Lower Muskegon River Reconnection Project
Pre-Restoration Monitoring Report

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Introduction

Muskegon Lake is a 4,150-acre drowned river mouth-lake that connects directly to Lake Michigan through a navigation channel. It was designated an Area of Concern (AOC) in 1985 due to ecological problems caused by industrial discharges, shoreline alterations, and the filling of open water and coastal wetlands. Historic sawmill debris, foundry sand, and slag filled 798 acres of open water and emergent wetlands in the AOC. Approximately 65 percent of the shoreline was hardened with wood pilings, sheet metal, and concrete (Steinman et al. 2008a). This resulted in the loss and degradation of shallow water benthic communities, isolation and fragmentation of coastal wetlands, and the associated degradation of water quality and fish and wildlife populations. Although the benthos has improved since the end of lake-filling practices and wastewater diversion in 1973, shallow water benthic communities remain degraded. Fish and wildlife populations, including lake sturgeon, walleye, white bass, and various species of reptiles, amphibians, and water birds, remain significantly impaired by the loss of habitat.

Loss of fish and wildlife habitat is one of the beneficial use impairments (BUIs) that has not yet met its restoration target, as part of the AOC delisting process. The 57.5 acre former Bosma property (now known as the Lower Muskegon River Reconnection Project: LMRRP), near where the north branch of the Muskegon River enters Muskegon Lake, includes floodplain acreage that is currently hydrologically separated from the river by an earthen berm. Reconnection can provide important floodplain habitat for fish and wildlife. However, similar to the restoration of the Willbrandt ponds, just a few miles away in the Bear Creek watershed (Steinman and Ogdahl 2016), the land was formerly used for celery farming until 1976, and subsequently hayed, off and on, through 2015. Pumping has kept standing water out of the diked fields until relatively recently. As a consequence, its sediment may have legacy phosphorus (P) that could be a major source of P to Muskegon Lake after reconnection. Currently, Muskegon Lake's P concentrations are meeting the restoration target for AOC delisting (Steinman et al. 2008), but contributing additional P through hydrologic reconnection and sediment P release to overlying water is clearly undesirable.

We are particularly concerned that this LMRRP site may release P under flooded (reduced) conditions, given that sulfate is a known contaminant of this site. P can bind to iron in soils and sediments, keeping it from being released to soil solutions or the water column; however, sulfides when present preferentially bind the iron, freeing the P to migrate into solution. Sulfides could be produced by bacterial decomposition in the absence of oxygen. Alternation between flooding and drying can enhance or reduce the potential for P release depending on the biogeochemistry of the soils/sediments (Kinsman-Costello et al. 2016). Hence, at least in the short-term, this site has the potential to become a source of P to Muskegon Lake. The current project involves examining the potential of P exchange between the sediment and water column **prior** to the reconnection of the Lower Muskegon River to its adjacent floodplain. The prior land use on this site could complicate restoration efforts, and if not addressed carefully, could lead to serious water quality impairment (cf. Conrow et al. 2011). The focus for the pre-restoration monitoring is on understanding the amount of P, and associated mechanisms, that could be released from the soils and flooded sediments into overlying water, which then could move back into the Muskegon River and ultimately Muskegon Lake.

Methods

The LMRRP wetland is located in the Lower Muskegon River watershed, approximately 1 mile upstream from Muskegon Lake in Muskegon, MI. An earthen berm separates the periodically flooded former farm fields from the Muskegon River. Two additional north-south berms further separate the property into west, central, and east wetland regions (Figs. 1, 2). The focus of our pre-restoration monitoring will be on the east (sites 1-4) and central (sites 5-15) wetland cells. We further split the central wetland region into north central (sites 5-8) and south central (site 9-15) wetland cells. Prior to the start of our pre-restoration monitoring, attempts were made to draw down the standing water in the central and east wetland cells by mechanical pumping, but due to heavy rainfall many cells remained inundated at the time of sampling (see below).

Sampling locations were determined using stratified random methods. First, an aerial photograph of the 52 acre wetland restoration area was traced and outlined in ArcGIS (Environmental Systems Research Institute). A grid mesh was overlaid on the outline and manually grouped together by region to create 15 parcel areas each averaging 3.5 (±0.4 SD) acres (Fig. 1). Mesh squares in each parcel were assigned a number and a random number generator was used to select one square per parcel; points landing on roadways, earthen berms, and trees were re-rolled. For each location a latitude and longitude was recorded using a handheld Garmin eTrex Venture HC 12-channel GPS at the location where the core was collected (Fig. 2, Table 1).

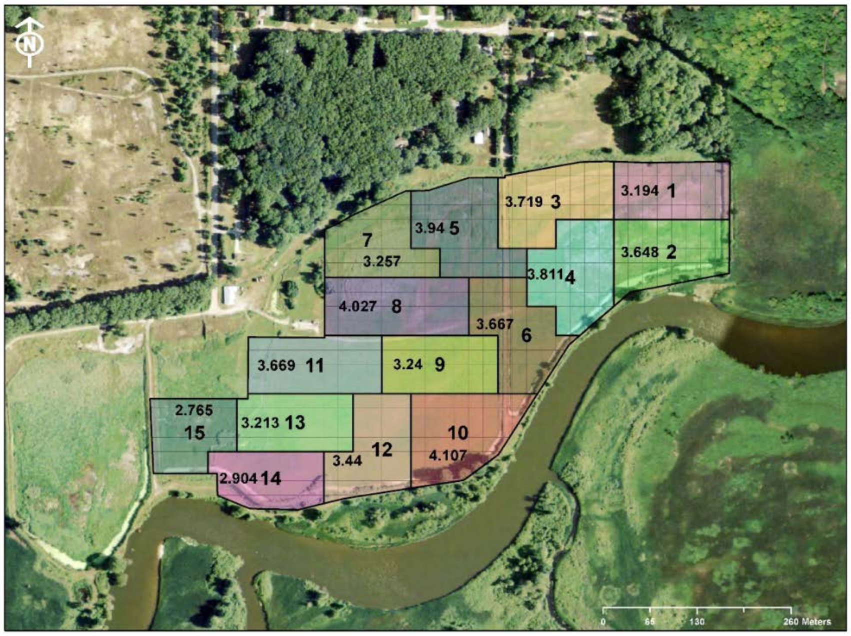

Figure 1. LMRRP wetland pre-restoration monitoring parcel areas. Large numbers inside each area represent their numeric designator (1-15); small numbers represent acreage of each parcel. Mean (±SD) area per site parcel = 3.5 (± 0.4) acres.

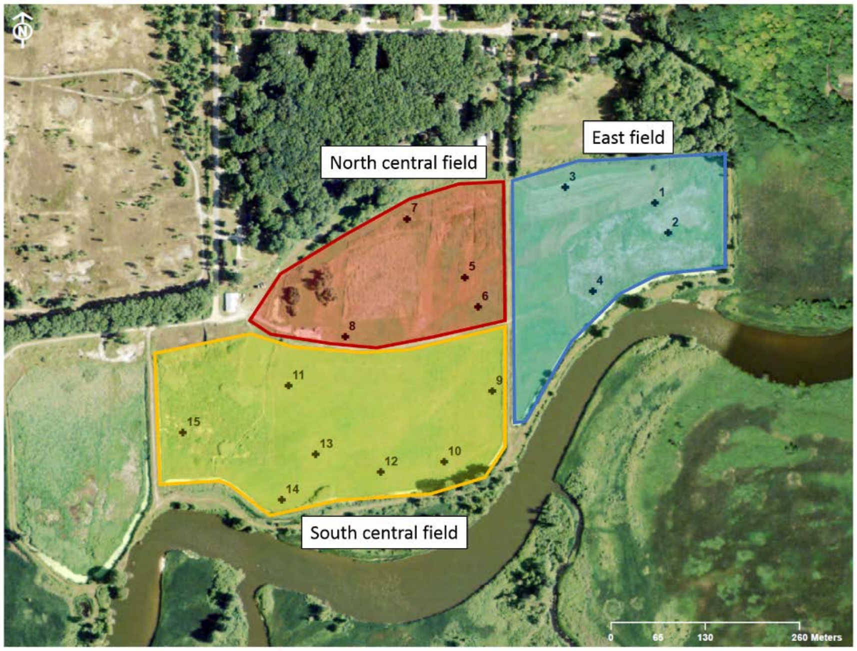

Figure 2. LMRRP wetland pre-restoration monitoring site locations (n=15).

Table 1. LMRRP wetland pre-restoration monitoring site location coordinates.

Wetland Cell	Site #	Latitude (°N)	Longitude (°W)
East	1	43.27222	86.22581
	2	43.27185	86.22559
	3	43.27242	86.22733
	4	43.27113	86.22688
North Central	5	43.27132	86.22905
	6	43.27095	86.22883
	7	43.27205	86.23002
	8	43.27060	86.23109
South Central	9	43.26991	86.22860
	10	43.26904	86.22943
	11	43.27000	86.23206
	12	43.26892	86.23051
	13	43.26915	86.23161
	14	43.26859	86.23219
	15	43.26943	86.23386

Spring 2016 - Field surveys and P isotherms

During 16-24 May 2016, we collected one sediment core from each of the 15 sites, sampling approximately 2 sites at a time over multiple days until all sites within the restoration area were sampled. Sediment cores of 7 cm diameter were obtained using a modified piston coring apparatus (Fisher et al.

1992; Steinman et al. 2004). The modified piston corer was constructed of a 0.6-m long, ~7-cm inner diameter, 7.6-cm outer diameter polycarbonate tube that was marked in 1-cm increments. The modified corer was positioned vertically at the sediment water interface and was hammered into the sediment, which was necessary due to the highly compacted soil within the cells, to a depth of 30 cm. The top and bottom of each core was sealed with a rubber stopper and duct tape. The cores were stored upright and transported back to the lab within 5 hours. At sites where standing water was present water depth was recorded. Where it was deep enough for water collection, a water sample was collected for total P (TP) and soluble reactive P (SRP); the latter sample was field-filtered (0.45 µm). The samples were stored on ice until transported back to the lab were they were stored at 4°C until analyzed on a Seal AQ2 Discrete Analyzer (U.S. EPA 1993). Where water was collected, general water quality variables were measured using a YSI 6600 data sonde which including temperature, dissolved oxygen (DO) concentration and percent, pH, specific conductance (SpCond), total dissolved solids (TDS), and turbidity (NTU). We excluded the Site 4 core from our reporting due to anomalously high sediment TP and especially OM values in the surface slice, which appear to be related to large amounts of plant biomass (*Phalaris arundinacea*: reed canary grass) contained in the core.

In the lab, sediment was extruded from each core and separated into a 0-10 cm surface sample and a 20-30 cm bottom sample, stored in plastic bags, and refrigerated at 4°C until additional analysis. Sediment samples were homogenized by hand and subsampled for analysis of organic matter (OM), ash-free dry mass (AFDM), sediment TP and P isotherm measurements. Sediment OM and AFDM were determined using gravimetric procedures (i.e., dry for 24 hours at 105˚C, weigh, ash at 550˚C for 4 hours, re-weigh; Steinman et al. 2016). The resultant ashed material was used for analysis of sediment TP on a Seal AQ2 Discrete Analyzer (U.S. EPA 1993). Additional subsamples were dried and ashed, and analyzed at the Kellogg Biological Station at Michigan State University (see Appendix).

The remaining wet sediment was used and subsampled for P isotherms to calculate Equilibrium P Concentrations (EPC_0). P isotherms, which provide an indication of the propensity of sediments to release or take up P from overlying water, were determined in triplicate for each 0-10 cm surface and 20-30 cm bottom section of sediment cores (modified from Mozaffari and Sims (1994) and Novak et al. (2004)). We added 20 mL of inorganic P solutions (KH_2PO_4 dissolved in 0.01 M KCl) as either 0, 0.01, 0.1, 1, 5, 10, 50, 100, or 500 mg P/L to 50 mL centrifuge tubes containing 3 g of wet sediment. At each concentration within each site, one of the triplicate samples served as a killed control by using chloroform, while the other two were left live. The centrifuge tubes were incubated for 24 hr on an orbital shaker table shaking at 250 RPM. Samples were centrifuged for 20 minutes at 3600 RPM and supernatant was filtered through a 0.45 µm filter before undergoing SRP analysis as described above. Phosphorus sorption is calculated as the difference between the amount of P initially added to the tube and that in the solution at equilibrium. Calculations were as follows (after Olila and Reddy 1993):

P lost after the 24-hr equilibration is considered sorbed (S_1):

$$S_1 = (V/m)(C_0 - C_{24})$$

where C_0 = the concentration of P added (µg/L); V = total volume (mL); C_{24} = solution P concentration after 24 hour equilibration (µg/L); and m = mass of dry sediment (g).

Native sorbed P (S_0) will be estimated using the least squares fit of the plot of S_1 vs. C_{24} at low P concentrations (i.e., during linear relationship):

$$S_1 = S_0 + bC_{24}$$

The constant (y-intercept) will be considered as the initial sediment P present in the adsorbed phase. The values for S_0 and S_1 are added to obtain the corrected P sorption (S):

$$S = S_1 + S_0$$

The equilibrium P concentration (EPC) of the sediments, defined as the solution P concentration at which $S_1 = 0$ will be calculated from the equation:

$$EPC = S_0/b$$

The P sorption isotherm will be constructed by plotting the mean quantity of P sorbed (mg/kg) against the mean P equilibrium concentration (mg/L) using the linear version of a Langmuir equation:

$$c/(x/m) = (1/S_{max})c + 1/(k)(S_{max})$$

where x/m (mg/kg) is the quantity of P sorbed by the sediment, S_{max} (mg/kg) is the P sorption maxima, k (L/mg) is a sorption constant relative to P binding energy, and c (mg/L) is the P equilibrium concentration.

Summer 2016 - Sediment re-wetting experiment and P fractionation

Two additional sediment cores were each collected on 25-26 July from the same 15 sites described above using a shorter (but still 7.5 cm diameter) modified sediment sampler (Davis and Steinman 1998) and similar methods as described above. The shorter core tubes were driven only to a minimum depth of 10 cm. All sediment cores were transported upright back to the lab within 5 hr of collection for a sediment desiccation and rewetting experiment, with subsequent P fractionation. The second set of cores from each site were used for sediment characterization (organic matter, ash-free dry mass, TP) and sediment metals analyses.

Before coring, the core tubes used in the desiccation and rewetting experiment were pre-drilled with 5 sampling ports along the length of the tube at 3 cm intervals, starting at 1.5 cm up from the bottom of the core tube. The sampling ports were covered with electrical tape to prevent sample loss during coring. The sampling ports were used to insert rhizons at 2 depths, near top and near bottom, for non-destructive sampling of pore water (Seeberg-Elverfeldt et al. 2005).

After transportation back to the lab, both sets of cores were allowed to settle for several hours and any overlying water was carefully drawn off via peristaltic pump and a Pasteur pipette. The height of the sediment cores within the core tube was adjusted to 10 cm, if needed, by removing excess sediment from the bottom. The set of cores used for the sediment characterization were extruded into a plastic bags and refrigerated until further analysis of AFDM and OM, as described above, and metal analysis, (Fe, Ca, and Mn (EPA Method 6010B, U.S. EPA 1996). The other set of cores used in the desiccation and rewetting experiment were placed in holding racks under metal halide lamps operating on a 12:12 light:dark photoperiod (photosynthetically active radiation [PAR] was 118 µmol/m^2/sec for entire incubation period near sediment surface) and allowed to dry naturally under ambient temperature conditions. Sediment moisture content was monitored throughout the drying period using a soil moisture probe (Extech Instruments, model number MO750). Cores were rotated weekly and all cores were incubated until the final core reached <1% soil moisture within 27-28 days of incubation.

Water from the Muskegon River adjacent to the restoration area was collected on 19 August 2016. Water quality was measured in situ with a YSI 6600 sonde and a grab sample was collected for TP and SRP analyses, as described above. Each core was gently rewetted with 500 mL of homogenized filtered river water and allowed to incubate for a total 48 hr under static conditions. We sampled at 24 and 48 hr after rewetting. We first measured temperature and DO in the overlying water of each core using a YSI ProDO probe, rinsed with DI water after each core to avoid cross contamination. A syringe was used to subsample 60 mL from the overlying water column, 20 mL each for TP and SRP analysis, which was stored and analyzed as described above, and a 20 mL subsample went to MSU for further analyses. Rhizons were installed across the diameter of the core at 3.5 cm and 9.5 from the top for near-surface and near bottom depths, respectively, to sample porewater from undisturbed rewetted cores. Water leaks were patched with marine epoxy which was added to the exterior of rhizon sampling port holes and around the bottom of the knockout caps and electrical tape; however, water loss was sufficiently large that porewater sampling was not possible at 48 hr. Any remaining standing water was slowly removed via peristaltic pump, and water quality variables were measured with a YSI 6600. The porewater samples were collected via rhizon ports for P flux calculations at AWRI and analysis for dissolved H_2S, Fe(II), Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-} and NO_3^- at MSU (see Appendix).

After completing water sampling, sediment samples were refrigerated until further processing, at which time sediment in each core was homogenized. Sediments were subsampled for OM, AFDM, and TP measurements, using methods described above. A subsample of 2 g of sediment were placed in centrifuge tubes for sequential fractionation (Psenner et al. 1998; modified from Hupfer et al. 2009). Extracts were analyzed for the following sediment P fractions: 1) NH_4Cl-extracted labile P (loosely sorbed); 2) Bd-extracted reductant-soluble P (iron hydroxides, Mn-bound); 3) NaOH-extracted Fe- and Al-bound P; and 4) HCl-extracted Ca- and Mg-bound P.

Additional sediment cores from six sites (2, 6, 7, 8, 14, and 15) were resampled on 16 September 2016 for a second rewetting experiment and P flux analysis to last 48 hr. We used the same methods as above, except that these cores did not have pre-drilled holes or rhizon ports installed to avoid leakage. All samples achieved <1% moisture within 52 d of incubation. The lights were lowered 5 days into incubation which increased PAR from 118 to 247.9 µmol/m^2/sec to help decrease the drying time. Sediment cores were carefully rewetted with freshly collected, filtered Muskegon River water to avoid sediment disturbance, and at both 24 and 48 hr, we measured temperature and DO with a YSI ProDO, as described above. A total of 40 mL subsample was removed with a syringe from the overlying water column, 20 mL each for TP and SRP analysis as described above. The water removed was gently replaced with the same filtered Muskegon River water for the final 24 hr for a total of 48 hr of rewetted incubation. After 48 hr, temperature, DO, and TP and SRP were sampled as after the first 24 hours. The remaining overlying water column was removed via a peristaltic pump and water quality was measured using a YSI 6600 as described above. Sediment cores were not fractionated or sent for metal analysis after rewetting, but OM, AFDM and sediment TP were analyzed as described previously.

Results

Spring 2016 - Field survey and P isotherms

An initial reconnaissance of the site early in the Spring indicated that soils were highly organic mucks and most of the area was covered with the previous summer's dense growth of reed canary grass. Sediment porewater close to the sediment-water interface contained measurable dissolved Fe(II) but no detectable free hydrogen sulfide; the latter observation is expected because any free sulfide would readily precipitate with the Fe(II).

Upon returning to sample multiple sites, we observed varying surface water depths based on their location within the property. Sites with insufficient standing water for collection and measurement occurred more often in the east and north central sites due to the patterns of sloped terrain. Mean surface-water SRP at east and south central sites was generally double the Muskegon River concentration of 7 µg/L, whereas site 6 in the north central wetland greatly exceeded the Muskegon River, at 579 µg/L (Table 2, Fig. 3). TP concentrations at all sites exceeded Muskegon River TP concentrations by ~6 to 26× (Table 2, Fig. 3). Temperature and pH values were similar across all sites; however, site 6 in the north wetland had uniquely low DO and high specific conductance in addition to high SRP compared to sites in other areas of the wetland (Table 2).

Sediment core TP concentrations were variable among sites and even within regions (Fig. 4A). On average, surface and bottom core sediment TP concentrations within a region exceeded 1000 mg/kg (dry wt) (Table 3), although individual sites ranged from 400-3000 mg/kg (Fig. 4A). Mean surface sediments (0-10 cm) in cores by region had higher concentrations of sediment TP and organic matter than bottom sediments (20-30 cm, Table 3), although this pattern was not consistent at every site (Fig. 4A, B).

Comparison of these data with sediment TP concentrations at other west Michigan lakes and flooded celery fields sampled by AWRI showed that LMRRP sediment TP falls within the range between the highest (Black Creek muck fields, Muskegon Co.) and the lowest (Bear Creek east pond—previously dredged) concentrations (Fig. 5).

Equilibrium phosphorus concentrations using surface sediments were similar in the east and south central regions (Table 3); however, EPC_o values in the drier north central sediments were almost two orders of magnitude greater, far exceeding Muskegon River water column SRP concentration (Table 3, Fig. 6). Although EPC_o values in the bottom sediments (20-30 cm) of the northern region sites were lower than surface sediments, they still were very high and well above Muskegon River SRP concentrations, indicating these sediments also would serve as a P source to the overlying water column once inundated with Muskegon River water.

Although a few sites in the east and south central fields had EPC_0 means that were less than the P concentration of that site's overlying water column (Fig. 7), most were well above the overlying water SRP concentration, suggesting they too would serve as a P source. In addition, several of these sites had EPC_o values higher in the bottom than surface sediments, indicating that any restoration activity involving sediment removal must focus on depths at least to 30 cm, and likely even deeper.

Table 2. Mean (1 SD) water quality of surface waters at the wetland sites and the adjacent Muskegon River measured on 30 June 2016. Sites 1 & 3 (East), and sites 5, 7, & 8 (North) were either dry or had insufficient water to collect and measure. Site 4 (East) has been removed as an outlier during June sampling. SRP = soluble reactive P, TP = total P, DO = dissolved O_2, SpCond = specific conductance, TDS = total dissolved solids. ND = no data; NA = not applicable.

	East (n=1)	North (n=1)	South (n=7)	River (n=1)
Site Water Depth (m)	0.47 (NA)	0.36 (NA)	0.45 (0.12)	ND
Water column SRP (µg/L)	15 (NA)	579 (NA)	15 (19)	7
Water column TP (µg/L)	301 (NA)	619 (NA)	134 (61)	24
Temp (°C)	30.08 (NA)	24.33 (NA)	27.61 (1.62)	22.5
DO (mg/L)	9.79 (NA)	1.48 (NA)	7.01 (3.40)	9.17
DO (%)	129.8 (NA)	17.8 (NA)	88.2 (39.9)	106
pH	6.35 (NA)	6.39 (NA)	6.89 (0.27)	7.95
SpCond (µS/cm)	395 (NA)	1179 (NA)	680 (143)	404
TDS (mg/L)	261 (NA)	766 (NA)	442 (93)	263
Turbidity (NTU)	257.0 (NA)	54.7 (NA)	39.7 (27.1)	74.5

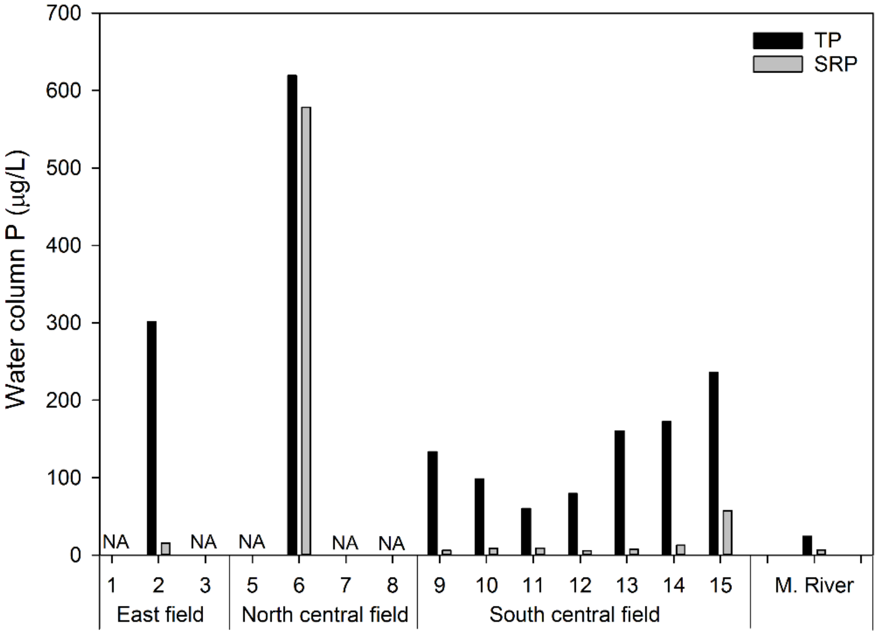

Figure 3. Water column total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations at each inundated site in the east field, north central field, and south central field areas of the pre-restoration wetland. Muskegon River water collected from adjacent to the wetland is provided for context. Site 4 (East) has been removed as an outlier during June sampling. Numbers along x-axis refer to site # (refer to Fig. 1 for site locations). Sites marked NA (not applicable) were either dry or had insufficient water for collection and measurement.

Table 3. Mean (±SD) sediment characteristics from cores collected 16-24 May 2016. Data at surface (0-10 cm) and bottom (20-30 cm) core depths are presented separately. Site 4 (East) has been removed as an outlier during June sampling. TP = total phosphorus, OM = organic matter, EPC_0 = equilibrium phosphorus concentration, S_{max} = phosphorus sorption maximum.

	Depth	East (n=3)	North (n=4)	South (n=7)
TP (mg/kg, dry wt.)	0-10 cm	1503 (501)	1676 (1084)	1329 (737)
	20-30 cm	903 (648)	1548 (960)	894 (417)
OM (%)	0-10 cm	24 (11)	25 (18)	27 (24)
	20-30 cm	23 (22)	24 (25)	16 (14)
EPC_0 (µg/L)	0-10 cm	53 (43)	3124 (3680)	44 (68)
	20-30 cm	97 (106)	1107 (1047)	43 (55)
S_{max} (mg/kg)	0-10 cm	1051 (370)	648 (251)	1559 (1203)
	20-30 cm	874 (463)	835 (431)	1977 (785)

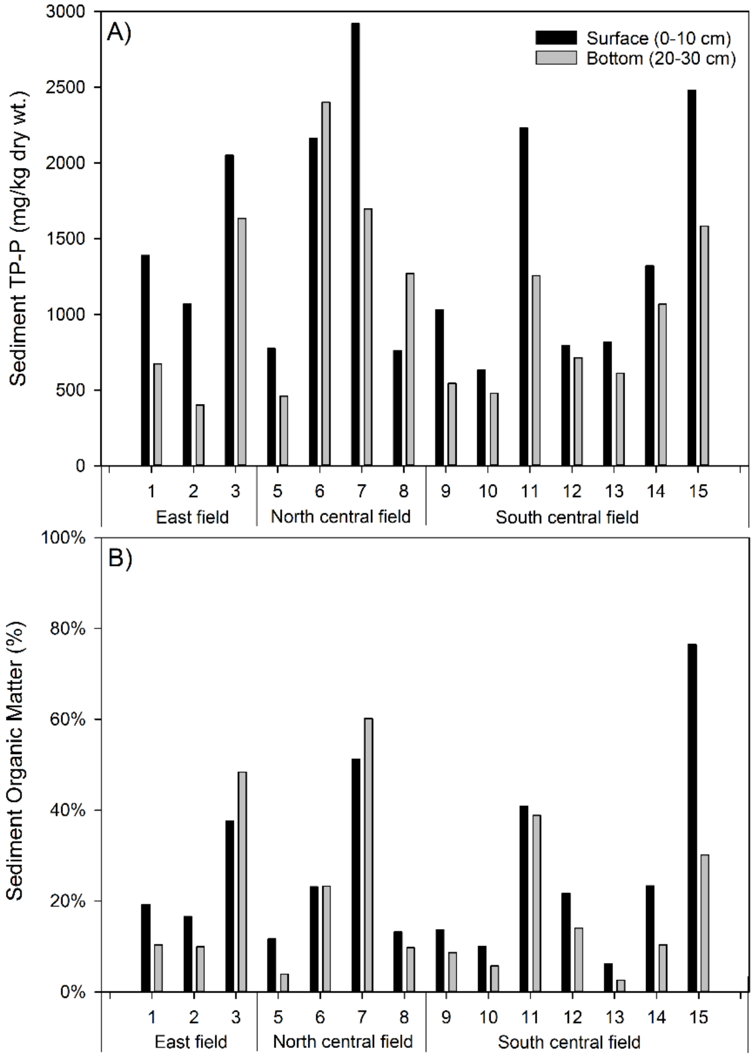

Figure 4. Sediment TP (A) and organic matter (B) in the sediments of the east field, north central field, and south central field areas of the pre-restoration wetland. Site 4 (East) has been removed as an outlier during June sampling. Legend in panel A also applies to panel B.

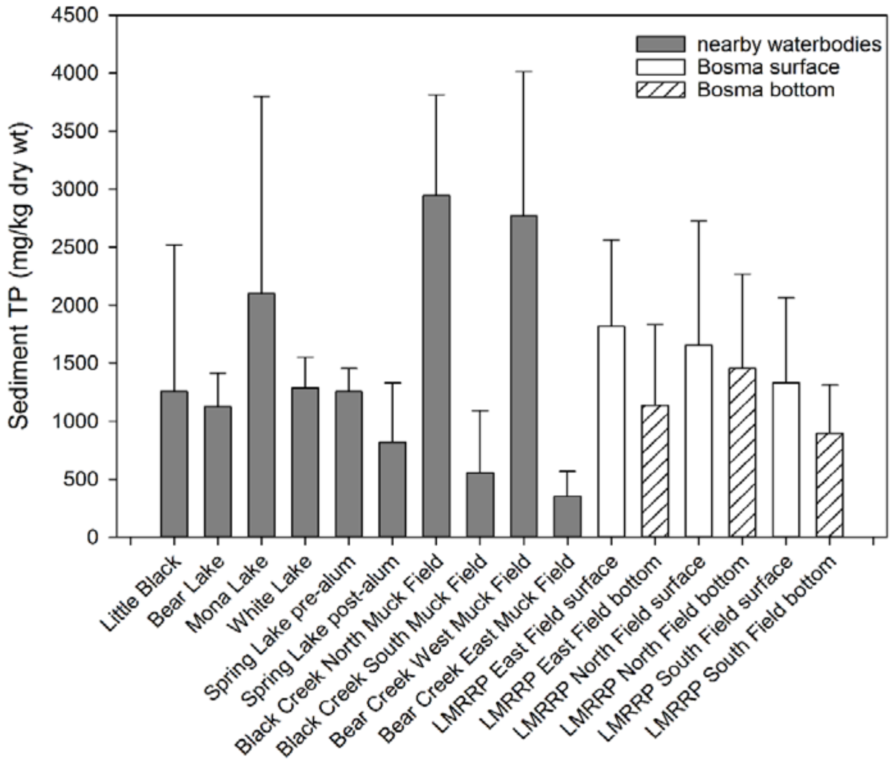

Figure 5. Comparison of mean (±SD) sediment TP measured in the LMRRP pre-restoration wetland and other west Michigan waterbodies. Sources: Little Black Lake: Steinman et al. 2011; Mona Lake: Steinman et al. 2009; White Lake: Steinman et al. 2008a; Spring Lake pre-alum: Steinman et al. 2004; Spring Lake post-alum: Steinman and Ogdahl 2008; Bear Lake: unpublished data; Black Creek muck fields: Steinman and Ogdahl 2011; Bear Creek: Steinman and Ogdahl 2013.

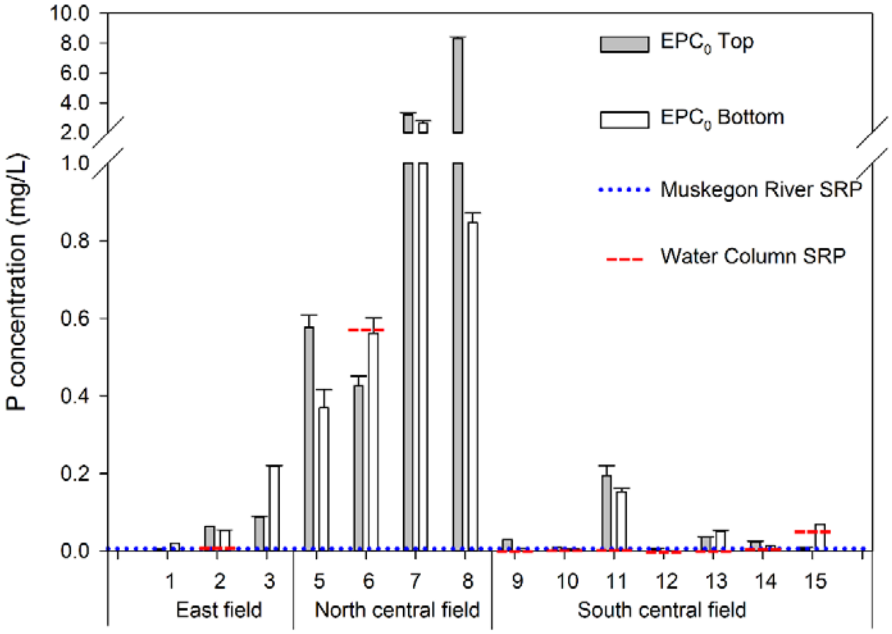

Figure 6. Mean (±SD) equilibrium P concentrations (EPC$_0$) in non-sterilized live cores (n=2) and water column soluble reactive P (SRP) concentrations at coring sites. Dotted reference line (blue) = Muskegon River SRP sampled adjacent to the wetland restoration area. Dashed lines (red) = water column SRP at inundated sites with sufficient water for collection. Site 4 (East) has been removed as an outlier during June sampling.

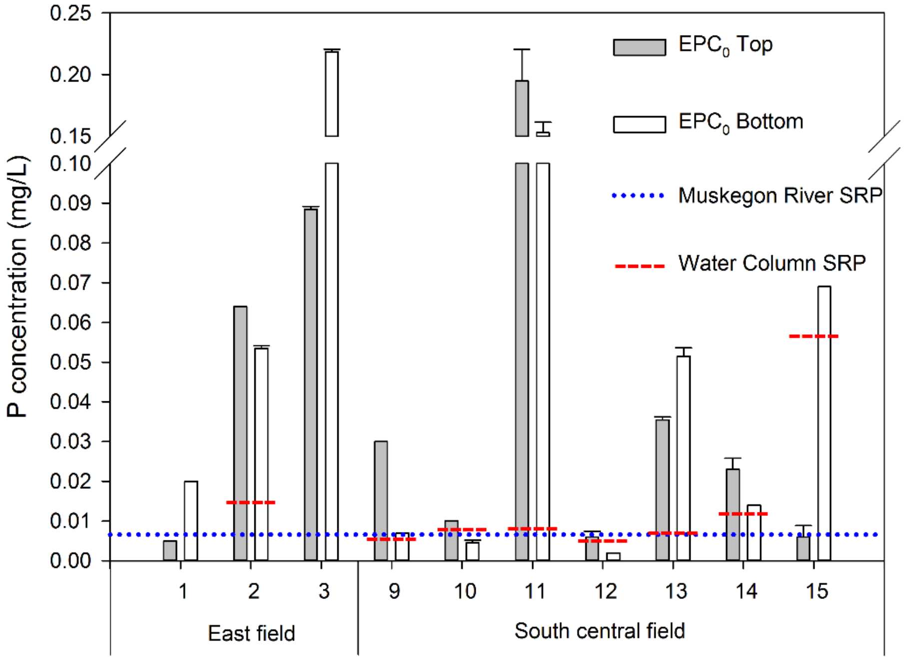

Figure 7. Additional detail of east and south central field (B) mean (±SD) equilibrium P concentrations (EPC$_0$; mg/L; n=2 cores) and water column SRP concentrations. Dotted reference line (blue) = Muskegon River water column SRP. Dashed lines at sites (red) = water column SRP at inundated sites with sufficient water for collection. See Fig. 6 for comparison to the North central field. Site 4 (East) has been removed as an outlier during June sampling.

Summer 2016 – Sediment P fractionation and rewetting experiment

During the summer 2016 sampling, physicochemical conditions throughout the wetland were generally similar to those measured during isotherm core sampling one month earlier; however, one key difference was mean water depth had increased by 35 cm in the south central field (Table 4).

Sediment TP and OM values were variable among sites and regions (Table 5, Fig. 8), and generally consistent with the patterns observed in June. Sediment TP ranged from 490 mg/kg dry weight (site 1) to 2277 mg/kg (site 7), with the highest TP values at Sites 6 and 7 in the north central field (Fig. 8).

Total sediment calcium and iron were abundant at all sites, ranging from 800 to 41,000 mg/kg and 1900-20,000 mg/kg, respectively (Fig. 9). Throughout the wetland property, calcium was more abundant than iron at upland sites throughout the property (especially sites 3 and 7), whereas iron was dominant at sites closer to the berm on the southern end of the property bordering the Muskegon River, primarily in the south central field (Fig. 9). Manganese was found in smaller concentrations than calcium and iron, ranging between 84-1000 mg/kg and sites with the highest Mn concentrations were upland or located near the north central field (Fig. 9).

Sediment P fractionation of the top 10 cm of sediment revealed that the loosely sorbed NH_4Cl-P fraction exists in minimal quantities (0-3 µg/g) throughout the wetland (Fig. 10). Across all wetland sites, the BD-P, NaOH-P, and HCl-P fractions each averaged 72-74 µg/g; when grouped by area, the east field contained more NaOH-P (48±27 µg/g), the highly variable north central field tended to have more HCl-P

(111±91 µg/g), and the south central field favored BD-P and NaOH-P (103±69 µg/g and 91±45 µg/g, respectively) (Fig. 10).

During the first rewetting experiment, core leakage ended the experiment after 24 hr, precluding measurements at 48 hr. At 24 hr, temperature and dissolved oxygen values in the overlying water were similar across regions (Table 6). Mean SRP flux, normalized by either sediment core area or OM, was much larger in the north central field cores than in east or south central cores, with the notable exception of site 6, which had minimal observed flux (Table 6, Figs. 11, 12), but unlike the other non-inundated sites in the north central region, this site had 35 cm of standing water. Several east and south central field sites were found to have slightly negative SRP flux, indicating P leaving the water column in these cores (Fig. 12). While this negative flux may be due to core leakage, the sites do have other traits in common: these sites (#9, 10, 12, 13, & 14) are all similarly located near the southern edge of the wetland boundary and in addition to site #1, each site had iron as the dominant sediment metal (Fig. 9).

Major cation and anion concentrations in water samples are presented in the Appendix (Appendix Tables 1-8 and Appendix Figures 1-2). In general, ion concentrations in the porewater were elevated compared to the Muskegon River and other unpolluted surface waters in west Michigan. High spatial variability was observed, with some evidence of likely historical pollution legacies that could be attributable to brines from petroleum wells (e.g., chloride and bromide: Appendix Figure 2). Sulfate also was elevated in porewaters.

Dissolved Fe(II), the reduced form of iron, was measurable in most samples, and presumably concentrations measured in the rewetting experiment represent iron reduction processes over the short duration of experimental flooding since conditions were oxidizing prior to that (Appendix Tables 9 and 10 and Appendix Figure 3). The East and North Central fields produced more Fe(II) than the South Central Field. Dissolved free sulfide (H_2S) was also measured but was never found at measurable concentrations (data not shown).

Table 4. Mean (±SD) site depth and general water quality variables of overlying wetland water columns during sediment coring for P fractionation and the first rewetting experiment collected 25-26 July 2016. Site 3 in the east field and sites 5, 7, & 8 in the north central field were either dry or had insufficient water to collect and measure.

	East (n=3)	North (n=1)	South (n=7)
Depth (m)	0.42 (0.25)	0.50 (NA)	0.70 (0.09)
Temp (°C)	26.18 (0.65)	27.40 (NA)	22.47 (4.41)
DO (mg/L)	7.02 (0.35)	5.63 (NA)	7.85 (0.90)
DO (%)	86.9 (4.9)	71.3 (NA)	90.3 (8.2)
pH	7.08 (0.40)	6.69 (NA)	7.60 (0.29)
SpCond (µS/cm)	510 (313)	843 (NA)	611 (88)
TDS (mg/L)	331 (204)	548 (NA)	397 (57)
Turbidity (NTU)	35.5 (35.5)	31.5 (NA)	8.7 (8.4)

Table 5. Mean (±SD) sediment TP and organic matter (OM) in top 10 cm of cores collected for P fractionation and the first rewetting experiment in Summer 2016.

	East (n=4)	North (n=4)	South (n=7)
TP (mg/kg dry wt)	825 (286)	1608 (652)	1200 (264)
OM (%)	15 (13)	23 (13)	22 (14)

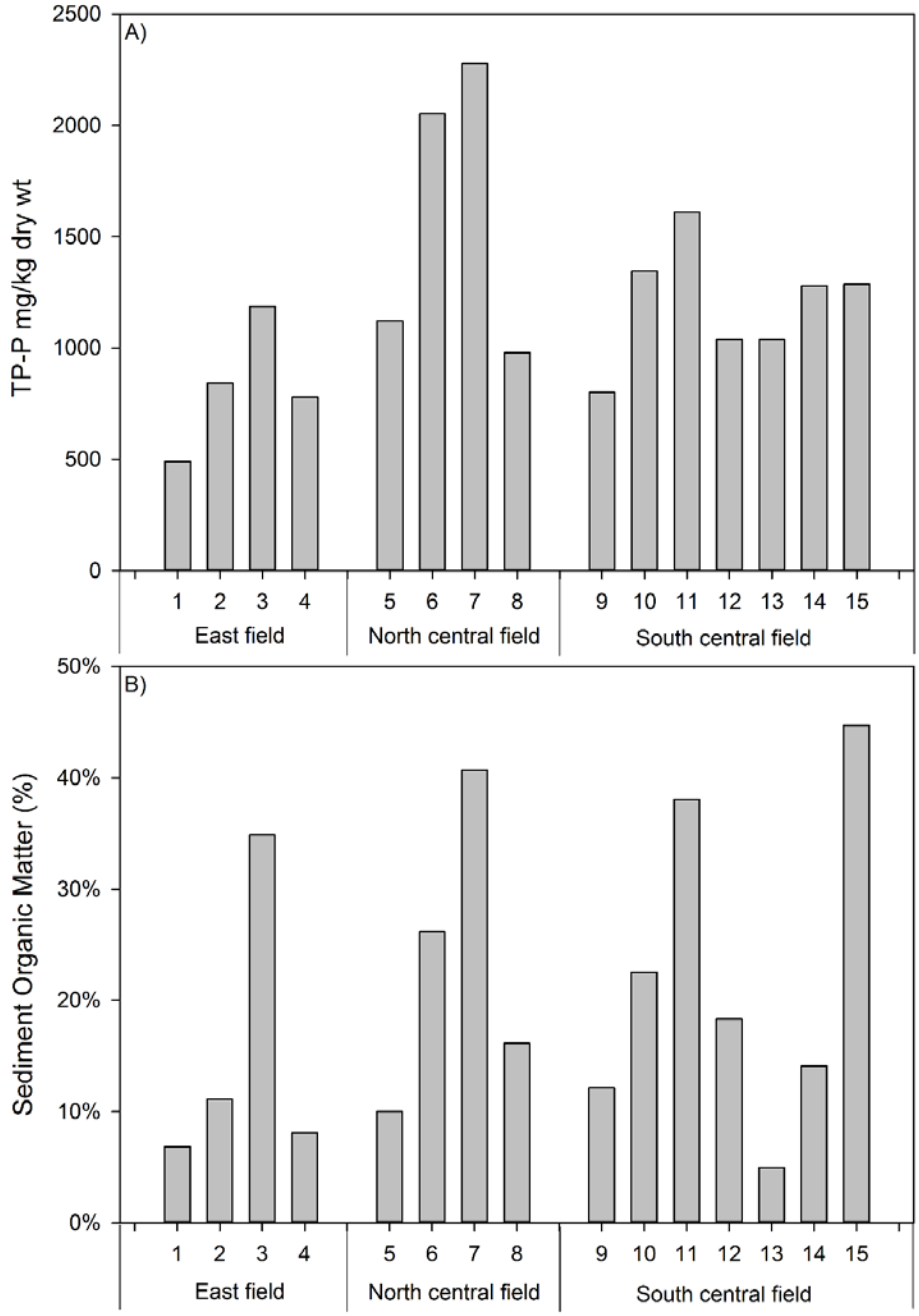

Figure 8. Sediment TP (A) and organic matter (B) in cores collected for P fractionation and the first rewetting experiment in Summer 2016.

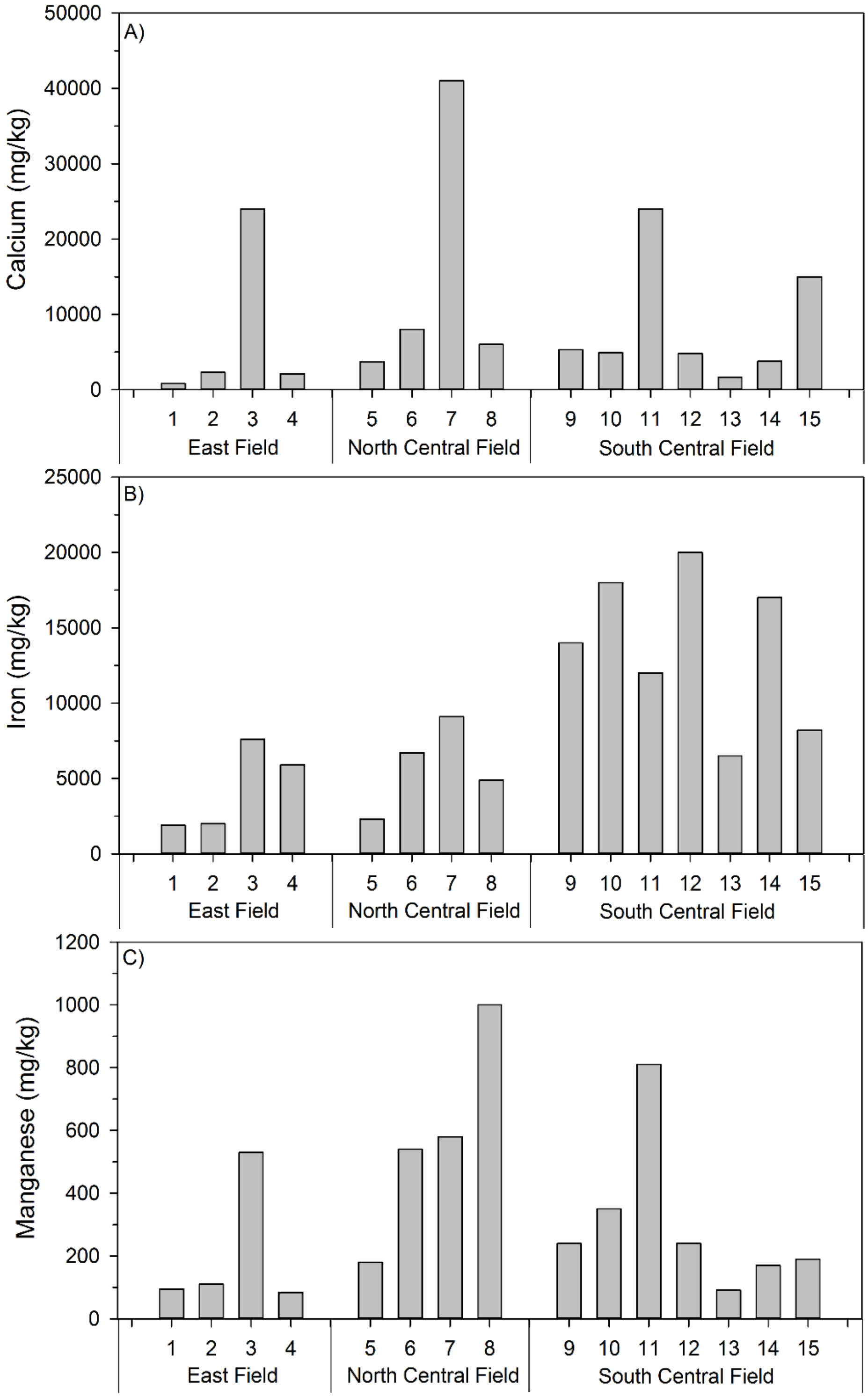

Figure 9. Sediment core concentrations of calcium (Ca), iron (Fe), and Manganese (Mn) from each pre-restoration wetland site collected in Summer 2016. Note different scales for y-axes.

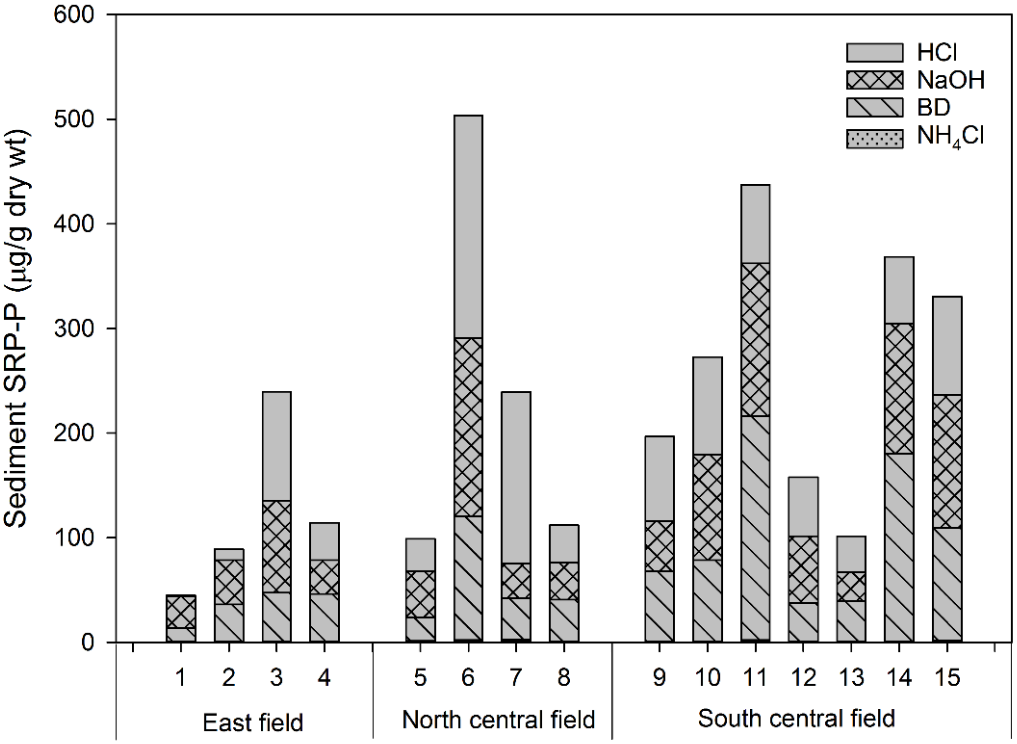

Figure 10. Sediment P fractions (top 10 cm) shown as stacked columns by site. Note that SRP concentrations from NH_4Cl (loosely sorbed P) are too low to appear in this figure.

Table 6. Mean (±SD) values of water overlying the sediment cores measured via ProDO and P flux at 24 hours post-rewetting during the first rewetting experiment in August 2016. Water was measured in cores with minimal disturbance from the sonde; however, cores leaked overnight. DO =dissolved O_2, SRP =soluble reactive P.

	East (n=4)	North (n=4)	South (n=7)
Temp (°C)	21.48 (0.67)	21.45 (0.17)	21.50 (0.14)
DO (mg/L)	7.16 (0.99)	5.99 (1.89)	7.34 (0.58)
DO (%)	81.0 (10.9)	67.9 (21.2)	83.2 (6.5)
SRP Flux (mg/m^2/d)	7 (6)	83 (56)	1 (2)
SRP Flux (mg/kg OM/d)	25 (28)	152 (115)	1 (4)

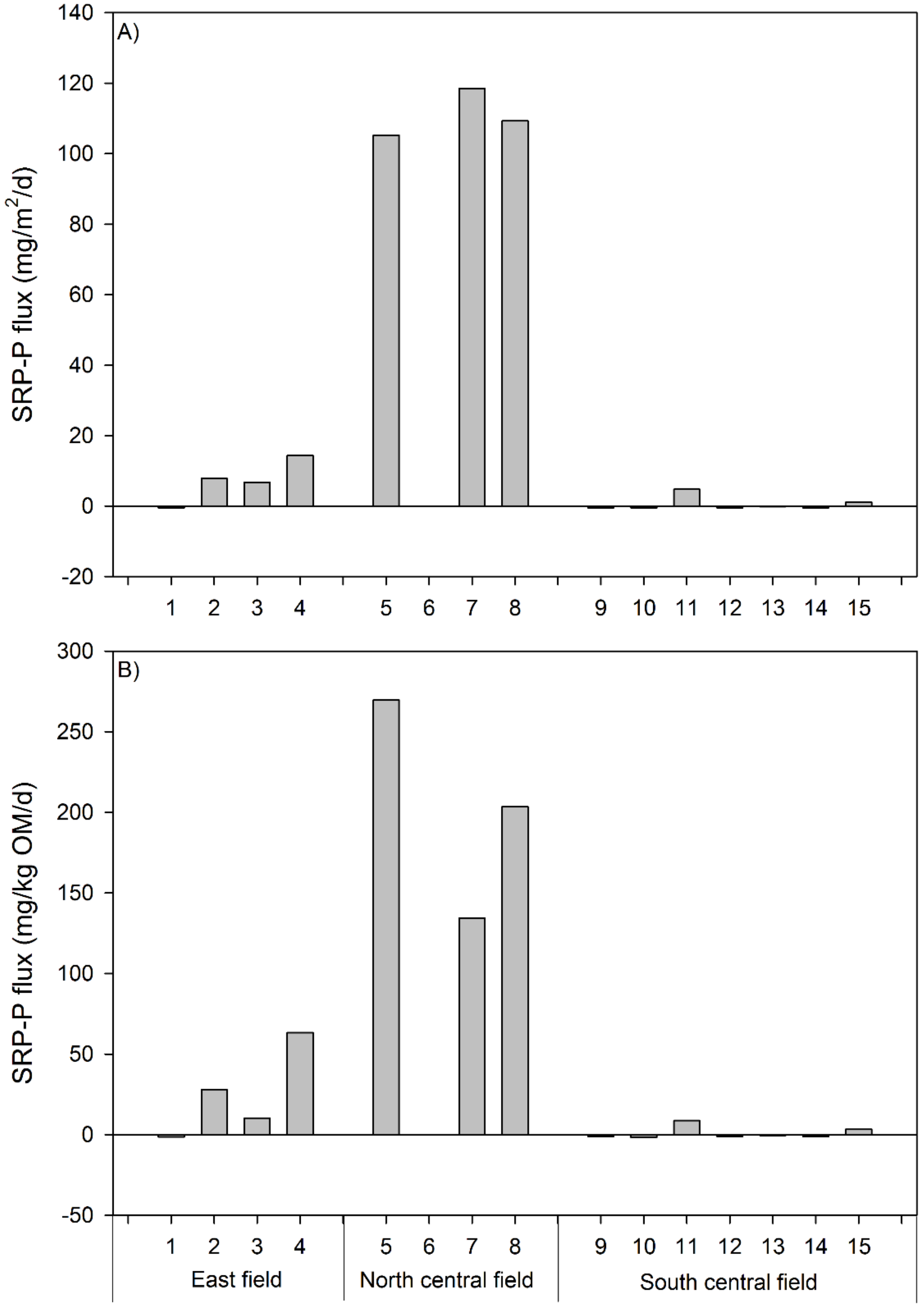

Figure 11. P fluxes from sediments to overlying water normalized by area (A) or by sediment organic matter mass (B) 24 hr post-rewetting. These data represent sediment cores from the original rewetting experiment collected in Summer 2016. Note different scales for y-axes.

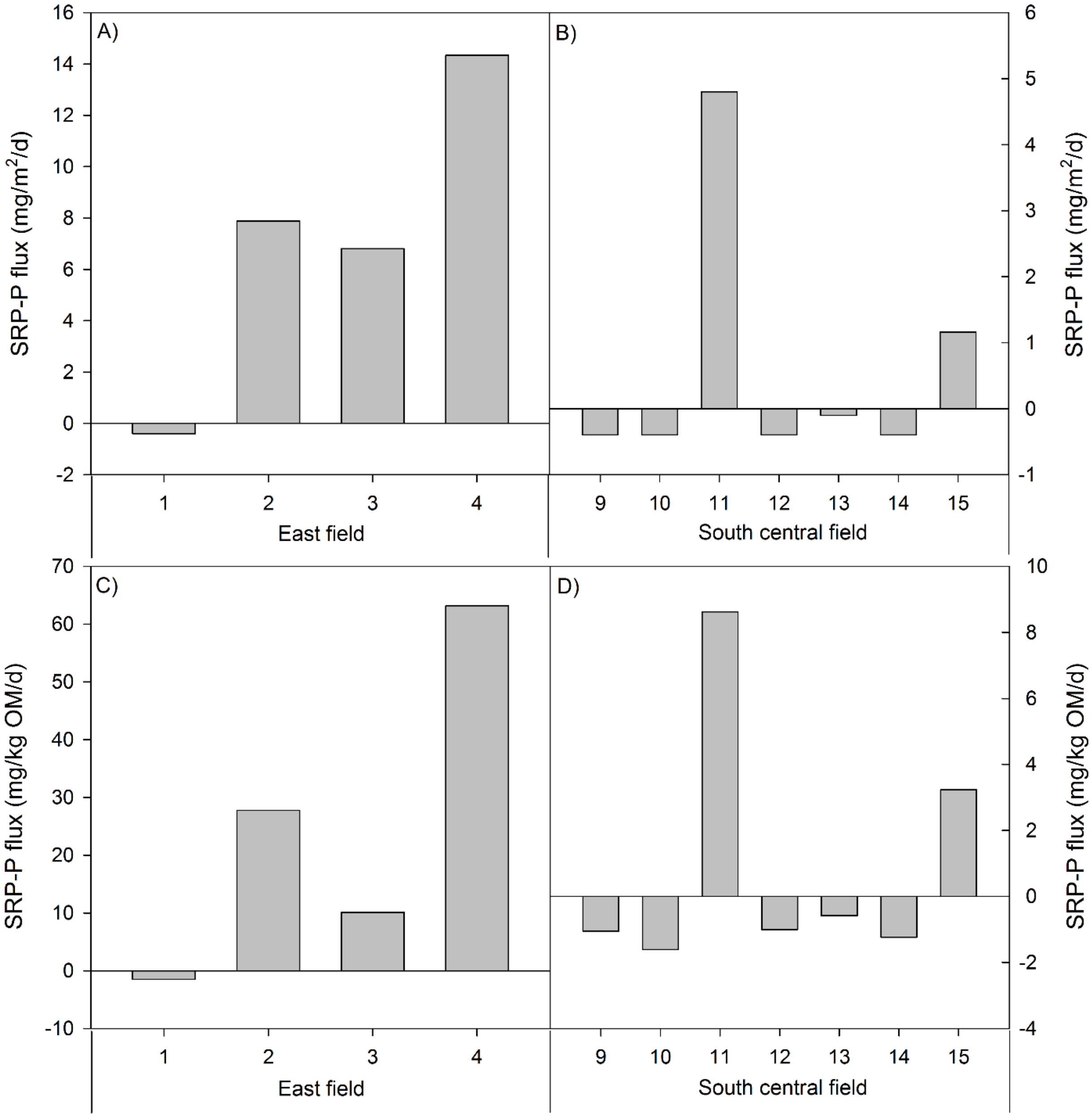

Figure 12. Increased detail of Summer 2016 rewetting P flux (blow ups of Fig. 11) normalized by sediment core area (panels A, B) and by sediment organic matter mass (panels C, D) at east and south central wetland sites. Note different scales for y-axes between all panels. See Fig. 11 A, B for flux comparison to North central field.

Fall 2016 – follow-up rewetting experiment

During this second rewetting experiment, water quality and depth in the wetland remained similar to our previous coring in the summer (cf. Tables 4 vs. 7); however, water temperature dropped 4-9°C and dissolved oxygen concentrations decreased at all sites where it was measureable (Table 7). Sediment cores collected for rewetting in fall were generally similar with respect to sediment TP and OM concentrations (Tables 5 vs. 8, Fig. 13).

Temperature was consistent between 24 and 48 hr, although DO concentrations increased between the two sampling days, in some cases more than doubling in the 24 hour timespan (Table 9). During the drying period prior to rewetting, herbaceous vegetation was observed growing from core sediments and was not removed prior to rewetting, so photosynthetic activity may have accounted for this increase.

SRP flux normalized by either area or sediment OM was positive in all cores and at both 24 and 48 hr but rates were very variable over time and space (Table 9, Fig. 14). At both sampling times, site 14 had the highest SRP flux (Fig. 14). Between the 24 and 48 hr sampling times, SRP fluxes in sediment cores from the east and north central sites (2, 6, 7) increased, whereas SRP fluxes in the more south central sites (8, 14, 15) decreased (Table 9, Fig. 14).

Table 7. Mean (±SD) depth and general water quality variables of overlying water during sediment coring for P fractionation and the first rewetting experiment in Fall 2016.

	East (n=1)	North (n=1)	South (n=2)
Water Depth (m)	0.44 (NA)	0.41 (NA)	0.74 (0.10)
Temp (°C)	17.66 (NA)	16.85 (NA)	18.02 (0.19)
DO (mg/L)	5.84 (NA)	6.45 (NA)	6.37 (0.83)
DO (%)	61.4 (NA)	66.7 (NA)	67.4 (8.6)
pH	7.75 (NA)	8.14 (NA)	8.19 (0.26)
SpCond (µS/cm)	590 (NA)	841 (NA)	634 (100)
TDS (mg/L)	384 (NA)	547 (NA)	412 (65)
Turbidity (NTU)	7.1 (NA)	29.1 (NA)	19.9 (3.1)

Table 8. Mean (±SD) sediment TP and organic matter in cores collected for the second rewetting experiment in Fall 2016.

	East (n=1)	North (n=3)	South (n=2)
TP (mg/kg dry wt)	877 (NA)	1905 (693)	1102 (553)
OM (%)	12 (NA)	25 (12)	19 (10)

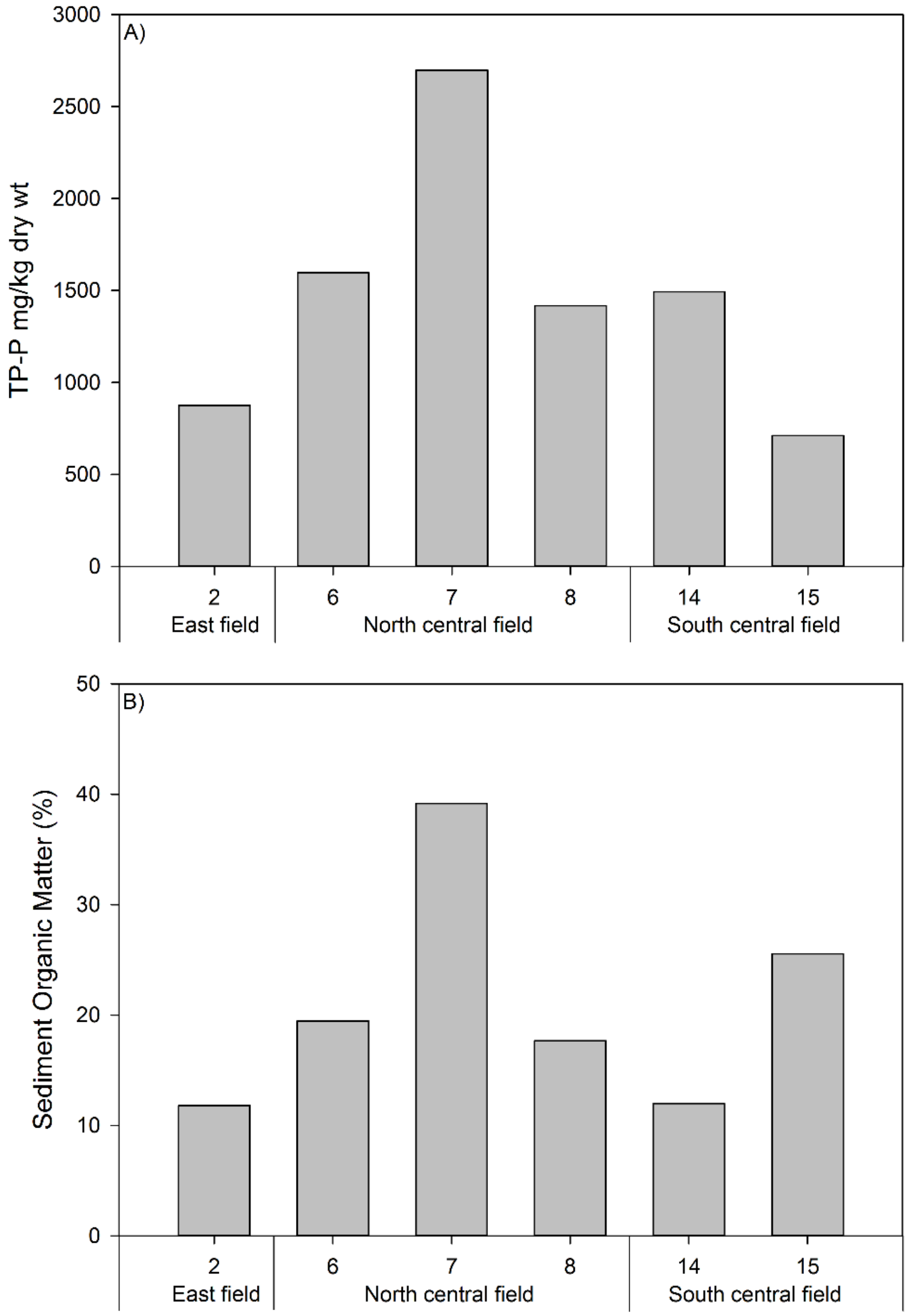

Figure 13. Sediment TP (A) and organic matter (B) in the sediment cores collected for the second rewetting experiment in Fall 2016.

Table 9. Mean (±SD) temperature and dissolved O_2 of sediment core overlying water measured via ProDO and SRP flux weighted by area or organic matter dry mass at 24 and 48 hours post-rewetting during the second rewetting experiment in Fall 2016. DO was measured in cores with minimal disturbance from the sonde and cores did not leak overnight.

	Time	East (n=1)	North (n=3)	South (n=2)
Temp (°C)	24H	22.60 (NA)	22.97 (0.21)	22.75 (0.21)
	48H	22.70 (NA)	22.53 (0.12)	22.60 (0.14)
DO (mg/L)	24H	1.65 (NA)	2.45 (0.59)	1.69 (0.07)
	48H	4.85 (NA)	3.92 (2.27)	4.42 (1.32)
DO (%)	24H	19.5 (NA)	28.6 (6.9)	19.8 (0.8)
	48H	56.5 (NA)	45.5 (26.3)	51.4 (15.3)
SRP Flux (mg/m^2/d)	24H	3 (NA)	22 (10)	72 (55)
	48H	5 (NA)	57 (47)	35 (41)
SRP Flux (mg/kg OM/d)	24H	6 (NA)	26 (10)	132 (126)
	48H	9 (NA)	63 (45)	69 (85)

Table 10. Mean (±SD) general water quality variables of sediment core overlying water measured at 48 hours post-rewetting via YSI 6600 during the second rewetting experiment in Fall 2016.

	East (n=1)	North (n=3)	South (n=2)
Temp (°C)	21.73 (NA)	22.36 (0.45)	21.99 (0.06)
DO (mg/L)	5.32 (NA)	5.83 (0.41)	4.69 (0.22)
DO (%)	60.4 (NA)	65.5 (4.2)	53.1 (1.6)
pH	7.28 (NA)	7.03 (0.15)	7.07 (0.30)
SpCond (µS/cm)	382 (NA)	491 (366)	522 (371)
TDS (mg/L)	248 (NA)	319 (237)	339 (241)
Turbidity (NTU)	91.2 (NA)	36.4 (56.3)	9.3 (2.2)

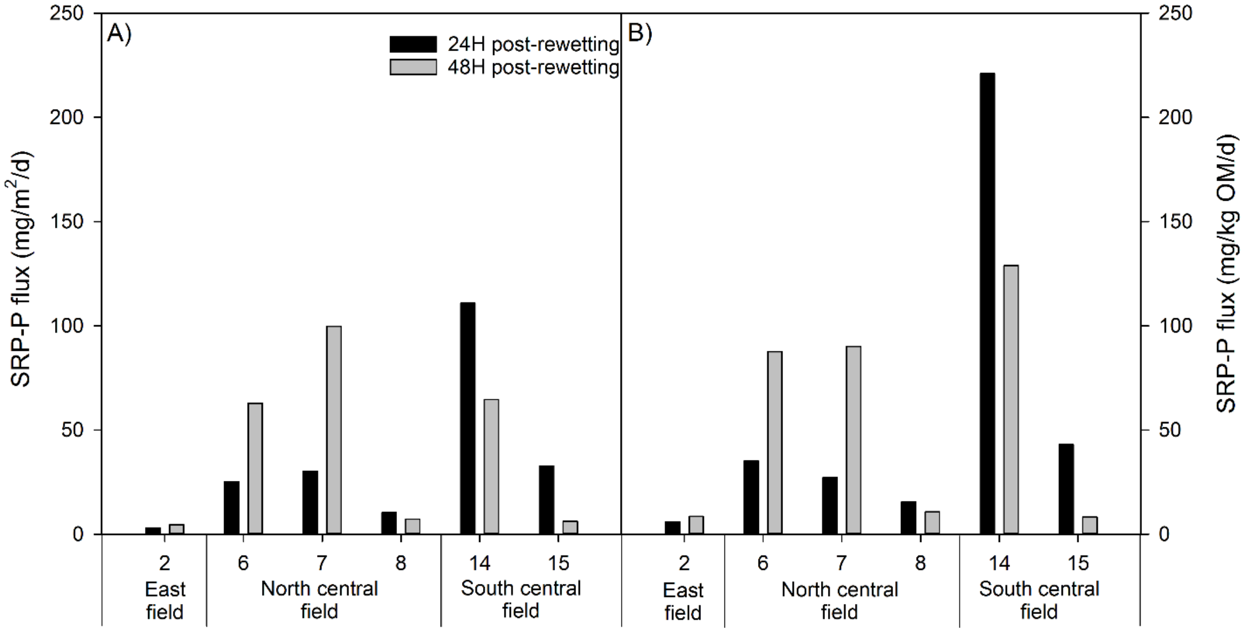

Figure 14. Water column P flux normalized by area (A) or by sediment organic matter mass (B) 24 and 48 hr post-rewetting. These data represent sediment cores from the second rewetting experiment conducted in Fall 2016. Legend in A also applies to B.

Discussion

The reconversion of agricultural lands to functional wetlands can restore critical ecosystem services, such as nutrient retention, contaminant filtration, and fish and wildlife habitat; however, legacy phosphorus held in soils (cf. Ardón et al. 2010; Steinman and Ogdahl 2011a; Jarvie et al. 2013; Sharpley et al. 2013; Chen et al. 2015) can complicate restoration activities, as reflooding of drained, P-rich soils can mobilize phosphorus (Baldwin, 1996; Pant and Reddy, 2003; Kinsman-Costello et al. 2014; Steinman et al. 2014; Steinman and Ogdahl 2016). If the restored wetland is hydrologically reconnected to the active floodplain, this released phosphorus can result in downstream water quality impairment. This potential consequence is a key concern in the current study, given that Muskegon Lake is an Area of Concern and one of its current beneficial use impairments is eutrophication and nuisance algae. Although total phosphorus concentrations in Muskegon Lake have declined dramatically since the rerouting of wastewater to the Muskegon County Wastewater Treatment Plant (Steinman et al. 2008a), and in 2016 were below the restoration goal of 25 µg/L, chlorophyll a concentrations in 2016 were above the restoration goal (http://www.gvsu.edu/wri/director/muskegon-lake-water-quality-dashboard-78.htm). This indicates that we must be vigilant in reducing new nutrient loads to Muskegon Lake.

These preliminary results (i.e., pre-restoration construction) clearly indicate there is considerable spatial variation in the P concentrations and dynamics of the sediment in the restoration footprint. For example, the sites in the north-central region had much higher sediment TP concentrations and P release rates (first release experiment) compared to the other regions. Site 6 was an exception—despite relatively high sediment TP and OM, it had a very low P release rate, likely because unlike the other sites in this region, it had ~35 cm of standing water when we sampled, with low DO and relatively high SRP concentrations (Fig. 6); the absence of a concentration gradient between sediment and overlying water P resulted in almost no positive release. The high release rates in the other 3 north-central sites may have been related to 1) prior land use, with greater application of fertilizer in this more upland area; and 2) tendency to be more desiccated than the other regions. Prior studies have shown that exposed sediments release more phosphorus after inundation than sediments that remain inundated (DeBusk and Reddy 2003; Schönbrunner et al. 2012; Steinman et al. 2012). Mechanisms potentially responsible for this effect include: 1) mineralization of organic P originating from lysed cells after desiccation, resulting in inorganic P diffusing into the water column (Sparling et al. 1985, but see Qiu and McComb 1994); 2) inundation-induced anoxia resulting in dissociation of P-bound Fe oxyhydroxides (Boström et al. 1982); 3) increasingly oxidized and more crystalline sediments, which result in fewer binding sites and reduced binding capacity (Baldwin 1996); and 4) P release from apatite if sulfide oxidation or respiration are sufficiently extensive to lower sediment pH, resulting in dissociation of P from $CaCO_3$ (Pant and Reddy 2003).

The presence of measurable concentrations of dissolved Fe(II) in most sediment porewater samples suggests that Fe oxyhydroxides could be important in P binding under oxidized conditions (i.e., desiccation of soils), and they would tend to release P under reducing conditions (i.e., reflooding). The abundant sulfate in the sediment porewaters would support bacterial sulfate reduction once iron reduction becomes limited by the availability of Fe oxyhydroxides, and the resultant sulfide could tie up Fe that would otherwise bind P, releasing the P into solution (Burgin et al. 2011). Although further study would be required to understand the importance of these biogeochemical reactions to sediment P release at this site, the evidence presented here suggests that alternating between oxidized and reduced conditions as a result of drying and flooding could result in redox transformations of iron and sulfur that influence P binding and release.

To determine if sediment exposure to air (i.e., oxidation) affected P release rates, we regressed the depth of standing water and P release rates from our first rewetting experiment and found a very strong inverse logarithmic relationship ($R^2 = 0.92$). Consistent with prior studies, the exposed north central sites (red) with no standing water had high SRP flux, while sites in the south central region (yellow) had high levels of standing water and very low SRP flux. The east region sites (blue) had low release rates despite a range of standing water values (Fig. 15).

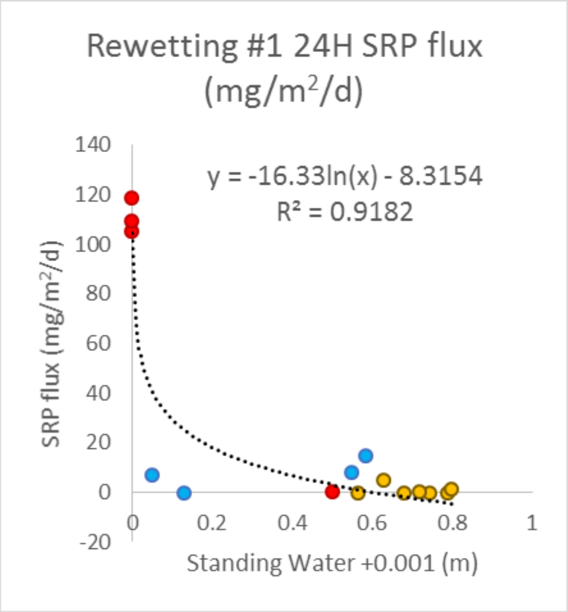

Figure 15. Regression of adjusted water depth and SRP flux from first rewetting experiment in August 2016. North central sites (red: #5, 7, 8); east field sites (blue: #1, 3); and south central sites (yellow).

We conducted a second release experiment, using a subset of sites from different regions, which again reflected high P release rates from the north-central region, but also relatively high release rates from the south-central region, where sites were inundated (Fig. 16). These results were unexpected, given the very low release rates from the south-central region in the first release experiment (Fig. 11). Sediment TP and OM concentrations were generally similar at the south-central region sites in the two experiments, so that cannot account for this difference. Given that the first experiment had water leakage through the rhizon ports in the core tubes, it is possible that water with high P concentrations leaked out from these sites, resulting in artificially low P concentrations, although if true, it is unclear why the north-central sites did not experience the same phenomenon. Although there was still a negative relationship between water level and P release, the R^2 was quite low (0.08) and the function was not logarithmic (Fig. 16).

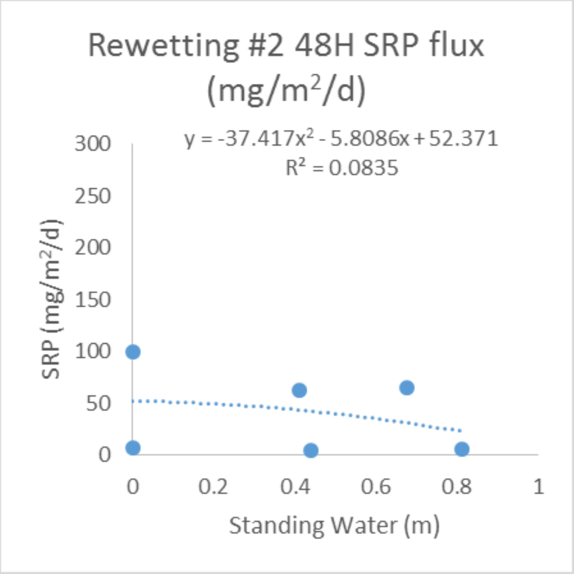

Figure 16. Regression of adjusted water depth and SRP flux from second rewetting experiment in Fall 2016.

The P release rates measured were unusually high at the north-central sites (both experiments) and the south-central sites (second experiment). Nürnberg and LaZerte (2004) looked at TP release rates in comparison to lake trophic state for 91 small lakes, and found that hypereutrophic systems had release rates ranging from 6 to 47 mg P/m^2/d. Many of our short-term release rates far exceeded even the high range of hypereutrophic systems; while these short-term release rates are clearly worst-case scenarios, as the release rates will decline over time, they do indicate a very high potential for P release, especially after sediments have been desiccated.

This variability in P release and potential association with sediment drying leads to the question of whether the other regions will release higher P amounts if they desiccate as well. Management strategies to mitigate this result could include sediment removal (a more permanent but expensive strategy) or intentional inundation while the wetland is hydrologically contained inside the berm, followed by application of a chemical inactivation agent, such as alum or phoslock (Spears et al. 2016).

The isotherms indicated that many of the sites were likely to release P once exposed to Muskegon River water, results that are consistent with our rewetting experiments. Again, there was considerable spatial variation in EPC values although sediments in the north-central region tended to show the greatest likelihood of P release. The sediment fractionation revealed that there was very little loosely sorbed P in the sediment, regardless of region, although the redox-sensitive fraction could account for half of all the fractions at some sites, especially in the south-central region. This suggests that if the sediments at these sites went anoxic, a significant amount of P could be liberated through iron reduction (Boström et al. 1982). It is also worth noting that there wasn't a distinct difference in EPC values at the shallow (0 – 10 cm) and deep (20 – 30 cm) sediment depths. This indicates that if sediment removal becomes a P mitigation approach, the dredging depth must be below 30 cm, and additional cores should be analyzed to determine the appropriate depth. In the long run, the cost of this analysis will result in considerable savings in the long run.

Although our analyses indicate these sediments have the potential to release significant amounts of P in this localized area, it is important to place this P release in a larger context. That is, how much P could this site contribute to Muskegon Lake relative to the P load currently reaching the lake? To address this question, we extrapolated the P release rates from our sampling sites to the entire restoration area and compared that to P load data from Marko et al. (2013). Although there are multiple inflows into Muskegon Lake, the Muskegon River accounts for ~95% of the total flow entering the lake, so this calculation includes loads from only the Muskegon River. Marko et al. (2013) estimated the Muskegon River contributed a seasonal (March-September) TP load of 24 metric tons to Muskegon Lake. They did not measure SRP loads, but they did provide dissolved reactive P concentration data, so we can estimate the percent of TP that is in the form of dissolved reactive P, and use that ratio to estimate SRP loads in the River. The SRP:TP ratio was 48.05%, which translates into a seasonal SRP load (assuming SRP and DRP are equivalent) of 11.53 metric tons.

We used two approaches to estimate the SRP load from the restoration site. The first approach simply used the mean SRP release rate from our 15 sites, which was ~24.5 mg/m^2/d. By extrapolating that areal rate to the entire 52 acre site, and multiplying by 180 to convert a daily rate to the March-September time frame of Marko, the potential SRP load from the entire restoration site is 0.93 metric tons, or ~4% of the Muskegon River SRP load. The second approach was more site-specific, where we used geospatial techniques to interpolate among the sites, thereby accounting for spatial differences and gradients within the restoration area (Fig. 17). In this case, we estimated a SRP load of 0.52 metric tons from the site, or ~2% of the Muskegon River SRP load.

Regardless of approaches, these estimates indicate that the potential SRP load from the restoration site is very small compared to the total load entering Muskegon Lake. Indeed, these estimates, albeit small, are undoubtedly *overestimates* of the restoration site's actual contribution, given that 1) we do not account for all the SRP loads into Muskegon Lake; and 2) our release rates were based on short-term, optimal conditions for release. While these are admittedly coarse-level calculations, they provide a first-order estimate of P contributions from the LMRRP.

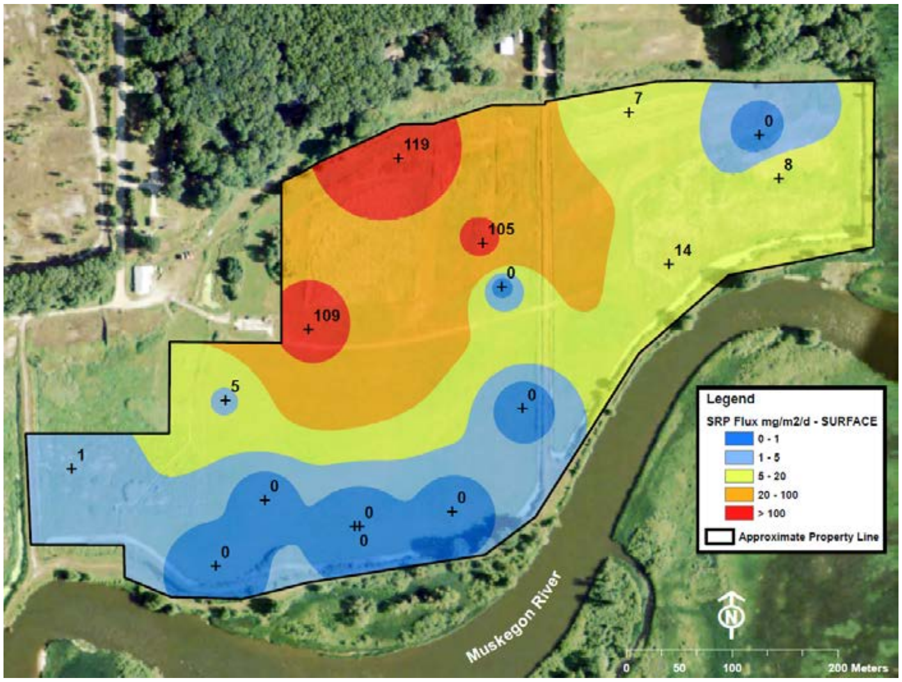

Figure 17. SRP flux map calculated using the Inverse Distance Weight interpolation method in ArcGIS 10.4.

Conclusions

It is not surprising that the sediments in the LMRRP have high sediment P concentrations with the potential to release significant amounts of P. Our results indicate that there is spatial variability in the restoration zone, with greater P release potential in sediments that have experienced drying, where the "Birch effect" (Birch 1958) can result in nutrient release from sediments.

Our results indicate that, for the most part, the sediments in this restoration area have limited capacity to adsorb additional P, and therefore reconnection is likely to result in potentially high concentrations of bioavailable phosphorus to Muskegon River and then to Muskegon Lake, which may result in localized (and short-term) impairment. Despite potentially high P concentrations, our load estimates suggest the mass of SRP coming off the restoration site is likely to be very small compared to the total SRP load coming into Muskegon Lake (i.e., <4%). This should be taken into consideration when evaluating mitigation strategies for the site.

Although our study was not designed to address specific mitigation strategies, we note that sediment removal presents a more permanent solution than chemical inactivation. However, we recommend additional long cores be extracted in select locations to measure how sediment total phosphorus and organic matter change with depth (and perhaps some fractionations), which can be used to determine the appropriate sediment removal depth (cf. Steinman and Ogdahl 2016).

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Supplemental Table 1. May 2016 sediment core characterization sample summary. Sediment total phosphorus (TP), organic matter (OM) and water column soluble reactive phosphorus (SRP) were each sampled once per site. Equilibrium phosphorus concentration (EPC_0) and P sorption maximum (S_{max}) were each subsampled and measured three times (two live replicates, one dead) from site sediment cores. Water column SRP at sites that were dry or had insufficient standing water to collect and measure are marked not available (NA). The first row of each core depth is highlighted gray to improve readability. Site 4 was removed from this analysis (see main body of report).

Site	Depth, cm	Description	Replicate	Sediment TP (dry), mg/kg	Sediment OM, %	EPC_0, mg/L	S_{max}, mg/kg	Water column SRP, mg/L
1	surface (0-10)	very wet, many roots, hydrocarbon smell	L1	1390	19%	0.005	1250	NA
			L2			0.005	1111	
			D			0.008	769	
	bottom (20-30)	sand	L1	673	10%	0.020	909	NA
			L2			0.020	833	
			D			0.026	833	
2	surface (0-10)	very wet, sandy muck	L1	1069	17%	0.064	769	0.0154
			L2			0.064	500	
			D			0.102	667	
	bottom (20-30)	sandy clay muck	L1	402	10%	0.054	556	0.0154
			L2			0.053	270	
			D			0.064	333	
3	surface (0-10)	wet muck, large roots	L1	2051	38%	0.089	1429	NA
			L2			0.088	1250	
			D			0.116	1429	
	bottom (20-30)	sandy clay muck	L1	1634	48%	0.217	1250	NA
			L2			0.220	1429	
			D			0.287	1429	
5	surface (0-10)	sandy muck and manure smell	L1	774	12%	0.599	625	NA
			L2			0.554	500	
			D			1.193	556	
	bottom (20-30)	sand	L1	460	4%	0.336	333	NA
			L2			0.402	278	
			D			0.443	286	
6	surface (0-10)	very wet, sandy muck	L1	2164	24%	0.444	526	0.5785
			L2			0.408	667	
			D			0.505	1250	
	bottom (20-30)	sandy clay	L1	2400	23%	0.589	1429	0.5785
			L2			0.532	1250	
			D			0.639	1250	

7	surface (0-10)	muck	L1	2920	51%	3.096	588	NA
			L2			3.276	1429	
			D			6.404	1429	
	bottom (20-30)	lots of plant material	L1	1696	60%	2.564	909	NA
			L2			2.735	1000	
			D			3.871	833	
8	surface (0-10)	sandy with many roots	L1	762	13%	8.416	294	NA
			L2			8.195	556	
			D			7.669	256	
	bottom (20-30)	sandy muck	L1	1271	10%	0.830	769	NA
			L2			0.864	714	
			D			1.028	714	
9	surface (0-10)	clay with hydrocarbon smell	L1	1030	14%	0.030	1250	0.0062
			L2			0.030	1250	
			D			0.046	1429	
	bottom (20-30)	clay with hydrocarbon smell	L1	545	9%	0.007	2000	0.0062
			L2			0.007	2000	
			D			0.010	2000	
10	surface (0-10)	very wet, sandy muck	L1	632	10%	0.010	1429	0.0087
			L2			0.010	1429	
			D			0.019	1429	
	bottom (20-30)	clay	L1	478	6%	0.004	1667	0.0087
			L2			0.005	1429	
			D			0.005	2500	
11	surface (0-10)	sandy clay muck	L1	2230	41%	0.177	1429	0.0089
			L2			0.213	1250	
			D			0.353	1667	
	bottom (20-30)	sandy clay	L1	1256	39%	0.159	1667	0.0089
			L2			0.147	2000	
			D			0.180	1667	
12	surface (0-10)	clay muck with large roots	L1	796	22%	0.007	1000	0.0058
			L2			0.005	1000	
			D			0.025	1250	
	bottom (20-30)	light colored clay	L1	713	14%	0.002	3333	0.0058
			L2			0.002	2500	
			D			0.004	3333	
13	surface (0-10)	clay muck with smell	L1	816	6%	0.036	400	0.0077
			L2			0.035	385	
			D			0.090	455	

	bottom (20-30)	sandy with many roots	L1	612	3%	0.050	526	0.0077
			L2			0.053	556	
			D			0.041	625	
14	surface (0-10)	clay with many roots	L1	1320	23%	0.021	1429	0.0126
			L2			0.025	1250	
			D			0.210	1667	
	bottom (20-30)	clay with many roots and hydrocarbon smell	L1	1068	10%	0.014	2500	0.0126
			L2			0.014	2500	
			D			0.013	2500	
15	surface (0-10)	very wet with hydrocarbon smell	L1	2481	76%	0.004	5000	0.0574
			L2			0.008	3333	
			D			0.285	1667	
	bottom (20-30)	dark colored sandy clay	L1	1584	30%	0.069	2500	0.0574
			L2			0.069	2500	
			D			0.083	2500	

Appendix

MSU Data Table of contents:

Appendix Table 1. Concentrations (mg/L) of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in overlying surface water collected from sediment cores after rewetting experiment #1 in August 2016 and the filtered Muskegon River water used during rewetting.

Site	Na^+	K^+	Mg^{2+}	Ca^{2+}
Muskegon River	19.07	1.36	15.22	47.09
1	24.50	1.44	9.96	26.58
2	24.56	2.08	16.90	53.04
3	26.71	1.90	15.96	56.61
4	28.71	3.96	18.96	58.96
5	17.41	2.80	9.71	35.90
6	28.15	1.35	16.85	55.62
7	17.73	19.54	9.67	39.38
8	16.54	10.02	7.48	32.18
9	29.61	2.08	19.65	58.54
10	33.03	1.60	15.08	50.09
11	28.78	2.12	17.72	61.33
12	27.60	1.54	17.15	56.03
13	30.27	2.76	17.55	58.43
14	28.83	2.42	17.35	57.86
15	20.85	1.39	17.34	65.75

Appendix Table 2. Mean (±SD) concentrations (mg/L of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in overlying surface water collected from sediment cores after rewetting experiment #1 in August 2016 and the filtered Muskegon River water used during rewetting.

	East (n=4)	North (n=4)	South (n=7)	River (n=1)
Na^+	26 (2)	20 (5)	28 (4)	19 (NA)
K^+	2 (1)	8 (8)	2 (1)	1 (NA)
Mg^{2+}	15 (4)	11 (4)	17 (1)	15 (NA)
Ca^{2+}	49 (15)	41 (10)	58 (5)	47 (NA)

Appendix Table 3. Concentrations (mg/L) of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in top and bottom porewater collected via rhizon from sediment cores after rewetting experiment #1 in August 2016. Top sample from core 5 (North) was lost due to core leakage.

Site	Depth	Na^+	K^+	Mg^{2+}	Ca^{2+}
1	top	26.88	2.00	3.18	7.50
	bottom	50.46	3.78	1.62	5.57
2	top	43.01	3.89	17.78	61.21
	bottom	44.73	6.39	15.80	42.13
3	top	55.90	3.25	14.37	70.70
	bottom	105.48	3.30	27.03	146.03
4	top	50.68	10.99	19.66	60.77
	bottom	62.06	19.50	15.40	43.08
5	top	NS	NS	NS	NS
	bottom	19.06	2.59	8.74	61.79
6	top	66.27	4.14	10.99	59.01
	bottom	72.82	2.00	15.11	73.06
7	top	19.34	34.57	7.10	36.03
	bottom	22.05	84.86	16.60	107.63
8	top	17.68	6.85	5.13	28.95
	bottom	19.03	4.89	6.85	42.46
9	top	53.17	4.70	24.26	63.41
	bottom	48.17	8.92	30.24	68.65
10	top	41.78	1.48	11.65	40.66
	bottom	39.75	1.54	13.19	44.62
11	top	58.95	3.32	18.40	85.50
	bottom	54.63	3.31	18.35	96.27
12	top	51.84	2.01	15.18	55.84
	bottom	52.40	2.53	14.02	53.67
13	top	68.11	8.28	11.47	48.95
	bottom	45.40	7.81	13.28	50.14
14	top	46.13	6.36	13.46	53.67
	bottom	42.29	7.64	13.72	53.98
15	top	35.47	0.19	24.79	147.02
	bottom	32.60	0.38	25.82	133.48

Appendix Table 4. Mean (±SD) concentrations (mg/L) of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in top and bottom porewater collected via rhizon from sediment cores after rewetting experiment #1 in August 2016. Top sample from core 5 (North) was lost due to core leakage; otherwise, East n=4, North n=4, and South n=7.

	Depth	East	North	South
Na^+	top	44 (13)	34 (28)	51 (11)
	bottom	66 (27)	33 (26)	45 (8)
K^+	top	5 (4)	15 (17)	4 (3)
	bottom	8 (8)	24 (41)	5 (3)
Mg^{2+}	top	14 (7)	8 (3)	17 (6)
	bottom	15 (10)	12 (5)	18 (7)
Ca^{2+}	top	50 (29)	41 (16)	71 (36)
	bottom	59 (60)	71 (27)	72 (32)

Appendix Table 5. Concentrations (mg/L) of chloride (Cl^-), bromide (Br^-), nitrate-N (NO_3^--N), and sulfate (SO_4^{2-}) anions in overlying surface water collected from sediment cores after rewetting experiment #1 in August 2016.

Site	Cl^-	Br^-	NO_3^--N	SO_4^{2-}
Muskegon River	25.66	0.054	0.33	19.57
1	33.56	0.067	1.71	28.11
2	34.95	0.050	11.02	25.91
3	55.19	0.297	0.05	20.89
4	42.96	0.049	9.54	29.26
5	24.58	0.068	10.40	30.83
6	43.87	0.075	1.72	38.34
7	27.63	0.065	1.48	22.50
8	33.53	0.057	5.73	24.17
9	47.97	0.082	3.12	43.57
10	57.47	0.038	4.76	50.26
11	43.98	0.042	1.24	51.74
12	44.49	0.052	4.40	31.61
13	47.52	0.052	3.69	36.44
14	47.11	0.061	1.17	41.86
15	27.44	0.052	3.37	63.83

Appendix Table 6. Mean (±SD) concentrations (mg/L) of chloride (Cl^-), bromide (Br^-), nitrate (NO_3^--N), and sulfate (SO_4^{2-}) anions in overlying surface water collected from sediment cores after rewetting experiment #1 in August 2016.

	East (n=4)	North (n=4)	South (n=7)	River (n=1)
Cl^-	42 (10)	32 (9)	45 (9)	26 (NA)
Br^-	0.12 (0.12)	0.07 (0.01)	0.05 (0.01)	0.05 (NA)
NO_3^--N	6 (6)	5 (4)	3 (1)	0 (NA)
SO_4^{2-}	26 (4)	29 (7)	46 (11)	20 (NA)

Appendix Table 7. Concentrations (mg/L) of chloride (Cl^-), bromide (Br^-), nitrate (NO_3^--N), and sulfate (SO_4^{2-}) anions in top and bottom porewater collected via rhizon from sediment cores after rewetting experiment #1 in August 2016. Top sample from core 5 (North) was lost due to core leakage.

Site	Depth	Cl^-	Br^-	NO_3^--N	SO_4^{2-}
1	top	38.23	0.651	0.49	35.41
	bottom	43.58	0.431	0.09	40.56
2	top	53.00	0.543	31.49	51.08
	bottom	49.68	0.005	33.19	58.45
3	top	103.98	7.291	0.01	22.82
	bottom	189.59	2.066	0.01	22.46
4	top	74.97	1.043	21.63	62.04
	bottom	108.93	0.285	6.82	79.19
5	top	NS	NS	NS	NS
	bottom	21.72	0.071	18.44	56.47
6	top	90.53	2.144	4.37	122.91
	bottom	91.01	0.005	9.25	129.15
7	top	29.67	0.426	0.74	24.68
	bottom	59.80	0.063	29.39	86.08
8	top	37.29	0.364	2.18	27.76
	bottom	39.00	0.065	4.66	29.43
9	top	82.99	1.610	3.23	90.68
	bottom	83.36	0.123	4.39	92.40
10	top	65.25	0.639	1.89	64.03
	bottom	62.06	0.041	3.83	57.38
11	top	78.09	0.005	0.81	148.85
	bottom	78.32	0.870	0.19	155.04
12	top	80.03	0.005	8.86	61.73
	bottom	84.28	0.046	5.71	70.50
13	top	87.00	0.077	4.87	76.31
	bottom	68.14	0.084	5.10	59.39
14	top	74.90	0.998	1.41	81.45
	bottom	68.18	0.093	5.35	68.55
15	top	44.87	0.220	14.98	256.88

	bottom	40.87	0.005	12.08	240.01

Appendix Table 8. Mean (±SD) concentrations (mg/L) of chloride (Cl^-), bromide (Br^-), nitrate (NO_3^--N), and sulfate (SO_4^{2-}) anions in top and bottom porewater collected via rhizon from sediment cores after rewetting experiment #1 in August 2016. Top sample from core 5 (North) was lost due to core leakage; otherwise, East n=4, North n=4, and South n=7.

	Depth	East	North	South
Cl^-	top	68 (29)	52 (33)	73 (14)
	bottom	98 (68)	53 (30)	69 (15)
Br^-	top	2.38 (3.28)	0.98 (1.01)	0.51 (0.61)
	bottom	0.70 (0.93)	0.05 (0.03)	0.18 (0.31)
NO_3^--N	top	13 (16)	2 (2)	5 (5)
	bottom	10 (16)	15 (11)	5 (4)
SO_4^{2-}	top	43 (17)	58 (56)	111 (71)
	bottom	50 (24)	75 (43)	106 (68)

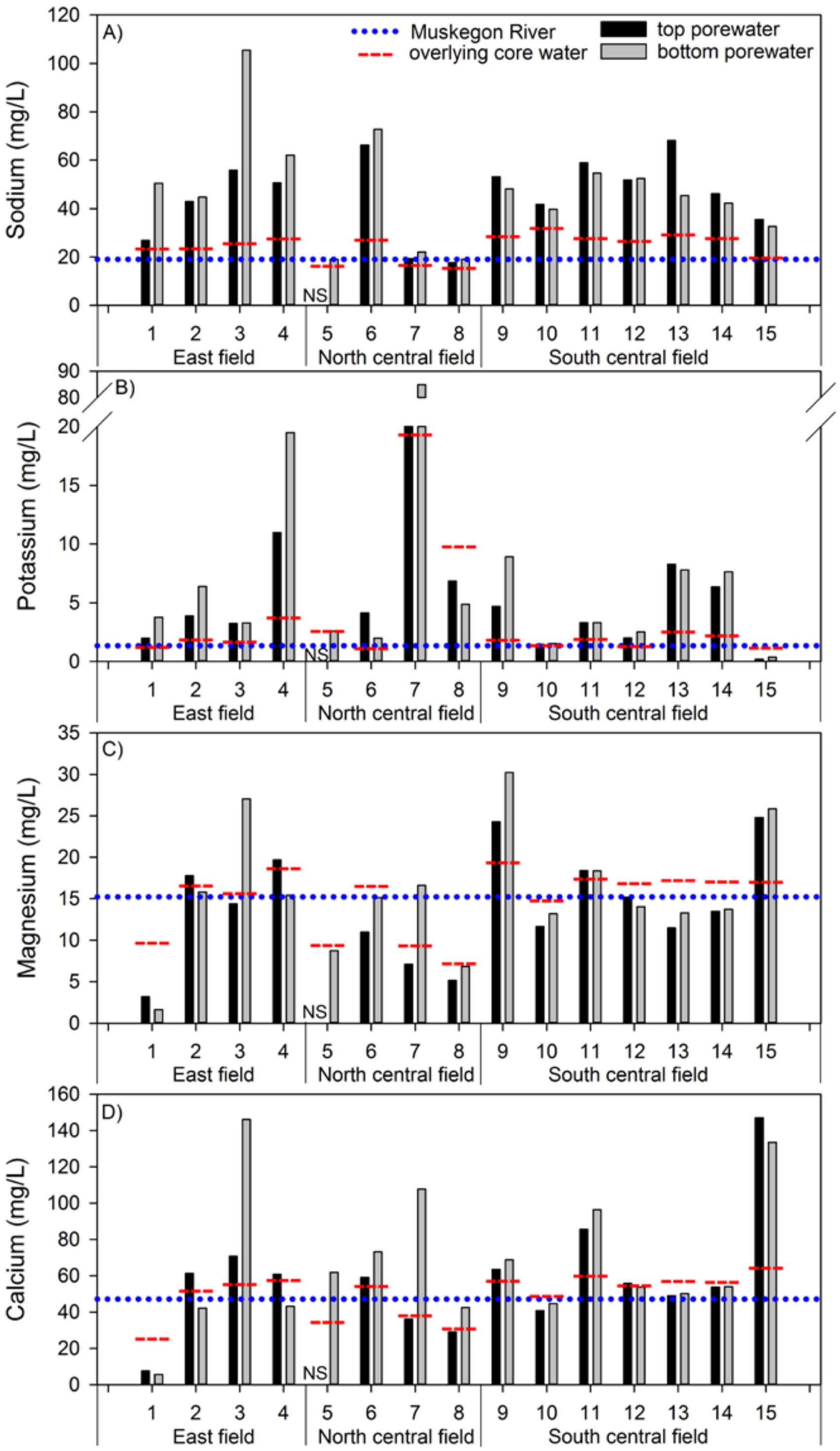
Appendix Table 9. Concentrations of iron (II) in top and bottom porewater collected via rhizon from sediment cores after rewetting experiment #1 in August 2016. Top samples from core 5 (North) and core 13 (South) were lost due to core leakage.

Site	Depth	Fe(II) (mg/L)
1	top	1.21
	bottom	2.03
2	top	0.13
	bottom	0.18
3	top	0.21
	bottom	0.27
4	top	0.22
	bottom	0.46
5	top	--
	bottom	0.44
6	top	0.48
	bottom	0.19
7	top	0.056
	bottom	0.068
8	top	0.12
	bottom	0.13
9	top	0.030
	bottom	0.037
10	top	0.043
	bottom	0.036

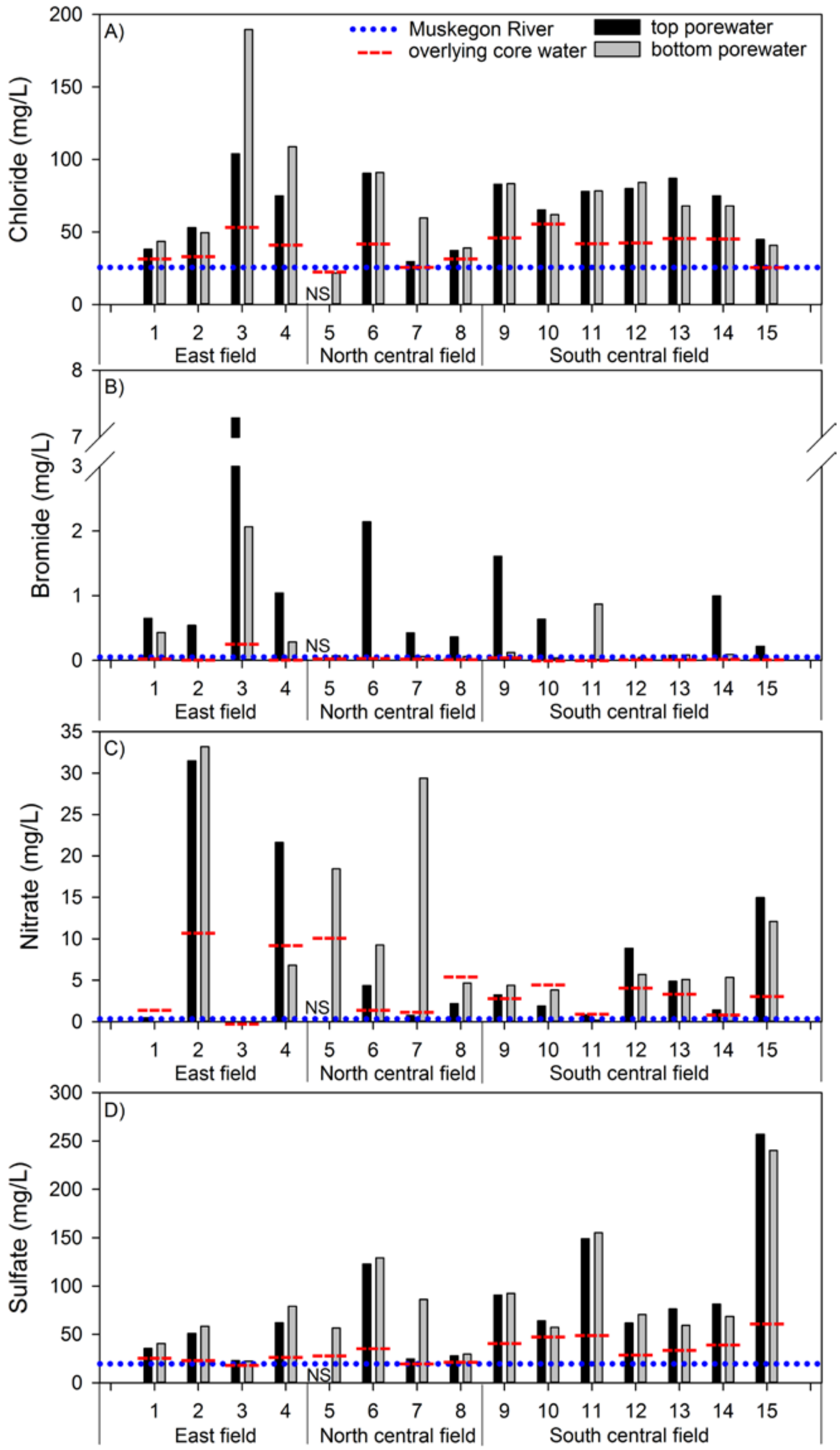
11	top	0.029
	bottom	0.050
12	top	0.029
	bottom	0.19
13	top	--
	bottom	0.035
14	top	0.072
	bottom	0.060
15	top	0.075
	bottom	0.025

Appendix Table 10. Mean (±SD) concentrations by region of iron (II) in top and bottom porewater collected via rhizon from sediment cores after rewetting experiment #1 in August 2016. Two top samples from core 5 (North) and core 13 (South) were lost due to core leakage; otherwise, East n=4, North n=4, and South n=7.

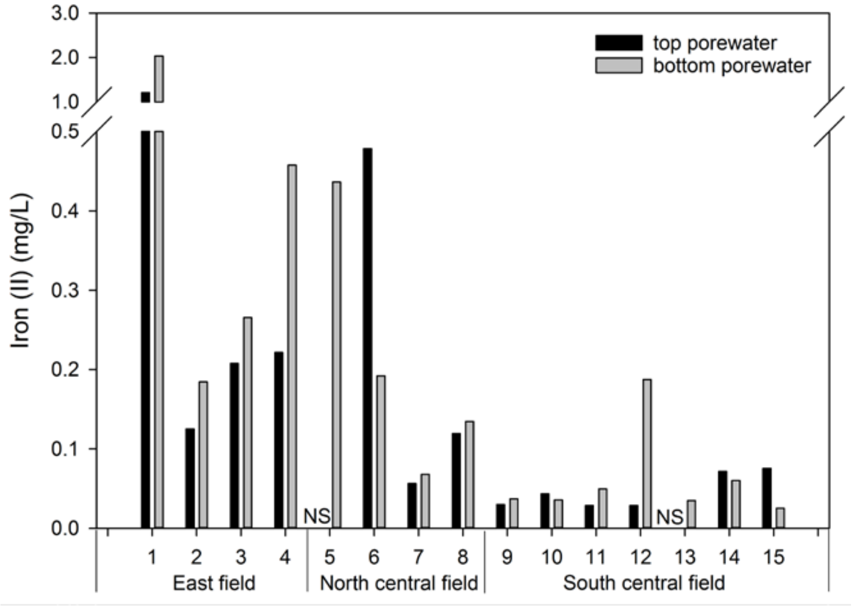
	Depth	East	North	South
Fe(II) (mg/L)	top	0.44 (0.51)	0.22 (0.23)	0.046 (0.022)
	bottom	0.74 (0.87)	0.21 (0.16)	0.062 (0.058)



Appendix Figure 1. Concentrations of sodium (Na^+), potassium (K^+), and magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in overlying core water and top and bottom porewater accessed via rhizon as a result of rewetting experiment #1 and filtered Muskegon River water used during rewetting. Site 5 top porewater is marked NS (no sample) due to core leakage. Note different scales for y-axes.



Appendix Figure 2. Concentrations of chloride (Cl^-), bromide (Br^-), nitrate (NO_3^-), and sulfate (SO_4^-) anions in overlying core water and top and bottom porewater accessed via rhizon as a result of rewetting experiment #1 and filtered Muskegon River water used during rewetting. Site 5 top porewater is marked NS (no sample) due to core leakage. Note different scales for y-axes.



Appendix Figure 3. Iron (II) concentrations in top and bottom porewater accessed via rhizon as a result of rewetting experiment #1. Sites 5 and 13 top porewater are marked NS (no sample) due to core leakage.