; OM, organic matter; PVC, polyvinyl chloride.

In the western continental United States, freshwater wetlands occupy less than 3% of the land surface but provide innumerable ecosystem services, including acting as wildlife habitat, cycling nutrients, mediating groundwater and surface hydrology, storing C, and providing biodiversity (United States Geological Survey, 1996). Despite the importance of these ecosystems, wetlands are being converted to nonwetland ecosystems through many pathways, including urban and rural development as well as conversion to agriculture and forested plantations, among others. To ensure the proper identification of wetlands, a three-parameter approach is employed to identify wetland hydrology, hydrophytic vegetation, and hydric soils (United States Army Corps of Engineers, 1987).

Wetland hydrology is observed through water being present at or near the soil surface at some time during the growing season and hydrophytic vegetation includes macrophytic plants typically adapted for life in saturated soil conditions (United States Army Corps of Engineers, 1987). Hydric soils are defined as "...soils formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part" (Soil Survey Staff, 2015). The major soil morphological features used to indicate anaerobic conditions are (i) the accumulation of organic matter (OM) through slow decompo-
The accumulation of OM is used as an indication of anaerobiosis because the rate at which soil microbes decompose OC is considerably lower in a saturated and anaerobic environment than under aerobic conditions. Therefore, in saturated soils, partially decomposed OM may accumulate (Soil Survey Staff, 2015). Redoximorphic features form as a result of soil microorganisms using alternative electron acceptors when anaerobic conditions persist long enough that oxygen is depleted. The order in which electron acceptors are used after oxygen is exhausted is: \(\text{NO}_3^- \rightarrow \text{Mn}^{4+} \rightarrow \text{Fe}^{3+} \rightarrow \text{SO}_4^{2-} \rightarrow \text{finally CO}_2\) (Vepraskas and Craft, 2016). Under anaerobic conditions, soil microorganisms reduce ferric iron (Fe\(^{3+}\)) to ferrous iron (Fe\(^{2+}\)) [Eq. 1], subsequently oxidizing OM [Eq. 2].

\[
\text{Fe}^{3+} + e^- \leftrightarrow \text{Fe}^{2+} \quad [1]
\]

\[
\text{CH}_3\text{O} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + 4e^- + 4\text{H}^+ \cdot [2]
\]

Because of the distinctive color and ubiquity of Fe, a reduction of Fe leading to the formation of hydromorphological features is typically the most visible and abundant evidence of reduction throughout the soil profile. Therefore, Fe redoximorphic features are used to visually confirm anaerobic conditions (Vasilas et al., 2017).

The field indicators of hydric soils are used as a proof-positive test to determine if hydric soils are present (National Technical Committee for Hydric Soils, 2007). Under some conditions, these indicators of hydric soils do not form despite the presence of an anaerobic reduced soil environment. These soils are considered “problematic” because of issues related to their field identification as hydric soils. Studies have explored problematic hydric soils by documenting their hydrology, vegetation community, and redox status (e.g., Vepraskas and Sprecher, 1997).

Situations arise where hydroporphic vegetation and wetland hydrology requirements are met but field indicators of hydric soils are not. Reasons for this discrepancy range widely, from cold temperatures and mineralogical barriers to the soils being newly developed, among others (Vepraskas and Craft, 2016; Vepraskas and Sprecher, 1997). An example of newly developed soils that do not exhibit traditional hydric soil indicators are floodplain soils (Lindbo, 1997; Castenson, 2004). As a result of frequent flooding, soils experience regular depositions of material on the soil surface, consequently restarting soil formation and not allowing adequate time for redoximorphic features to form (Vepraskas and Craft, 2016). Specific mineralogical conditions may also inhibit the formation of redoximorphic features. Research conducted on problematic soils derived from red parent material revealed that the crystallite sizes of hematite influenced the propensity of the soil to change color in response to a reducing environment (Mack et al., 2019). Another study explored anomalous bright loamy soils along the coastal plain of Maryland that did not possess soil morphological features in equilibrium with their hydrologic condition (Zurheide, 2009). These anomalous soils had not developed adequate redoximorphic concentrations or depletions to meet any of the hydric soil field indicators, despite maintaining wetland hydrology and hydrophytic vegetation.

In southwestern Wyoming, highly calcareous (>70% CaCO\(_3\)) by weight) soils with high color values and low color chromas have been described and documented (Fig. 1). These calcareous landscapes meet the wetland criteria for hydrophytic vegetation and hydrology; however, because no field indicators of hydric soils have been observed, these areas cannot be delineated as wetlands by standard techniques (Malone and Williams, 2010). Although wetlands only occupy 3.8% of the land in Sublette County, these areas are critical in providing valuable ecosystem services, including water storage and flood abatement, C sequestration, and providing a wildlife habitat among others. Of the areas mapped as hydric soils, 13.5% of these are characterized as having a carbonatic mineralogy class or more than 40% CaCO\(_3\) or gypsum by weight in the fine-earth fraction (Fig. 1).

To perform accurate hydric field identification of highly calcareous hydromorphic soils, the objectives of this study were (i) to determine and document the hydric status of these soils, (ii) to identify the limiting factor(s) in the development of redoximorphic features in highly calcareous soils, and (iii) to create an environment that encourages the formation of redoximorphic features by amending them with Fe, OC, or both (Fe + OC). We hypothesize that these soils are, in fact, hydric and the low inherent OC and or Fe content prevents the formation of the visible Fe redoximorphic features traditionally used in hydric soil determinations. To further explore this, we developed and performed a mesocosm study to create a synthetic environment in which these features could form.

**METHODOLOGY**

**Study Site Establishment**

A study site containing highly calcareous hydromorphic soils was identified with the assistance of NRCS soil scientists, approximately 15 km northwest of Daniel, WY (Fig. 1). The site is located at 2265 m.a.s.l. with a mean annual temperature of 1.1°C (cryic) and mean annual precipitation of 33 cm (aridic) (USDA-NRCS, 2018). The soils at the site are classified as Toddhole (fine-loamy over sandy or sandy-skeletal, carbonatic over mixed, superactive Typtic Cryaquepts), Whehigh (fine-loamy over sandy or sandy-skeletal, carbonatic over mixed, superactive, frigid Fluvaquentic Endoaquepts), and Whelan (fine-loamy over sandy or sandy-skeletal, carbonatic over mixed, superactive, frigid Fluventic Aquicambids).

The criteria used to select the study site included: moist soil matrix color values of 7, moist soil matrix color chromas of 2, strong effervescence on application of 1 M HCl (indicative of high carbonate presence), evidence of inundation with water near the surface (overland flow, water-stained leaves, surface crusting, etc.), and no evidence of redoximorphic features or significant OM accumulation in the upper 50 cm. Upon site confirmation, a soil profile was excavated by hand to 1 m, described according to standard techniques, and sampled by morphological
horizons (Schoeneberger et al., 2012; Soil Survey Staff, 2014).

Vegetation Transects

The line–point intercept method was used on two transects within the study site (Coulloudon et al., 1999). The line–point intercept is conducted with vertical linear measurements of plant intercepts along the course of a line. This method measures composition (by cover), foliar, and basal cover (Coulloudon et al., 1999). Transects 100 m long were used with intercept points every 1 m. The absolute cover percentage of the vegetation species was calculated by taking the frequency of a species and dividing it by the total number of intercept points along the transect (Coulloudon et al., 1999). The absolute cover percentage is used to determine whether the vegetation species is the dominant species for the site and thus determine whether the hydrophytic vegetation indicators are met (United States Army Corps of Engineers, 2010). Indicator 1 (dominance test) requires 50% of the dominant plant species to have the indicator status of obligate, facultative wet, and/or facultative. Absolute cover is also used for Indicator 2 (prevalence index), which is an average based on a weighted index of the plant species indicator status (United States Army Corps of Engineers, 2008).

![Fig. 1.](image1.png)

**Fig. 1.** (a) Study site location in western Wyoming. (b) Soil profile (fine-loamy over sandy or sandy-skeletal, carbonatic over mixed, superactive Typic Cryaquepts) adjacent to where the mesocosms cores were removed, shown with the corresponding landscape view. (c) The distribution of nonhydric and hydric soils with 13.5% of all hydric soils mapped in Sublette County being classified as calcareous hydric soils (all map units with Toddhole, Whehigh, and Whelan series as a major or minor component) in the carbonatic mineralogy class (USDA-NRCS, 2018; Soil Survey Staff, 2015).

![Fig. 2.](image2.png)

**Fig. 2.** (a) Study site layout schematic showing the slotted groundwater monitoring well with the pressure transducer, indicator of reduction in soil (IRIS) tubes, and the location of the soil profile description. (b) The mesocosms’ extraction site and vegetation transects are shown in a planar view across the site surface.
Drilled into the center of the bottom of each cap to allow for water movement. The caps were then placed back onto the bottom of the cores to ensure the soil remained in place once saturated.

Each mesocosm was secured by perpendicular cam straps into 75.7-L barrels measuring 66.4 cm tall with a diameter of 36.2 cm at the top and 32.4 cm at the bottom. Dechlorinated tap water was added to each barrel to bring the water level to 2.5 cm above the top hole drilled onto the side of the core. The water level was maintained at this level through weekly additions of dechlorinated tap water. Within each block, a temperature sensor connected to a data logger (HOBO Pro v2 2x External Temperature Data Logger, Onset Computer Corporation) was installed to monitor the temperature to account for any possible gradient.

Mesocosms were arranged into four completely randomized blocks. Each block was amended with Fe (FeCl₃), OC (C₆H₁₂O₆, dextrose), or Fe+OC (FeCl₃ and dextrose). Three mesocosms were not amended and served as controls (Block 4 did not contain a control). The Fe-treated mesocosms were amended with 2% Fe per unit weight of the soil in the core or 1.3 g L⁻¹ as FeCl₃. The 2% per unit weight was established as a higher-end estimate of the Fe contents commonly observed in Wyoming soils to ensure that Fe would not be a limiting factor in the formation of redoximorphic features (Bayer, 1992). The OC-treated mesocosms were amended with 36 mg L⁻¹ dextrose as the OC source, whereas the mesocosms treated with OC and Fe were amended with 2% Fe as FeCl₃ and 36 mg L⁻¹ dextrose. The amendments, by treatment, were thoroughly mixed into the dechlorinated tap water used to saturate the mesocosms.

**Oxidation–Reduction Potential and pH Monitoring**

Oxidation–reduction (redox) potential was measured weekly in the upper 10 cm of each soil core with Pt-tipped electrodes, AgCl reference electrodes, and a research grade voltmeter (Orion, ThermoFisher Scientific, Waltham, MA). Platinum-tipped and reference electrodes were implanted and removed weekly into the same pilot hole to reduce the disturbance within the mesocosms. Oxidation–reduction potential readings were measured weekly in Light's solution (Light, 1972) to ensure the accuracy of the equipment. The redox potential measurements were corrected by adding 250 mV to the measured value to account for the use of the AgCl reference electrode (0.6 mol kg⁻¹ KCl). Soil pH was also measured directly in the soil cores at the same intervals. The pH measurements were used to determine the redox potential (Eh) required to indicate anaerobic conditions via the National Technical Committee for Hydric Soils (2007) Technical Standard equation:

\[ \text{Eh} = 595 - 60 \times \text{pH}. \]  

Any redox potential voltage recorded below the Eh calculated via Eq. [3] was considered to be reduced with respect to Fe and met the criteria to be considered a hydric soil (National Technical Committee for Hydric Soils, 2007).
Mesocosm Soil Descriptions

After 18 wk of inundation, the barrels were drained and the residual water in the mesocosms cores was allowed to drain for 12 h. To open the mesocosms, cores were placed into a vice and the end cap was removed with a hammer and punch. A circular saw was then used to cut lengthwise down two sides of the PVC pipe. Half of the PVC pipe was removed and the soil was photographed immediately. The soil cores were described in 5-cm increments, with special attention given to document matrix color and the amount, color, type, and contrast of redoximorphic features (Schoeneberger et al., 2012). Alpha-α-dipyriyl strips were applied to each 5-cm section of core to test for the presence of reduced Fe.

Laboratory Analyses

Inorganic C analysis was conducted via the gravimetric method for loss of CO₂ (Loeppert and Suarez, 1996). Loss on ignition analysis to determine organic C content was conducted by following the standard procedure of combustion at 400°C for 16 h (Soil Survey Staff, 2014). Mineral content and OM content were calculated. To convert OM to OC content, the percentage of sample weight lost on combustion was divided by 1.72, with this conversion assuming that OM contains 58% OC (Soil Survey Laboratory Staff, 2004). Soil pH and electrical conductivity analyses were conducted on replicates of five samples via the 1:2 soil/water method (Soil Survey Laboratory Staff, 2004).

Total elemental analyses were performed on untreated soil horizons. All samples were ashed at 500°C to remove OM, fused with Li-metaborate, dissolved in dilute HNO₃, and analyzed for a suite of elements, including Fe and S, by inductively coupled plasma spectroscopy at ACME Analytical Laboratories Ltd. (Vancouver, BC, Canada). Total C and N were measured by dry combustion (Nelson and Sommers, 1996). Internal standards, blind standards, and duplicates were analyzed for quality control.

Statistical Analyses

The experimental design was a completely randomized block design with four treatments in each block, including a control (except Block 4). The data were analyzed with SAS University Edition via the PROC MEANS procedure (SAS Institute Inc., 2017). The Fe concentration means by treatment from the mesocosms descriptions were then compared via Tukey’s post-hoc test.

RESULTS AND DISCUSSION

Documentation of Wetland Hydrology

The groundwater table was within 25 cm of the soil surface for 73 consecutive days, from 11 Mar. 2017 to 15 May 2017 and 87 cumulative days between March and June (Fig. 3, Fig. 4b). According to the technical standard for hydric soils, soil saturation must occur within 25 cm of the soil surface for at least 14 consecutive days (National Technical Committee for Hydric Soils, 2007). Therefore, the hydrology of this site meets these requirements and reinforces the presence of wetland hydrology. The water temperature measured during the period of continuous saturation ranged from 2.1 to 5.8°C, with a mean of 3.2°C (Fig. 3). During the warmest 14-d period, the mean temperature was 5.4°C (Fig. 3), greater than the value established for the growing season (Rabenhorst, 2005; United States Army Corps of Engineers, 1987), which is linked to the concept of biological zero. This is, theoretically, the soil temperature (5°C) at 50 cm below the surface in which the growth and function of locally adapted plants are negligible (e.g., Rabenhorst, 2005; Weil and Brady, 2017).

Presence of Hydrophytic Vegetation

Analyses of the vegetation transects performed met Indicator 1 (the dominance test) for hydrophytic vegetation with more than 50% of the dominant plant species being obligate, facultative wet, or facultative (United States Army Corps of Engineers, 2010) (Supplemental File S1). Transect 1 had 67% of the dominant species meeting the requirements for Indicator 1, whereas Transect 2 had 100% of the dominant species meeting the requirements for Indicator 1 (Supplemental File S2). The vegetation transects also met Indicator 2 (prevalence test) for hydrophytic vegetation with a prevalence index of <3.0 (United States Army Corps of Engineers, 2010) (Supplemental File S1 and Supplemental File S2). Transect 1
had a prevalence index of 2.9, whereas Transect 2 had a prevalence index of 1.9 (Supplemental File S1 and Supplemental File S2). With the vegetation meeting the requirements to qualify as hydrophytic, this further supports the wetland classification at this site.

**Field Hydric Soil Confirmation**

The IRIS tubes removed from the study site met the Technical Standard for Hydric Soils with greater than 30% Fe removal within the upper part (Fig. 4a) (Castenson and Rabenhorst, 2006; National Technical Committee for Hydric Soils, 2007). A mean of 57% Fe was reduced and removed from the upper 30 cm of the five IRIS tubes, indicating the soil environment was conducive to Fe reduction during the time the tubes were installed. As stated above, the mean temperature for the period, the IRIS tubes were deployed was 3.2°C, with the warmest 14-d period being 5.4°C (Fig. 3). Despite this favorable, albeit cool, environment for facilitating Fe reduction, redoximorphic features did not develop in the soil matrix (Table 1). However, by meeting the technical standard for IRIS tubes, these soils qualify functionally as hydric.

**Morphological, Physical, and Chemical Soil Properties**

The soils described on-site and cores collected from the study site comprised a thin Ak over three Bk and one Ck horizons (Table 1). Colors were white and light gray, with strong reaction to 1 M HCl while moist. Textures throughout were silty clay loams with weak granular and weak and moderate subangular blocky structures. No redoximorphic features were observed throughout the soil profile. Within the Bk3 and Ck horizon, some CaCO₃ cementation was observed. No field indicators of hydric soil were met (Vasilas et al., 2017).

Electrical conductivity values recorded indicated a nonsaline classification (Schoeneberger et al., 2012; Soil Survey Staff, 2014) with an average of 201.5 µS m⁻¹ (Table 1). The pH of the soils from this site resulted in a classification as moderately alkaline (Schoeneberger et al., 2012; Soil Survey Staff, 2014), with mean pH values of 8.4 (Table 1).

The elemental data support the hypothesis that Fe may be a limiting factor for redoximorphic feature development, with both the upper two horizons having a low concentration of total Fe at 5.7 and 6.0 g kg⁻¹, respectively (Table 1) compared with the typical range of total Fe in this area of Wyoming, which is 20 to 50 g kg⁻¹ (Shacklette and Boerngen, 1984). The OC ranged from 0.17 to 0.21 g kg⁻¹ (Table 1), which is far below the typical OC content for sagebrush steppe, which ranges from 11 to 21 g kg⁻¹ (Norton et al., 2004). The low amount of OC also leans toward the possibility that OC could be limiting microbial activity, preventing the microbially mediated transformation of Fe.

Inorganic C and CaCO₃ were approximately 90.1 and 750 g kg⁻¹, respectively. The extremely high amounts of CaCO₃, which resulted in alkaline soils can impact Fe availability (Hochmuth, 2011). As pH increases by 1 unit (above a

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**Table 1. Morphological, physical, and chemical soil properties from the highly calcareous study site profile†.**

| Horizon | Depth Boundary | Color‡ | Texture | Structure | pH | EC µS m⁻¹ | OC g kg⁻¹ | IC g kg⁻¹ | CaCO₃ g kg⁻¹ | Fe g kg⁻¹ | S
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<tr>
<td>Ak</td>
<td>0–7</td>
<td>A-S</td>
<td>10YR 7.5/1</td>
<td>SICL 1</td>
<td>GR ST</td>
<td>8.4</td>
<td>201.5</td>
<td>0.21</td>
<td>89.7</td>
<td>747.8</td>
<td>5.7</td>
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<tr>
<td>Bk1</td>
<td>7–30</td>
<td>C-S</td>
<td>10YR 8/1</td>
<td>SICL 2</td>
<td>SBK ST</td>
<td>8.4</td>
<td>198.2</td>
<td>0.17</td>
<td>93.4</td>
<td>778.4</td>
<td>6.0</td>
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<tr>
<td>Bk2</td>
<td>30–48</td>
<td>C-S</td>
<td>10YR 7/1</td>
<td>SICL 1</td>
<td>SBK ST</td>
<td>8.5</td>
<td>200.5</td>
<td>0.15</td>
<td>93.8</td>
<td>781.4</td>
<td>6.1</td>
</tr>
<tr>
<td>Bk3</td>
<td>48–61</td>
<td>A-S</td>
<td>10YR 7/2</td>
<td>SICL 1</td>
<td>SBK ST</td>
<td>8.6</td>
<td>199.1</td>
<td>0.14</td>
<td>94.1</td>
<td>784.3</td>
<td>6.3</td>
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<tr>
<td>Ck</td>
<td>61+</td>
<td>–</td>
<td>10YR 7/6</td>
<td>SICL 1</td>
<td>SBK ST</td>
<td>8.8</td>
<td>196.4</td>
<td>0.11</td>
<td>95.1</td>
<td>792.2</td>
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† The taxonomic classification of this soil is fine-loamy over sandy or sandy-skeletal, carbonatic over mixed, superactive Typic Cryaquepts. Soil cores were collected for the mesocosm study within 1 m of this profile. Note that redoximorphic features were absent from this profile and the cores extracted for the mesocosm study. A, abrupt; S, smooth; C, clear; SICL, silty clay loam; 1, weak; 2, moderate; GR, granular; SBK, subangular blocky; ST, strongly reactive; EC, electrical conductivity; OC, organic C; IC, inorganic C.

‡ Moist color.
§ Effervescence (efferv): reaction with 1 M HCl.
pH of 6), the availability of Fe\(^{3+}\) decreases 1000-fold as a result of the formation of Fe(OH)\(_3\), which is unavailable to the soil microbes (Hochmuth, 2011). This is especially important for redoximorphic feature formation, since there is less available Fe for anaerobic microbial respiration. Without the available Fe, the Fe\(^{3+}\) cannot be reduced to Fe\(^{2+}\), mobilized and reorganized into soft masses or pore linings, nor form visible redoximorphic features. The high pH, high CaCO\(_3\) composition, and low total Fe content resulted in an environment where Fe redoximorphic feature formation was inhibited.

**Laboratory Mesocosm Experiment**

**Oxidation–Reduction Potential and pH**

Weekly pH measured in each core over an 18-wk period illustrated a steady decline over time with the mesocosms treated with Fe reaching an overall lower pH (Supplemental File S3). Within the Fe-amended cores, the pH values recorded throughout the 18-wk duration were substantially lower because of the following reaction:

\[
2\text{FeCl}_3 + 3\text{H}_2\text{O} \rightarrow \text{Fe}_2\text{O}_3 + 6\text{HCl},
\]

with the production of HCl drastically lowering the pH.

The corrected weekly Eh values relative to the technical standard line [Eq. 3] for each treatment are shown in Fig. 5. By Week 2, the Eh values recorded in all of the mesocosms were below the technical standard (0 mV in Fig. 5) for hydric soils, indicating anaerobic conditions (dashed line in Fig. 5) (National Technical Committee for Hydric Soils, 2007). The zone of expected Fe reduction and S reduction in Fig. 5 are shown as the orange and gray zones, respectively (Vepraskas and Craft, 2016). All measurements recorded after Week 2 were plotted as falling in either of these two zones or below. By Week 18, the mesocosms amended with Fe (Fe and Fe + OC) were more highly reduced, with values falling below the predicted sulfate–sulfide stability line (Fig. 6), where the control and OC-amended mesocosms were reduced with respect to Fe as both goethite and ferricydrite (Fig. 6).

A positive reaction to the application of \(\alpha\)-alpha-dipyridyl strips was observed as a faint to bright pink color in all cores at all depths, except several of the upper 0- to 15-cm sections in the control and OM-amended cores. Despite the low concentration of Fe in these cores, there was evidence of Fe reduction in the majority of the profile.

**Redoximorphic Feature Formation**

After allowing the mesocosm cores to drain for 12 h, the morphological descriptions revealed that the mesocosms treated with Fe and Fe + OC showed a mean of 21.4 and 22.6% for the distinct and prominent Fe concentrations, respectively, on the surface of the soil core (Fig. 7a). In contrast, the control and the mesocosms treated with only OC showed a mean of 0.05 and 0.16% distinct and prominent Fe concentrations, respectively.
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on the outer surfaces (Fig. 7a). Regarding the formation of these redox concentrations, it is important to note that the addition of FeCl₃ in a high-pH environment may have been sufficient to induce precipitation of already oxidized Fe in the added solution.

The presence of FeS concentrations was observed within the cores amended with Fe, with a mean of 1.5 to 2.8% in the Fe and Fe + OC treatments, respectively (Fig. 7b, c). These soils contain relatively high levels of total S (0.3–0.4 g kg⁻¹) compared with the other soils mapped in the region (<0.1 g kg⁻¹) (Shacklette and Boerngen, 1984), possessing conditions conducive to monosulfide formation. The formation of FeS indicated a highly reduced environment that was predicted from the measured Eh and pH (Fig. 5 and Fig. 6). Upon exposure, 3% H₂O₂ was applied to the black FeS coatings and a color change (loss of black pigment) occurred immediately, proving these zones were, in fact, FeS.

There was no significant block effect (p > 0.05) observed for redoximorphic feature formation. The mean soil temperature within the four blocks over the 18-wk period was 23.6°C and showed no difference among blocks.

Limitations to Redoximorphic Feature Formation

On the basis of the formation of redoximorphic features after the 18-wk incubation, it is clear that Fe in the natural setting is limiting the development of both Fe oxy-hydroxide concentrations and FeS concentrations under native conditions. The cores amended with Fe (Fe and Fe + OC) showed significantly (p > 0.05) higher concentrations than the other treatments (Fig. 7). We observed no difference in redox feature formation for the cores treated with Fe and OC compared with Fe only, indicating that C is not limiting microbial activity.

The mesocosms were located in a controlled laboratory environment with a mean temperature of 23.6°C, nearly 20°C warmer than the field measurements (Fig. 6). The Eh measurements were corrected by adding 250 mV to the measured value to account for the use of the AgCl reference electrode. Stability lines indicate the predicted phase of Fe as ferrihydrite and goethite (oxidized: above the Fe³⁺ line; reduced: below the Fe²⁺ line), sulfate versus sulfide (oxidized: above the line; reduced: below the line), and the National Technical Committee for Hydric Soils Technical Standard [Eh = 595 – 60(pH)], where the measurements that fall below this line meet the criteria for anaerobic conditions (National Technical Committee for Hydric Soils, 20075).

Fig. 6. Corrected oxidation–reduction (Eh) and pH measurements from the mesocosms in the final week of the study (Week 18). The Eh measurements were corrected by adding 250 mV to the measured value to account for the use of the AgCl reference electrode. Stability lines indicate the predicted phase of Fe as ferrihydrite and goethite (oxidized: above the Fe³⁺ line; reduced: below the Fe²⁺ line), sulfate versus sulfide (oxidized: above the line; reduced: below the line), and the National Technical Committee for Hydric Soils Technical Standard [Eh = 595 – 60(pH)], where the measurements that fall below this line meet the criteria for anaerobic conditions (National Technical Committee for Hydric Soils, 20075).

Fig. 7. (a) Iron oxide and (b) FeS concentrations described by treatment type on soil cores. Box plots show median values (solid horizontal line), 50th percentile values (box outline), 90th percentile values (whiskers), and outlier values (circles, data falling outside 1.58 times the interquartile range above or below the upper or lower quartile). (c) Representative images of the cores from each treatment group, showing an example of a FeS concentration (black color, x) and an iron oxide concentration (orange color, o).
higher than the soil temperature at the time when the field site is seasonally saturated. Low temperatures slow microbial activity and may contribute to the lack of redoximorphic features. In the nonamended control mesocosms, redoximorphic features did not form, proving that cold temperature alone is not responsible for the lack of features in situ.

The pH recorded in the mesocosms varied considerably between the control and OC-amended cores, and the Fe- and Fe + OC-amended cores. This change in acidity altered the environment to allow for the formation of Fe redoximorphic features. Because these two variables (pH and Fe content) changed in tandem, the decrease in pH alone cannot be credited for the ability of these soils to form redoximorphic features. A future experiment should examine the addition of an alternative Fe source that would not also result in strong acidification. An objective of this study was to prove that redoximorphic features can form under synthetic conditions. This project has demonstrated that anaerobic or reducing soil conditions exist that do not necessarily give rise to the formation of typical hydromorphological features. The addition of Fe in two sets of the mesocosms resulted in high amounts of Fe-based redoximorphic features forming in a short amount of time (18 wks). Both Fe oxy-hydroxides and FeS formed, further demonstrating that a reduced anaerobic environmental was generated. To identify anaerobic conditions in the field in these highly calcareous hydric soils, an alternative demonstration of reduction, such as IRIS devices or α-alpha-dipyridyl must be used.

CONCLUSIONS

The highly calcareous soils forming under wetland conditions examined in this study show no observable evidence of redoximorphic features or other field indicators of hydric soils. Despite maintaining wetland hydrology, hydrophytic vegetation, and reduced soil conditions measured via IRIS tubes, these soils did not develop morphological features indicative of wet, anaerobic conditions. Upon extraction from the field and after 18 wk of inundation at ~25°C, the soil within the mesocosms showed significant differences in redoximorphic feature formation between mesocosms treated with Fe (Fe and Fe + OC) and those that were not amended with Fe (OC and control). There were no significant differences in redoximorphic feature formation between the mesocosms amended with the OC and the control mesocosms.

Reduction was measured directly via Eh and pH measurements and was specifically observed by the formation of FeS in the mesocosms amended with Fe, indicating the creation of the reduced environment required in hydric soils. Through this study, it was demonstrated that redoximorphic features can form in these soils, but not without the addition of Fe. We determined that the limiting factor for the development of redoximorphic features is the presence of available Fe, coupled with the formation of a more acidic environment. The low total Fe concentration (<0.6 g kg⁻¹) in these soils was responsible for the lack of visible features that could be used to identify hydric soils in the field.

With no typical soil morphological features to indicate anaerobic conditions, an alternate field indicator must be used to identify these areas as hydric soils. In addition to the use of IRIS tubes and/or the application of α-alpha-dipyridyl dye, we propose the following as a working concept specific to Major Land Resource Area 34A (Cool Desertic Basins and Plateaus): (i) dominant matrix colors with a value of ≥5 and a chroma of ≤2 from the soil surface to a depth of ≥30 cm; (ii) strong or greater effervescence after the application of 1 M HCl within 30 cm of the soil surface; and (iii) the sites observed under this indicator require either the presence of hydrophytic vegetation and wetland hydrology indicators or a positive reaction to α-alpha-dipyridyl dye. A user note should be added, stating that this indicator should be limited to use in riparian floodplains and depressional landforms, unlike Indicator F3, which excludes calcic horizons without the presence of redoximorphic features and requires the presence of CaCO3, though not necessarily pedogenic in origin (Vasilas et al., 2017).

Problematic hydric and hydromorphic soils present unique challenges in many environmental settings and require detailed examination of the conditions to ensure that all wetland parameters are met and the sites are properly functioning as wetlands. In arid climates, proper wetland identification and delineation is of utmost importance because of the relatively small area wetlands occupy in these regions and their ecological value.

SUPPLEMENTAL INFORMATION


CONFLICT OF INTEREST DISCLOSURE

The authors declare that there is no conflict of interest.

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REFERENCES
