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A comparison of soil properties observed in farmed, restored and natural closed depressions on the Des Moines Lobe of Iowa

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ABSTRACT

Extensive artificial soil drainage systems, including subsurface tiles and surface ditches, have been installed throughout the agricultural Midwest to remove excess water from perennially wet soils. Factors of soil formation, such as soil climate and biota, have been substantially altered by artificial drainage and the associated land use change. Efforts to restore wetlands are ongoing but success has been limited in some cases. The objectives of this study were to 1) quantify alterations of wetland soils due to artificial drainage in the recently glaciated, Des Moines Lobe region of north-central Iowa; and 2) compare physical and chemical soil properties of farmed (artificially drained) wetlands to those undergoing restoration efforts and those considered natural (undrained). Wetlands in thirteen Des Moines Lobe closed depressions were sampled during this study representing three distinct populations: farmed, restored and natural soils. There were distinct visual differences in soil morphological properties between farmed and restored wetlands and farmed depressions had significantly higher soil nutrients (NO_3, P and K). Fewer differences were noted between restored and natural wetlands, implying that restoration of wetlands was returning soils to a more natural state in a relatively short time (15–20 years) compared to the time since they were initially drained (50–100 years). Study results suggest soil alteration due to artificial drainage and provide important context for establishing realistic timeframes for wetland soil restoration in closed depressions located on the Des Moines Lobe.

1. Introduction

Large scale subsurface drainage of wetlands on the Des Moines Lobe of Iowa began in the mid-19th century when the Swamp Land Acts were passed (Pavelis, 1987). These acts exchanged over 24 million hectares of public land from Federal to State ownership in order to enhance agricultural crop production (Committee et al., 1953). Extensive drainage systems, including subsurface tiles and surface ditches, were installed to remove excess water from perennially wet soils, beginning in earnest in the late 19th century and continuing today. In Iowa, up to 80% of some counties have had drainage systems installed (David et al., 2010). Subsurface drainage removes soil water via tile systems placed at depths of approximately 1.2 m and spaced at specific intervals typically from 24 to 30 m apart (Singh et al., 2006). Drainage is considered necessary by many in the agriculture industry to allow earlier field operations, reduce yield variability and maximize crop yields in soils that are intermittently to perennially wet (Nolte and Duvick, 1985; Schilling et al., 2012).

Due to drainage of wetlands, factors of soil formation, such as soil climate and biota, have been altered. Soil climate is defined by Jenny (1941) as a function of several meteorological and pedo-climatic properties including soil moisture and soil temperature. When soils are drained, faster soil warming is observed due to the differences in specific heat of water and soil (Manu and Schafer, 2003). Increased soil temperatures allow for longer growing seasons. Aerobic and anaerobic microorganisms also play a crucial role in soil formation, regulating nutrient cycles of carbon, nitrogen, phosphorus, sulfur and iron (Gambrell and Patrick, 1978). Microbial populations have been altered due to oxidation of naturally wet soils, as aerobic microbes are favored over the anaerobic microbes. Lindsay and Schwab (1982) note that in well drained soils iron (Fe) precipitates as Fe_3^+ which can then become insoluble in high pH soils, readily combining with calcium carbonate and saline salts and becoming unavailable to plants. In contrast, in poorly drained soils, iron is reduced from Fe_3^+ to soluble Fe_2^+ and translocated through the soil profile freely becoming readily available to plants. Soil organic carbon concentration is also effected by drainage and the associated land use change specifically in relation to soil aggregate changes and decomposition through oxidation (Kay and Lal, 1998). Hence, with artificial drainage, natural cycles have been disrupted and decomposition of organic matter has been accelerated (Holden et al., 2004; Wallage et al., 2006).

Wetland restoration is a process of preserving, restoring and enhancing wetlands (Ewing et al., 2012). This process has had limited success (Zedler, 2000), with restoration attempts often found to be

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unsatisfactory in terms of hydrologic quality. Examples of poor hydrologic quality include insufficient nutrient levels for flora, lack of organic matter accumulation and high levels of nitrates and phosphorous in the soil and surface waters (Gallihugh and Rogner, 1998). Only 38% of wetland soil restoration efforts in the U.S. Midwest have been deemed a success (Wilson and Mitsch, 1996). While this statistic is somewhat dated, there is limited current research being conducted to analyze the process of soil restoration during wetland restoration efforts. Ballantine et al. (2012) observed that restoration processes that used amendments to enhance establishment of wetland flora and fauna often left key soil properties including carbon, nitrogen and bulk density, more altered than before restoration attempts. It is thus critical that soil properties are adequately characterized prior to implementing any restoration efforts. This will allow the effects of wetland restoration on soil properties to be more effectively analyzed.

The objectives of this study were to 1) quantify alterations of wetland soils due to artificial drainage in the recently glaciated, Des Moines Lobe region of north-central Iowa; and 2) compare physical and chemical soil properties of farmed (artificially drained) wetlands to those undergoing restoration efforts and those considered natural (undrained). This study serves to provide important context for establishing realistic timeframes for wetland soil restoration in closed depressions located on the Des Moines Lobe.

2. Materials and methods

The Des Moines Lobe landform region of Iowa was glaciated until 12,000 years ago by the Wisconsin glaciation (Ruhe, 1969). Most Des Moines Lobe soils formed in glacial drift and/or local alluvium. The major soil association of the area is the Clarion (Fine-loamy, mixed, superactive, mesic Typic Hapludoll), Nicollet (Fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and Webster (Fine-loamy, mixed, superactive, mesic Typic Endoaquoll) (Soil Survey Staff et al., 2013a). The Des Moines Lobe represents the southernmost extension of the Prairie Pothole Region (PPR), a region that extends from Alberta, Canada and occupies more than 700,000 km^2. The PPR is dominated by hummocky topography that formed after ice melt of the Wisconsin ice sheet and contains many thousands of small, shallow closed depressions (Miller et al., 2009; Sloan, 1972). These depressions were the area of interest for this study.

For this study, a subset of histic and mineral soils from representative depressions were selected for detailed description and laboratory analysis, including Okoboji (Fine, smectitic, mesic Cumulic Vertic Endoaquoll), Palms (Loamy, mixed, euic, Mesic Terric Haplosaprist), Houghton (Euic, Mesic Typic Haplosaprist), Canisteo (Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll), Colo (Fine-silty, mixed, superactive, mesic Cumulic Endoaquoll), Brownton (Fine, smectitic, calcareous, mesic Vertic Endoaquoll) and Kossuth (Fine-loamy, mixed, superactive, mesic Typic Endoaquoll) soil series. Slopes for these depressional soils ranged from 0 to 6%. These soils developed under wet-site tall prairie grasses and marsh grasses. While the Des Moines Lobe is not a uniform landscape (Miller et al., 2009), wetlands chosen for this study were all located on till plains with parent materials of glacial till, local alluvium or organic materials.

Thirteen sample sites were selected for detailed study and split into three groups based on wetland type: undrained wetlands (natural), wetlands that had been drained and drainage tile was either removed or plugged 15–20 years before the study (restored), and wetlands that are currently tile drained and managed for row crop production (farmed). The term natural may have several different definitions. For this study, we sought to select natural wetlands that were considered as having never been drained, but could not rule out that farming may have been attempted at these sites prior to their incorporation into state land. However, these natural wetlands experience semi-permanent flooding which makes agricultural production without artificial drainage unfeasible. Many wetlands across the Des Moines Lobe are selected for restoration based on certain hydrologic qualities (Miller et al., 2012). For our study, we used soil map units (SMUs) as the basis for selecting farmed and restored wetland sites as the two wetland populations included similar SMUs (Soil Survey Staff et al., 2013b) which have been classified as experiencing temporary and semi-permanent flooding, respectively. Agricultural production on these SMUs would have necessitated installation of artificial drainage. Soil series including Okoboji, Houghton and Palms were equally represented among all three wetland types. The farmed wetlands contained four additional soil series (Colo, Canisteo, Brownton and Kossuth), but these soils were similar in terms of landscape position, parent material and hydrologic regime. Overall, the three wetland soil populations evaluated in our study (farmed, restored, natural) were comprised of both histic and mineral soils formed in closed depressions to ensure that the range of soil properties in each wetland type were represented in the comparisons. In this way, differences identified between wetland populations could be attributed to land use and the presence or absence of artificial drainage within the depression.

The number of wetlands sampled for this study varied among the three types. Three natural and three restored wetlands were selected, whereas the population of farmed wetlands totaled seven (Fig. 1). The farmed wetlands were previously selected as part of an ongoing project focused on hydrology, water quality, and avian use of temporary wetlands. For this project, six townships were selected randomly from the Des Moines Lobe region and within each township, digital elevation models (DEMs) (Iowa DNR, 2013) and SMU polygons (Soil Survey Staff et al., 2013b) were used to identify depressions that were at least 0.4 ha in area and at least 30 cm deep. The depression area was determined from the corresponding SMU polygon and depth was determined using the DEM to identify the maximum difference in elevation within the SMU polygon. Wetlands were selected that did not appear to be impacted by roads or farmsteads. Restored and natural wetlands were selected randomly from a database of state restoration complexes made available for this study.

At all study sites, a 2 m negative buffer was created around the perimeter of each wetland and within each buffered area, a randomized sampling pattern was generated using the “Create Random Points (Data Management)” tool to identify three random sampling points (Environmental Systems Research Institute, 2012). Soil core samples were collected to a depth of 100 cm using a hand auger. Soil profiles collected with a 2.5 cm hand probe at the time of sampling were described according to Schoeneberger et al. (2012). After characterization, soil core samples were composited into 20 cm sections and sent to a laboratory for chemical and physical analysis.

Soil samples were air dried and ground to pass through a 2 mm sieve. Analyses were performed in triplicate for quality assurance purposes. The following chemical analyses were performed according to Brown (1998): Phosphorus (P) was determined by weak Bray extraction methods. Neutral ammonium acetate extractable potassium (K), magnesium (Mg) and calcium (Ca) were determined using an inductively coupled argon plasma mass spectrometer. Organic matter (OM) was determined by weight loss on ignition. The pH was determined by using a 1:1 soil to water ratio and a glass electrode and nitrate nitrogen (NO_3) was determined by segmental flow analysis. Cation exchange capacity (CEC) was measured using the ammonium acetate saturation method (Page, 1982). Soil texture was determined using the pipette method (Soil Survey Staff et al., 2014).

SAS version 9.3 was used to perform all statistical analysis (SAS Institute, 2012). Statistical comparisons were made between each wetland group for each soil property by depth. Means were calculated using least square means in order to account for the unbalanced data set. These means estimate marginal means for a balanced population and can also be referred to as estimated population marginal means (SAS Institute, 2012; Searle et al., 1980). The Shapiro–Wilk test was used to test for normality. Pairwise correlations were determined using Pearson product moment correlations.

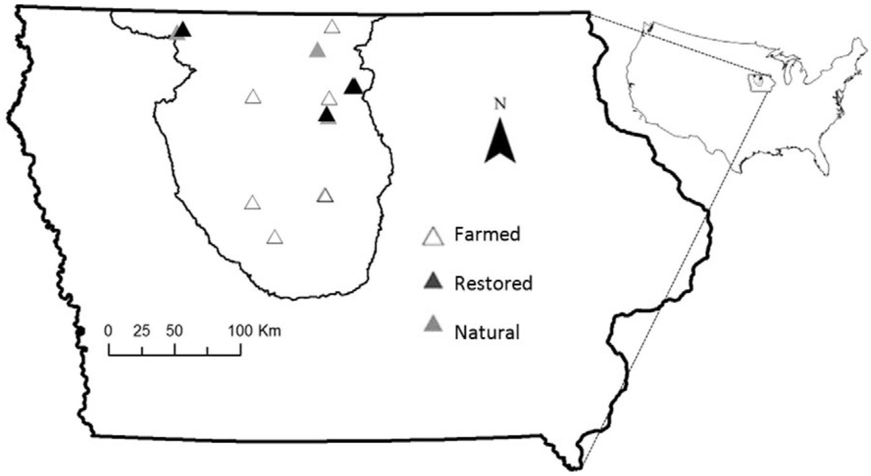

Fig. 1. Location of sample sites on the Des Moines Lobe of Iowa.

3. Results

3.1. Soil morphological properties

A comparison of soil morphological properties of a typical soil pedon characterized at each site is shown in Table 1. Histic and mineral soils were respectively similar between natural and restored wetlands with respect to soil horizon sequence, color, texture, structure and moisture. A plow layer evident in the restored wetlands was not observed in the natural wetlands. The plow layer was distinctly evident in the farmed wetlands as well as increased oxidation and drying of organic material. Farmed wetlands were shallower to the base of the A horizon and lighter soil colors were observed. Farmed wetlands were also characterized with a minimum depth to gleying below the O or A horizon. However, natural wetlands had evidence of gleying due to episaturation at the soil surface, whereas the restored wetlands had evidence of gleying due to endosaturation within the O or A horizon. Farmed wetlands contained Bw horizons within the top 100 cm, which were lighter in color and showed evidence of oxidation.

3.2. Comparison of wetland soil properties

Table 2 displays least square means soil property data for each defined soil depth by wetland type. Statistical comparisons were created to evaluate differences between wetlands at specific depths (Fig. 2). Significant differences were mainly associated with comparisons of

Table 1
Soil profile descriptions typical of mineral and histic soils within each wetland type.

Mineral soils			Histic soils		
Horizon	Depth (cm)	Description	Horizon	Depth (cm)	Description
Natural wetlands					
A1	0–52	Black (2.5/N) loam, weak fine granular structure; friable; clear boundary.	Oi	0–10	Black (2.5/N) fibric material; weak medium granular structure; clear boundary.
A2	52–82	Black (2.5/N) loam, weak fine granular structure; friable; gradual boundary.	Oa1	10–42	Black (2.5/N) sapric material; moderate medium granular structure; gradual boundary.
A3	82–100+	Black (2.5/N) clay loam, weak fine subangular blocky structure; friable.	Oa2	42–90	Black (10YR 2/1) sapric material; weak medium granular structure; clear boundary.
			Cg	90–100+	Gray (10YR 5/1) clay loam; massive; friable.
Restored wetlands					
Ap	0–22	Black (10YR 2/1) loam, weak fine granular structure; friable; abrupt boundary.	Oap	0–20	Black (10YR 2/1) sapric material; moderate fine granular structure; abrupt boundary.
A1	22–45	Black (2.5/N) loam, weak fine granular structure; friable; gradual boundary.	Oa1	20–45	Black (10YR 2/1) sapric material; weak medium granular structure; gradual boundary.
A2	45–70	Black (2.5/N) loam, weak fine subangular blocky structure; friable; gradual boundary.	Oa2	45–85	Black (10YR 2/1) sapric material; weak medium granular structure; abrupt boundary.
Bg	70–100+	Very dark gray (3/N) clay loam, weak fine subangular blocky structure; friable.	Cg	85–100+	Gray (10YR 5/1) clay loam; massive; friable.
Farmed wetlands					
Ap	0–25	Black (10YR 2/1) clay loam, moderate fine granular structure; friable; abrupt boundary.	Oap	0–22	Black (10YR 2/1) sapric material; weak medium granular structure; abrupt boundary.
A1	25–46	Black (10YR 2/1) clay loam, weak fine granular structure; friable; gradual boundary.	Oa1	22–39	Black (10YR 2/1) sapric material; weak fine subangular blocky structure; clear boundary.
A2	46–66	Black (10YR 2/1) clay loam, weak fine subangular blocky structure; friable; gradual boundary.	Oa2	39–75	Black (10YR 2/1) sapric material; weak medium granular structure; abrupt boundary.
Bw	66–80	Dark grayish brown (10YR 4/2) clay loam, moderate fine subangular blocky structure; friable; gradual boundary.	Cg	75–100+	Gray (10YR 5/1) clay loam; massive; friable.
Bg	80–100+	Very dark gray (3/N) clay loam, weak fine subangular blocky structure; friable.			

Table 2
Soil property least square means comparisons for each wetland type. Capital letters report significant differences ($p < 0.05$) between wetlands for each respective depth and soil property.

Depth (cm)	Extractable nutrients				NO_3	OM	pH	CEC	Clay
	P ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)	Ca ($mg\ kg^{-1}$)	($mg\ kg^{-1}$)	($g\ kg^{-1}$)		(meq 100 g^{-1})	($g\ kg^{-1}$)
Natural wetlands									
0–20	9A	74A	657A	6020A	8A	137A	7.0A	37A	130A
21–40	7A	32A	553A	5123A	8A	155A	7.1A	32AB	127A
41–60	8A	34A	443A	3993A	3A	87A	7.2A	24A	123A
61–80	4A	46A	393A	3568A	1A	52A	7.4A	21A	150A
81–100	4A	74A	436A	3596A	2A	60A	7.4A	22A	250A
Restored wetlands									
0–20	23A	161A	586A	4269B	13A	85A	7.3A	26B	137A
21–40	18AB	110A	572A	4349A	14A	80A	7.2A	26A	157A
41–60	19A	107AB	584A	4177A	14A	63A	7.4A	26A	133A
61–80	16A	114AB	592A	4061A	14A	62A	7.4A	25AB	130A
81–100	14A	118A	612A	4109AB	7A	52A	7.3A	26AB	167A
Farmed wetlands									
0–20	66B	339B	713A	5418AB	42B	79A	6.6A	36A	304A
21–40	48B	241B	699A	5508A	34A	82A	6.7A	35B	340A
41–60	36A	201B	685A	5456A	31A	83A	6.8A	35B	337B
61–80	22A	156B	660A	4856A	20A	67A	7.0A	31B	310A
81–100	19A	159A	672A	4586B	16A	49A	7.1A	29B	341A

natural and restored wetlands to the farmed wetlands. Differences in P, K, NO_3, CEC and clay content were evident in the farmed wetlands when compared to either natural or restored wetlands. When comparing natural and restored wetlands, the only significant differences were associated with Ca and CEC.

4. Discussion

4.1. Comparisons among wetlands

When comparing natural or restored wetlands to farmed wetlands, significant differences in soil nutrient levels were primarily associated with greater amounts applied to the farmed wetlands. Soil NO_3, P and K levels were significantly higher at the farmed wetlands due to fertilizer application in the row crop agriculture environment. In several cases, nutrient levels in farmed wetlands could be classified as either high or very high in comparison to optimum levels for environmental and plant health (Midwest Laboratories Inc., 2013). Using this same classification scheme, NO_3, P and K levels in natural wetlands were considered optimum or below. Decreasing NO_3-N concentrations in natural and restored wetlands may also be in part due to enhanced denitrification from resaturation of the organic rich wetlands (Neely et al., 1989). Although we do not have data to confirm this, we suspect that denitrification processes and lack of commercial nitrogen fertilizer are largely responsible for the low NO_3 concentrations in the restored and natural wetlands compared to the well-aerated and drained farmed wetlands

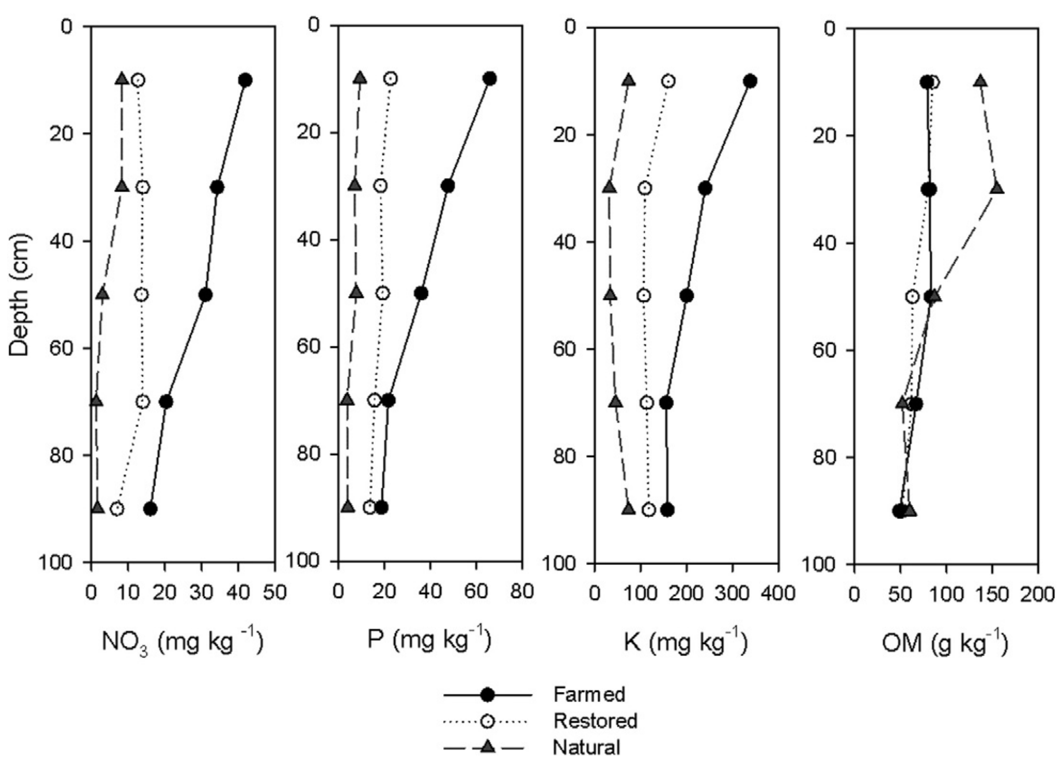

Fig. 2. Profile comparison of NO_3, P, K and OM content by wetland type.

(Galatowitsch and van der Valk, 1996). Hence, our results agree with Marton et al. (2014) who observed improved water quality and reduced soil nutrient levels in restored wetlands in Ohio.

Comparisons of soil properties were made by depth within each wetland type. In general, for natural and farmed wetlands, nutrient levels and CEC decreased with increased depth. No significant differences were identified when comparing restored wetland soil properties by depth. In the stable natural wetlands, long term pedogenesis translocated soil nutrient chemicals and weathered soil minerals within the profile (Biswas et al., 2012). Higher CEC and Ca found in natural wetlands may be due, in part, to increased OM content. In natural wetlands which are saturated most of the time, calcium carbonate and bicarbonate typically increase in the soil and thus contribute to changes in Ca content (Richardson et al., 1994). In farmed wetlands, soil morphological processes are heavily manipulated by humans. This observation agrees with Huang et al. (2007) who observed altered soil erosion, deposition and nutrient movement through the soil profile due to human impacts and with Tugel et al. (2005) who identified temporal variation in soil morphology due to both natural and anthropogenic pedogenesis.

Although differences in OM were statistically insignificant among the wetlands, mean levels of OM were almost double in natural wetlands compared to restored and farmed wetlands (Fig. 2). We can use a typical bulk density of the SMU reported by the Natural Resources Conservation Soil Survey Staff et al. (2013b) to estimate average organic carbon stock (kg/m^3) for each wetland type. Using this data, natural, restored and farmed wetlands would contain 161, 111 and 119 kg/m^3 of organic carbon, respectively. Bulk densities for each wetland were not measured in this study due to difficulties in measuring this property in highly organic and wet soils. however new methods are being developed to estimate bulk densities more reliably (Caldwell et al., 2005). Nevertheless, study results suggest that natural wetlands may contain 40 kg/m^3 more organic carbon.

We can look to the differences between farmed and natural wetlands to assess changes in soil properties due to long-term agricultural production. Soil differences that exist between farmed and natural wetlands can be explained by the development of aerobic soil environments within the farmed wetlands due to tile drainage and agricultural tillage (Richardson et al., 1994). When natural wetlands are artificially drained and farmed, oxidation of the soil alters the decomposition processes of soil flora and fauna (Kantrud et al., 1989). The introduction of annual rather than perennial crops affects rooting quantities and placement (Chantigny et al., 1997). Therefore, soil structure, color (due to mineral and organic oxidation), bulk density, infiltration and hydraulic conductivity are altered. Agricultural tillage creates structural discontinuities between the soil surface and subsurface thereby decreasing hydraulic conductivity at the base of the tillage operation (Euliss and Mushet, 1996). This process increases surface evapotransporation which in turn results in warmer soil surfaces and increased soil temperature fluctuations as well as increased decomposition of organic matter. This change in organic matter content can effect soil water retention (Rawls et al., 2003). Chemically, the soil is altered through the precipitation and decreased leaching of soil nutrients as well as alterations in weathering processes of soil minerals (Holden et al., 2004). These conclusions encourage further research to understand the anthropedogenic processes that occur in an agricultural environment over a very short geologic time scale. Ewing et al. (2012) noted that many of the chemical changes in drained organic soils were in part caused by the disappearance of Oi horizons which are composed of relatively undecomposed plant tissue. They go on to observe that total years of artificial drainage has a significant impact on soil fertility. In our study, farmed wetlands have likely been tile drained for 50 to 100 years (David et al., 2010).

Our results provide evidence that many physical and chemical soil properties in wetlands restored for 15 to 20 years are more closely related to natural wetlands than to farmed wetlands. Contrary to the expectations of Ewing et al. (2012), in which soluble phosphorous would increase due to the reduction of iron in anaerobic soil conditions, phosphorous levels at our restored wetlands were significantly lower at the soil surface and decreased throughout the soil profile. The phosphorous levels observed in restored wetlands were more comparable to levels observed in the natural wetlands than that of the farmed wetlands. These results also differ from those of Bruland et al. (2003) who observed that restoration did not show any apparent changes for most chemical soil properties due primarily to the intense alteration of the soil by agriculture. Even though restored wetlands were drained for an extensive period of time prior to restoration, study results suggest that several soil properties including deeper A and O horizons, shallower gleying, darker soil colors and less evident plow layers appeared to have developed over a period of restoration consisting of no more than 20 years. Despite similar chemical soil properties between natural and restored wetlands, evidence of human impacts on the soils morphology still exists implying that physical properties were slower to restore than chemical properties.

Table 3
Mean and standard deviation for soil properties by wetland type. Number of samples for each analysis for natural, restored and farmed wetlands are 3, 3 and 7, respectively.

Statistic	Depth (cm)	Extractable nutrients				NO3 (ppm)	OM (g kg^{-1})	pH	CEC (meq 100 g^{-1})	Clay (g kg^{-1})
		P (mg kg^{-1})	K (mg kg^{-1})	Mg (mg kg^{-1})	Ca (mg kg^{-1})					
Natural wetlands										
Mean (std. dev.)	0–20	9 (±6)	74 (±24)	657 (±49)	6020 (±490)	8 (±10)	137 (±31)	7 (±0.8)	37 (±4)	130 (±75)
Mean (std. dev.)	20–40	7 (±5)	32 (±6)	553 (±62)	5123 (±703)	8 (±11)	155 (±103)	7.1 (±0.9)	32 (±6)	127 (±59)
Mean (std. dev.)	40–60	8 (±6)	34 (±6)	443 (±60)	3993 (±1240)	3 (±3)	87 (±88)	7.2 (±0.9)	25 (±7)	123 (±67)
Mean (std. dev.)	60–80	4 (±3)	46 (±9)	393 (±73)	3568 (±995)	1 (±1)	52 (±58)	7.4 (±0.8)	22 (±6)	150 (±87)
Mean (std. dev.)	80–100	4 (±3)	74 (±42)	436 (±39)	3596 (±503)	2 (±1)	60 (±75)	7.4 (±0.9)	23 (±2)	250 (±147)
Restored wetlands										
Mean (std. dev.)	0–20	23 (±13)	161 (±84)	586 (±91)	4269 (±564)	13 (±5)	85 (±35)	7.3 (±0.3)	27 (±2)	137 (±71)
Mean (std. dev.)	20–40	18 (±10)	110 (±67)	572 (±141)	4349 (±647)	14 (±4)	80 (±20)	7.2 (±0.3)	27 (±3)	157 (±51)
Mean (std. dev.)	40–60	19 (±11)	107 (±70)	584 (±258)	4177 (±1026)	14 (±9)	63 (±26)	7.4 (±0.3)	26 (±6)	133 (±76)
Mean (std. dev.)	60–80	16 (±9)	114 (±72)	592 (±305)	4061 (±1423)	14 (±11)	62 (±42)	7.4 (±0.4)	26 (±9)	130 (±78)
Mean (std. dev.)	80–100	14 (±8)	118 (±61)	612 (±292)	4109 (±1005)	7 (±5)	52 (±31)	7.3 (±0.4)	26 (±7)	167 (±72)
Farmed wetlands										
Mean (std. dev.)	0–20	66 (±33)	339 (±138)	713 (±157)	5418 (±974)	42 (±24)	79 (±54)	6.6 (±0.6)	36 (±2)	304 (±147)
Mean (std. dev.)	20–40	48 (±33)	241 (±103)	699 (±162)	5508 (±934)	34 (±24)	82 (±62)	6.7 (±0.5)	36 (±3)	340 (±175)
Mean (std. dev.)	40–60	36 (±34)	201 (±107)	685 (±219)	5456 (±875)	31 (±30)	83 (±79)	6.8 (±0.5)	35 (±4)	337 (±153)
Mean (std. dev.)	60–80	22 (±23)	156 (±70)	660 (±199)	4857 (±615)	20 (±26)	67 (±80)	7 (±0.6)	31 (±3)	310 (±147)
Mean (std. dev.)	80–100	19 (±20)	159 (±59)	672 (±184)	4586 (±414)	16 (±16)	49 (±55)	7.1 (±0.6)	30 (±3)	341 (±129)

4.2. Study limitations

This study encompassed many natural variations in depressional wetlands on the Des Moines Lobe and substantial variability was observed in our sample population (Table 3). A larger sample size would give more confidence in our representation of the population, particularly with respect to the natural and restored wetlands. We composited both histic and mineral soils in our analysis but we note that all three wetland types had both histic and mineral soils in their representative composites, so the variation due to this technique was likely similar among all three populations and differences within wetlands was likely minimized. While differences in hydrologic regime within our wetlands may limit some conclusions, this study provides foundational information for future studies.

Mean results of some soil properties did not follow a normal distribution. Data shows that while in many cases significant differences in soil properties between wetlands were observed, there was also variability within each wetland type including non-normality that may have skewed mean values and increased standard deviations. Within type variability of the farmed sites has additional complications due to different farming histories and land management practices. Hence, in many cases, the standard deviations observed within the depth classes of the farmed wetlands are much higher than values for the natural and restored wetlands. However, despite the with-in site variability, it remains evident that large differences in many wetland soil properties exist among the three different wetlands (Table 3).

Future studies of Des Moines Lobe wetlands will include larger sample sizes and replication of within site data collection and analysis. To maintain a study with large scale implications for depressional wetland restoration, a variety of farmed wetland management systems and soil series must be evaluated. Subsequent studies will also encompass a variety of wetland restoration ages allowing a chronosequence of restoration progress to be assessed.

5. Conclusion

Study results provide evidence that artificial drainage and row crop agriculture have chemically and physically altered wetland soils throughout the top 100 cm of the soil profile. We sampled both histic and mineral soils formed in natural, restored and farmed closed depression wetlands across the recently glaciated Des Moines Lobe landform region of Iowa. Farmed wetlands had significantly higher soil nutrients (NO_3, P and K) than restored or natural wetlands. There were distinct visual differences in soil morphological properties between farmed and restored wetlands, including evidence of plow layers, thickness of A horizons, gleying, color and structure. Fewer differences were noted between restored and natural wetlands in regard to chemical soil properties than in regard to physical soil properties. This implies that chemical soil properties appear to advance toward recovery more quickly (15–20 years) than physical soil properties. Our study is leading us to ask more questions about the time scale for both chemical and physical soil restoration following restoration of formerly drained wetlands. We are also led to conduct studies which will analyze soils in specific wetland hydrologic regimes to obtain more specific understanding of restoration processes. Better understanding soil restoration processes will help quantify the success of wetland restoration programs and measure the progress made toward achieving greater soil sustainability.

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