Wetlands
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WETLANDS RESTORATION

Dredging Impacts on Soil Properties of the Kankakee River System 150 Years after Perturbation

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Abstract

Freshwater marshes provide ecosystem services such as improving water quality by storing water and filtering nutrients from upland runoff, minimizing erosion and flooding by reducing stream and river velocity and peak flows, and carbon sequestration by storing organic matter for long extended periods of time. These ecosystem services have increased interest in the protection and restoration of marshes and soil properties and are an important consideration for successful restoration. This study was conducted in Indiana, USA, within the historical extent of the Grand Kankakee Marsh that once encompassed 202,343 ha, until the dredging of the Kankakee River from 1852 to 1917 to convert the marsh to cropland. Current (in 2019) soil properties (organic matter mass and concentration, bulk density, moisture content, and carbonate concentration) were compared between (1) marshes that were dredged and presently in other land-use categories such as cropland and forests, and (2) remnant marshes that were not impacted by dredging. On average, organic matter mass and concentration were not significantly different between dredged areas and marshes ($p > 0.05$). However, marshes tended to have lower bulk densities, greater moisture contents, and greater carbonate concentrations compared to dredged areas. The soil properties of remnant marshes in this study can be used to evaluate the success of marsh restoration efforts in regions with similar soils, climate, and land-use history.

Keywords wetland restoration · freshwater marsh ecosystems · land-use change · soil organic matter · soil carbon storage · Grand Kankakee Marsh

Introduction

Since the Industrial Revolution, anthropogenic activities have accelerated the amount of greenhouse gases emitted to the atmosphere, which has contributed to changes in climatic regimes. These anthropogenic activities include changes in land use, such as the dredging and draining of wetlands for agricultural use, that can result in carbon emissions (IPCC 2014). Soil carbon is the largest pool of terrestrial organic carbon with two to three times more carbon than in the atmosphere or in terrestrial vegetation pools (Jobbagy and Jackson 2000; Trumbore 2009; Hossler and Bouchard 2010; Lange et al. 2015). Within wetlands, soil organic matter can persist for long periods of time because anaerobic conditions can slow decomposition of organic materials (Trumbore 2009). These conditions make wetlands one of the most important ecosystems on the planet for storing and accumulating vast amounts of organic matter and carbon (Drew and Lynch 1980; Artigas et al. 2015).

Wetlands are also important for storing water and filtering nutrients from upland runoff, and for minimizing erosion and

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flooding by reducing stream and river velocity and peak flows. These ecosystem services are especially important in the Midwestern USA because the region is predicted to experience more high-intensity precipitation events (Andresen et al. 2012; Byun and Hamlet 2018), which can lead to runoff before water infiltrates the soil. These conditions can lead to water scarcity and increased sediment erosion (Baker et al. 2012; Watson et al. 2016). Additionally, farmers in the region commonly apply fertilizer to fields before corn seedlings emerge, which can lead to leaching and runoff of nitrogen through precipitation events and snowmelt (Baker et al. 2012). Wetlands adjacent to such croplands have been shown to be important for filtering nitrogen transported from croplands (Baker et al. 2012), which is dependent on soil properties such as carbon stocks (Gelfand et al. 2015).

Marshes converted to other land uses have been the focus of restoration efforts to improve water quality and supplement water sources for agricultural use across many regions of North America (Verhoeven and Setter 2010; Baker et al. 2012). An important part of restoring function to freshwater marshes that were converted to other land uses is knowing the current range of variability in soil properties of remnant marshes within a region that were not converted to other land-use categories and that have evolved under changing climatic and disturbance regimes. The success of restoration projects can be evaluated, in part, by comparing the soil properties of remnant marshes to marshes where restoration efforts have been implemented. Restoring degraded marshlands or re-aligning them with current and expected future conditions (i.e., rather than restoration to historical pre-disturbance conditions (Millar et al. 2007)) can accomplish carbon objectives and improve water quality, decrease flooding, and reduce erosion of stream and river banks (Watson et al. 2016).

In the present study, soil properties across the historical extent of the Grand Kankakee Marsh (GKM) in Indiana, USA were examined to determine the current range of variability in soil properties across remnant freshwater marshes to assist natural resource managers involved in freshwater marsh restoration and re-alignment efforts. A related objective was to evaluate the potential organic matter consequences of freshwater marsh conversion to other land uses. For this objective, soil properties (organic matter mass and concentration, bulk density, moisture content, and carbonate concentration) in areas of the GKM that were dredged and presently (in 2019) in other land-use categories were compared to marshes that were not dredged and drained. We hypothesized that dredged locations would have less soil organic matter stocks compared to non-dredged locations because of the slow decomposition of organic matter under anerobic conditions in freshwater marshes. We also expected that soil bulk densities would be greater and that soil moisture contents would be lower in locations that had been dredged.

Methods & Materials

Study System

The Kankakee River stretches from near South Bend, Indiana to Wilmington, Illinois, where it joins the Des Plaines River to form the Illinois River. The Kankakee River is approximately 214 km long and is joined by the Yellow River and Iroquois River. The Kankakee basin, which is approximately 7740 km^2, was once home to the GKM. The GKM was one of the largest natural wetland complexes in North America, only second in size to the Everglades (Fig. 1) (Ivans et al. 1981). The GKM and adjacent lands created a matrix of deep open marsh, forest swamps, and wet prairies interspersed with islands that provided habitat for a large number of species including marsh grass, wild rice, freshwater mussels, elk, and bison (Hahn 1907; Wilson and Clark 1912). From 1852 to 1917, public works projects included dredging 402 km of the river in Indiana, first by hand and then by steam shovel, to straighten and remove the meanders, which reduced the size of the GKM from 202,343 ha to 12,141 ha (Ivans et al. 1981). However, the northern quarter of Indiana still included permanently ponded (27% of the region) or seasonally ponded (23% of the region) wetlands (Lindsey et al. 1965). The dredging and additional ditching of lateral drains over more recent decades has increased flooding and erosion along riverbanks, and has also prompted restoration efforts within the basin (Ivans et al. 1981; Janke 1998).

The present study was conducted within the Kankakee, Tippecanoe, and Iroquois watersheds in northwestern Indiana (40°56′ to 41°37′ N, 86°24′ to 87°39′ W). Soils throughout the region support freshwater marsh ecosystems and Aeolian sand dunes (Wayne and Zumberge 1983; Curry et al. 2014). In June 2019, during the time of sampling, total precipitation was 14.1 cm and mean temperature was 69.3ºC at the Valparaiso Porter CO Municipal Airport (NOAA 2019). For this study, eleven locations were sampled including forests and croplands that were formerly freshwater marshes, as well as, freshwater marshes that were not dredged (Table 1 and Fig. 1). The freshwater marshes that were a part of a marsh ecosystem or classified as muck were saturated with water for ≥ 30 consecutive days in normal years (Schoeneberger et al. 2012).

Sample collection and laboratory analysis

Soil samples were collected with a cylindrical stainless-steel tubular soil sampler with a 3.8 cm diameter using the direct push method. At each location, 5 soil samples were collected; soils were collected 1 m apart from each other and were stored separately. Samples were collected from the surface of the organic, Ap (the p suffix refers to an A horizon that has been plowed, tilled, or otherwise disturbed), or A horizon (Schaetzl and Anderson 2005) to a maximum depth of 20.3 cm. For

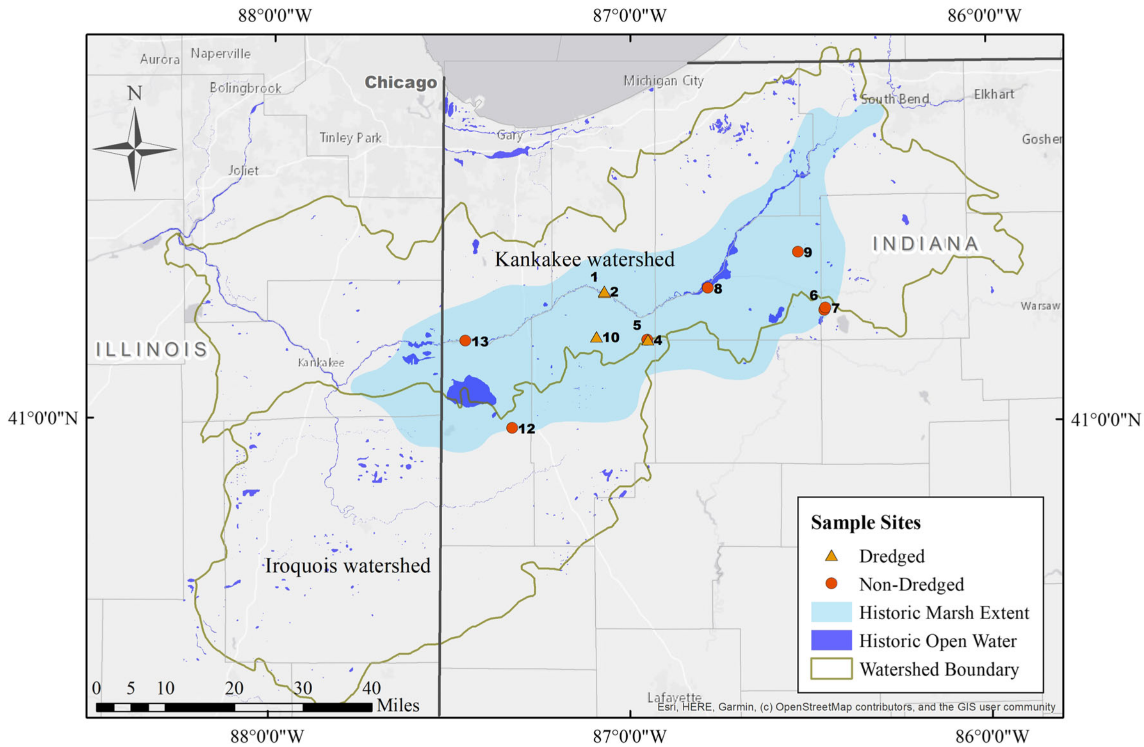

Fig. 1 Approximate Extent of the Grand Kankakee Marsh shown in red and described by Meyer (1935). Also shown are sample locations

dredged and non-dredged locations, the average sampling depths were 20.1 and 18.1 cm, respectively. Only soils from the O, Ap, and A horizons were collected. Across all locations, O and A horizons were usually present; the exception were croplands, which had Ap horizons (Fig. 2). For marshes, forests, and croplands, average O horizon depths were 16.7, 6.9, and 0.3 cm, respectively. For marshes, forests, and croplands, average Ap horizon depths were 3.6, 13.3, and 20.1 cm, respectively. Samples were sealed in bags and transported to the Biodiversity and Environments across Space and Time Lab at the University of Maine, Orono, ME.

Samples were weighed and then oven dried in a forced-hot air oven (Shel Lab model 10-505-14) at 65 °C for 24 hours to obtain dry mass for bulk density and moisture content calculations. For each sample, bulk density was calculated by dividing the sample's oven-dry mass by the volume the sample occupied in the soil sampler. Moisture content was calculated by dividing the sample's oven-dry weight by its field-based weight (i.e., before being oven dried). Loss-on-ignition (LOI) analysis was performed on 5 g of homogenized sample using a drying oven (Thermolyne Furnace F30400). These samples were combusted for 4 hours at 550 °C to determine organic matter concentration. Organic matter concentration and an expansion factor based on the area of the ground surface that was sampled were used to calculate organic matter mass on a per unit area basis. After measuring the mass of organic matter loss, the samples were placed in the oven at 1000 °C for 2 hours to determine carbonate concentration.

Data analysis

Mixed effects modeling was used to account for the nested structure of the data. The data are nested in the sense that soil samples were collected from various locations which included dredged and non-dredged areas. Hence, specific soil attributes associated with samples collected from the same location are likely to be correlated. In the mixed effects models, a categorical variable was used to identify whether or not specific locations were dredged. This variable was included as a fixed effect and location was included as a random effect. For the categorical variable, locations were not separated into more discrete categories (e.g., forests and croplands) because of limited replication of the sampled vegetative communities (e.g., only 2 forested locations). Each of the following response variables were evaluated in separate models: organic matter mass, organic matter concentration, bulk density, moisture content, and carbonate concentration. Because organic matter concentration, carbonate concentration, and moisture content were highly skewed, a logarithmic transformation ($\log_{10}$) was applied to these response variables which improved normality. The models also accounted for differences in magnitude of the observed range of response variable values between dredged and non-dredged areas. The *lme* function in the *nlme* package (Pinheiro et al. 2014) in R (R Development Core Team 2014) was used to fit the linear mixed-effects models. For each soil attribute, exploratory

Table 1 Location information categorized by land-use category and past perturbation. Depth to static water level shows the range of values for well data within 1 km of each location from the Indiana Department of Natural Resources Water Well Viewer. Locations inundated for at least seven consecutive days once every two years are checked under "7MQ2" (Fowler et al. 2019). Soil taxonomic classes were inferred from United States Department of Agriculture Natural Resources Conservation Service soil survey maps. GKM = Grand Kankakee Marsh

Location ID and Coordinates	Elevation (ft)	Depth to Static Water Level (ft)	7MQ2	History	Soil Map Unit Descriptions -Taxonomic Class
Forest/Dredged					
1 (41.2734481, -87.0709537)	646	0–10		Second-growth forest adjacent to dredged river channel	Maumee loamy sand - sandy, mixed, mesic Typic Endoaquoll
4 (41.173142, -86.950219)	715	7		Hardwood forest atop sand dune within historic game preserve	Oakville fine sand, 6 to 15% slopes - mixed, mesic Typic Udipsamments
Cropland/Dredged					
2 (41.2753306, -87.07209929)	646	0–10		Well-drained height of land and crossing point within GKM	Plainfield sand, 2 to 6% slopes - mixed, mesic Typic Udipsamments
10 (41.1792356, -87.0936183)	673	10		Restored prairie and sand oak savanna (Rothrock et al. 2016)	Watseka-Maumee loamy sands - sandy, mixed, mesic Aquic Hapludolls
Marsh/No dredging					
5 (41.1727288, -86.9518250)	712	7		Wetland within a game preserve established in 1930s	Newton loamy fine sand, undrained - sandy, mixed, mesic Typic Humaquepts
6 (41.2351126, -86.4576468)	725	28–42		Undeveloped alkaline lake shoreline in Tippecanoe drainage basin	Edwards muck, undrained, 0 to 1% slopes - coarse-silty over sandy or sandy--skeletal, carbonatic over mixed, mesic Histic Humaquepts
7 (41.2398606, -86.4543235)	735	28–42		Undeveloped wetlands and fens surrounding alkaline lake in in Tippecanoe drainage basin	Houghton muck, drained, 0 to 1% slopes - Euic, mesic Typic Haplosaprists
8 (41.28248639, -86.7823077)	663	5–22		Forest adjacent to dredged river channel, oxbow lakes, and levees	Craigmile fine sandy loam, frequently flooded - coarse-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Fluvaquentic Endoaquolls
9 (41.3582214, -86.5298918)	702	10–16		Meadow with shallow water patches and wetlands	Watseka loamy sand - sandy, mixed, mesic Aquic Hapludolls
12 (40.9862939, -87.3282033)	692	12–14		Mixed hardwood and evergreen woodland, savanna and vernal pools	Sumava-Ridgeville-Odell complex, 0 to 2% slopes - coarse-loamy, mixed, active, mesic Aquic Argiudolls
3 (41.5039584, -86.5815739)	682	4–5		Former manufacturing site north of Kankakee river, converted to wildlife and game habitat in 1960s	Craigmile mucky silt loam, frequently flooded, undrained - coarse-loamy, mixed, superactive, mesic Fluvaquentic Endoaquolls

Fig. 2 Examples of three soils within the corer that was used to collect samples. The first soil was typical of forests, the second of croplands, and the third of freshwater marshes

figures and descriptive statistics were derived using the mean values for each location.

Results

For dredged and non-dredged locations, soil organic matter mass was 40.1 ± 19.8 and 55.4 ± 32.5 Mg ha^{-1} (mean ± standard deviation; Mg ha^{-1} = megagrams per hectare), respectively (Fig. 3a). For dredged and non-dredged locations, soil organic matter concentrations were 4.9 ± 2.9 and 13.0 ± 11.2%, respectively (Fig. 3b). In the mixed effects models of organic matter mass and concentration, the categorical variable dredging was not significant ($p = 0.326$ and 0.069, respectively). Variation in organic matter mass and concentration among locations where the same management (i.e., dredging or no dredging) was applied accounted for 87 and 95% of the components of variance, respectively.

For dredged and non-dredged locations, soil bulk densities were 1.06 ± 0.07 and 0.72 ± 0.19 Mg m^{-3} (Mg m^{-3} = megagrams per cubic meter), respectively (Fig. 3c). The mixed effects model of bulk density included dredging as a statistically significant fixed effect ($p = 0.005$, $r = 0.67$). Dredging explained 45% of the variation in bulk density, and variation in bulk density among locations where the same management was applied accounted for 47% of the components of variance (Table 2). Pairwise comparisons indicated that locations that had been dredged had greater bulk densities than locations that were not dredged ($p = 0.005$; Table 3).

For dredged and non-dredged locations, soil moisture contents were 11.7 ± 7.1 and 58.9 ± 26.6%, respectively (Fig. 3d). The mixed effects model of moisture content included dredging as a statistically significant fixed effect ($p < 0.001$, $r = 0.85$). Dredging explained 73% of the variation in moisture content, and variation in moisture content among locations where the same management was applied accounted for 91% of the components of variance (Table 2). Pairwise comparisons indicated that locations that had been dredged had lower moisture contents than locations that were not dredged ($p < 0.001$; Table 3).

For dredged and non-dredged locations, soil carbonate concentrations were 0.44 ± 0.17 and 11.09 ± 15.75%, respectively (Fig. 3e). The mixed effects model of carbonate concentration included dredging as a statistically significant fixed effect ($p = 0.047$, $r = 0.61$). Dredging explained 37% of the variation in carbonate concentration, and variation in carbonate concentration among locations where the same management was applied accounted for 99% of the components of variance (Table 2). Pairwise comparisons indicated that locations that had been dredged had lower carbonate concentrations than locations that were not dredged ($p = 0.047$; Table 3).

Discussion

Our results show that dredging history accounted for significant differences in most of the soil properties examined across the historical extent of the GKM. However, there was no significant difference in mean organic matter mass between dredged and non-dredged locations. While mean organic matter mass was quantitatively greater for dredged locations, the soil of one location (a Histosol; location ID 7 in Table 1)

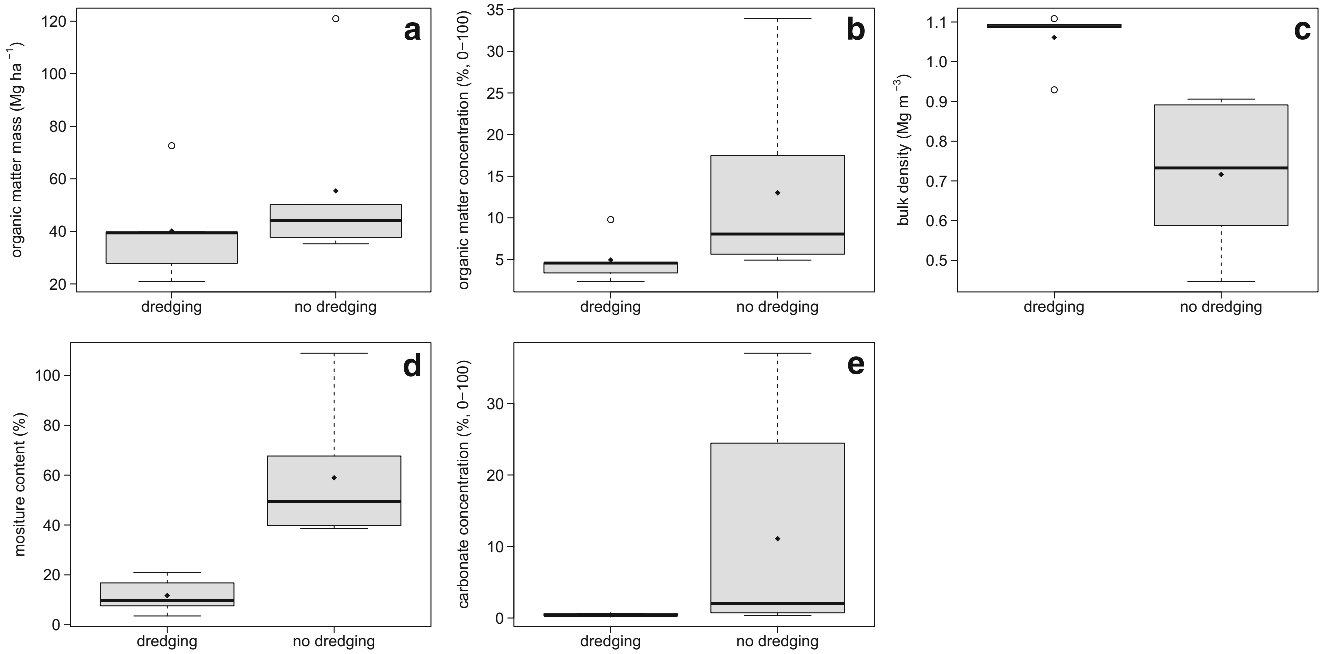

Fig. 3 Descriptive statistics for soil attributes by past management (i.e., dredging and no dredging). Black horizontal lines and black dots represent the median and the mean, respectively. The boxes define the interquartile range (25–75% quartile) and the vertical lines represent the whiskers of maximal 1.5 times the interquartile range. White dots beyond the whiskers may be considered outliers

increased the overall mean of the non-dredged locations. The greater quantitative difference in the non-dredged locations could partially be attributed to the slower rates of organic matter decomposition in freshwater marshes compared to forests and croplands (Loder and Finkelstein 2020). Soil organic matter can be protected from decomposition by several mechanisms such as climatic stabilization (e.g., freezing temperature), intrinsic recalcitrance (e.g., specific chemical structures that slow decomposition), physical stabilization, and inhibition of microbial activity (Trumbore 2009).

While the dredged locations were not broken into more discrete categories due to the limited number of sample locations, it is important to consider differences in land use among the dredged locations when interpreting our findings. Both forested locations were categorized as old growth oak-hickory forests. For this forest type, the carbon mass of the organic horizon and mineral soil can range from 7.6 to 14.1 and 35.5 to 45.1 Mg ha^{-1}, respectively, with the lower end of this range being associated with low-productivity stands (Kaczmarek et al. 1995). In our study, mean organic matter mass in the locations where dredging occurred was 37.9 Mg ha^{-1} from the top of the organic horizon to an average depth of 20.1 cm. In environments where there are continuous aerobic conditions, which is typical of soils having high sand percentages, decomposition is faster than under anaerobic conditions (Reddy and Patrick 1975). At our study sites, soils supporting oak-hickory forests were classified as having loamy sand and fine sand textures.

In wetlands composed purely of organic soils, bulk densities can range from 0.1 to 0.4 Mg m^{-3}, whereas bulk densities of wetlands with a mineral component can range from 1 to 1.5 Mg m^{-3} (U.S. EPA 2008). For non-dredged locations, our range of bulk density values were between the EPA values for pure organic and mineral soils. This is not surprising, because our samples tended to contain organic and mineral components as evidenced by their relatively low organic matter

Table 2 Model fit statistics for mixed-effects models of bulk density (Mg m^{-3}), $\log_{10}$ moisture content (%), and $\log_{10}$ carbonate concentration (%, 0-100) that contained condition (i.e., dredging and no dredging) as a fixed effect and location as a random effect (b_i)

	Marginal R^2	Conditional R^2	Residual SE	b_i SE
Bulk density	0.451	0.729	0.146	0.137
Moisture content	0.730	0.977	0.074	0.238
Carbonate concentration	0.368	0.991	0.075	0.625

SE, standard error

Table 3 Least-squares (LS) mean (standard error) of bulk density (Mg m^{-3}), log_{10} moisture content (%), and log_{10} carbonate concentration (%, 0-100) by past management

	Dredging	No dredging
Bulk density	1.061 (0.068) b	0.716 (0.062) a
Moisture content	0.985 (0.107) a	1.736 (0.098) b
Carbonate concentration	0.390 (0.280) a	0.483 (0.255) b

Different letters indicate significant differences between LS means at $P < 0.05$.

concentrations in comparison to those of pure organic soils. Soil carbonate levels in freshwater marshes can also be variable due to water table depth and disturbance history (Khan and Fenton 1994). In the present study, two of the non-dredged locations had high calcium carbonate concentrations; location 6 and 7 (Table 1) with average carbonate concentrations of 37 and 26%, respectively. Locations 6 and 7 are supplied with groundwater that has high concentrations of dissolved limestone, which form marl deposits in wetlands (TNC 2020). Calcium carbonate is also added to agricultural lands to stabilize residual fertilizer phosphorus. However, marshes that were undergoing restoration were not included in our analysis (Scholz 2006; Cook-Patton et al. 2014).

While the inference of this study is limited to the upper portion of the soil profile, future studies could quantify organic matter mass at greater depths. Also, there was high within-group variability in the soil properties of this study for areas that were dredged as well as in areas that were not dredged. The high levels of variation were partially due to the diversity of land-uses within each category (e.g., forests and croplands within the dredged category). Future studies could focus on increasing the number of forests and croplands sampled and to place them in separate categories to reduce within-group variability. Finally, the Kankakee watershed provides fertile soil for agriculture, and finding marshes within the watershed that were not dredged was challenging. For example, on the Illinois portion of the Kankakee watershed, while the river remains intact, few marshes remain due to extensive conversion to urban development and cropland.

Overall, our results can inform establishing benchmarks for the restoration of freshwater marshes and highlight the long-term impact of dredging on soil properties. For example, the success of restoration or re-alignment efforts could be evaluated based on the current study's statistics for soil properties of remnant marshes within the GKM that were not converted to other land-use categories. This study also highlights differences in soil properties between dredged and non-dredged locations, which has implications for the agricultural community as more wetlands are converted to other land-use categories. Specifically, the soil properties associated with freshwater marshes are conducive for water storage and purification (Baker et al. 2012). Therefore, these marshes will be important for supplying water to croplands during drought conditions and as global demand for agricultural products increases and climate change progresses.

Conclusions

In this study, soil properties across the historical extent of the GKM in northwestern Indiana were measured to evaluate the impact of land use change on freshwater marshes since Euro-American settlement. Settlement in the region included 65 years of public works projects that involved dredging, rerouting, and channelizing the Kankakee River, and draining marshlands for agriculture. Our study shows that the legacy of land-use change that occurred approximately 150 years ago is still measurable in soils throughout the Kankakee watershed. Our efforts to quantify soil properties can also be used as benchmarks for marsh restoration or re-alignment for locations with similar soils, climate, and land-use history. Specifically, the success these efforts could be evaluated based on our results for soil properties of remnant marshes within the GKM that were not converted to other land-use categories. Restoration and re-alignment efforts will be increasingly important because of need for freshwater marshes to store and purify water that is necessary for increasing the productivity of agricultural crops in the Midwestern USA, as well as, in regions with similar soils, climatic regimes, and land-use patterns.

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