

1 **Influence of a Freshwater River Diversion on Sedimentation and Phosphorus Status in a**
2 **Wetland Receiving Basin**

3
4 Alina C. Spera^a, John R. White^a, Ron Corstanje^b

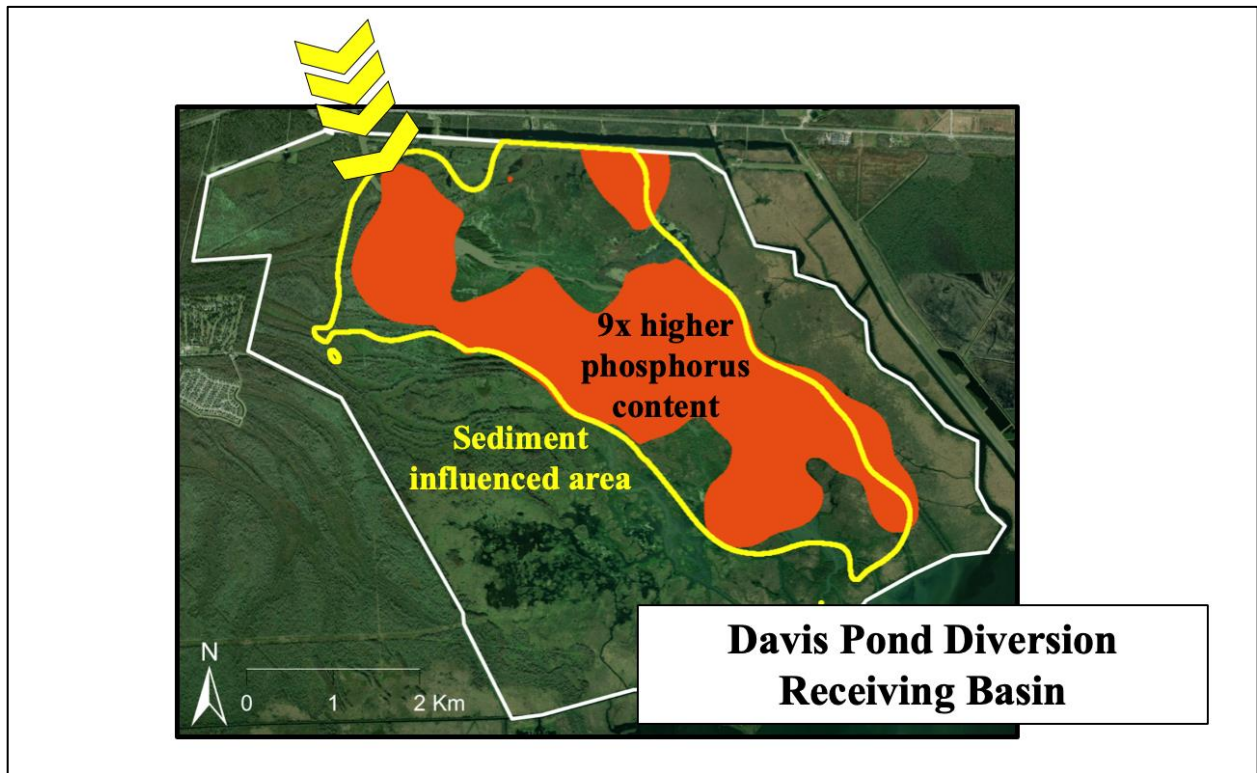
5 ^a Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge,
6 Louisiana

7 ^b National Soil Resources Institute, School of Applied Sciences, Cranfield University, Cranfield,
8 Bedfordshire, MK43 0AL, UK

9 **Abstract**

10 Mississippi River Delta wetlands were isolated from river influence due to leveeing in the
11 1900's. Surface water diversions were primarily designed to manage salinity and maintain marsh
12 vegetation by reintroducing Mississippi River water and nutrients into adjacent wetlands.
13 Phosphorus (P) is a major limiting nutrient that can control productivity, but in excess can
14 contribute to wetland eutrophic conditions and water quality degradation. Most wetland soil
15 characterization assessments consider soil total P, however, this parameter alone cannot describe
16 P bioavailability due to difference in organic and inorganic forms. A soil characterization of the
17 Davis Pond diversion was done in 2007, before full-scale operation began, and in 2018 after 11
18 years of river loading. The top 10 cm of soil from 140 stations each year were analyzed for
19 physiochemical properties and both organic and inorganic P forms. Mineral content is used to
20 delineate areas of river diversion influence and compare P stocks between hydrologically
21 isolated marsh areas and where effective river diversion reconnection took place. The river
22 diversion resulted in a nearly 100% increase in soil mineral content and 58% increase in bulk
23 density. The dominant source of soil P has changed from organic P to inorganic P in 29% of the
24 wetland area, significantly associated with mineral content of the soil. Inorganic P stocks in
25 diversion influenced areas are 9 times higher than those which remained isolated from riverine
26 materials. The study showed that long-term addition of mineral sediments and inorganic P did
27 not lead to deleterious effects in the wetland. This is the first study in the Mississippi River delta

28 to spatially track river reconnection driven wetland P dynamics and this study can provide
29 valuable information for predictive models for sediment diversions for coastal restoration.



30

31 **1. Introduction**

32 Many riparian wetlands serve as a natural buffer situated between anthropogenic-influenced
33 rivers and natural estuarine systems (Gilliam, 1994; Blinn and Kilgore, 2001; Ducey et al.,
34 2015). Wetland areas act as a transformer or sink for nutrients due to various biotic and abiotic
35 processes that remove nitrogen (N) and phosphorus (P) from the water column and improve
36 water quality (Zedler & Kercher, 2005). However, construction of continuous levees down the
37 length of the Lower Mississippi River over the past century has led to sediment and nutrient
38 deprivation in Louisiana's once connected riparian wetlands (Day et al. 2000, 2018). Wide
39 spread coastal land loss is confounded by increasing salinity gradients and flooding, driven by
40 sea level rise, which also threaten important fisheries (Chesney et al., 2000; Cowan et al., 2014)

41 and wetland vegetation in Barataria Basin (Delaune & White, 2012). The future of the
42 Mississippi River Delta depends on timely implementation of restoration projects by the state at
43 varying spatial scales (Day et al., 2016). One such project type is the large-scale sediment
44 diversion, still in planning and permitting stages, that will transport significant volumes of water
45 and associated mineral sediment from the Mississippi River into Louisiana coastal wetlands to
46 aid in building land in some locations and slowing land loss in others (CPRA, 2017). Diversion
47 projects from past restoration efforts, like the Davis Pond diversion, provide a small number of
48 real-life analogs for sediment diversions and can give some insight of how best to implement
49 restoration of the Louisiana coast. The Davis Pond diversion diverts an average of $45 \text{ m}^3\text{s}^{-1}$ water
50 from the Mississippi River through a diversion channel and empties into a freshwater wetland
51 which connects to the large coastal Barataria Basin at the southern end (McAlpin et al. 2008).
52 This river diversion was designed primarily to deliver freshwater and nutrients to the wetland
53 and coastal basin to control salinity. Operation of the diversion did not intend to deliver other
54 needed materials such as inorganic sediment (Barras et al. 2003, Snedden et al. 2007), although
55 others have reported locally significant land building in several freshwater diversion systems
56 (Lopez et al., 2014; Day et al., 2016; Keogh et al., 2019).

57 Concentrations of nutrients such as N and P have nearly doubled in the Mississippi River
58 since the early 20th century (Goolsby et al., 2000; Evers et al., 1992), and some evidence
59 suggests that river reconnection could encourage wetland eutrophication in response to nutrient
60 enrichment in the receiving basins and reduce wetland resilience (Darby and Turner, 2008;
61 Swarzenski et al., 2008, Turner et al. 2019). In addition to water and dissolved nutrients,
62 freshwater diversions are, in fact, transporting sediment from the river into their respective
63 basins (Keogh et al., 2019), although the rate of sedimentation throughout the entire Davis Pond

64 receiving wetland is unclear (DeLaune et al., 2008). Application of fine-grained inorganic
65 sediments increases the density of wetland soils (Anisfeld and Hill, 2012) and denser soils may
66 be more stable in contrast with highly organic soils that are more susceptible to erosion (Howes
67 et al. 2010, Sapkota and White, 2019). However, riverine sediments also contain dissolved and
68 particulate nutrients that can alter the biogeochemical processes within the system. DeLaune et
69 al. (2016) found that established marshes in an area receiving material from the Atchafalaya
70 River, called the Wax Lake Sub Delta, have enhanced rates of plant production and sediment
71 carbon (C) accumulation. In that case, the wetland serves as a means to remove or store
72 nutrients, however, under highly loaded conditions nutrient enrichment can lead to deleterious
73 effects on wetland soils. Wetland eutrophication is an increasingly common end result of nutrient
74 pollution which can reduce the quality of ecosystem functions provided by wetland habitats
75 (Zedler & Kercher 2005; Bargu et al, 2019).

76 Phosphorus is commonly a limiting nutrient, especially in wetland systems with low
77 mineral input (Reddy et al, 1995). Abundance of P in relation to C and N is a main determinant
78 in the net primary production of any aquatic system. Total P is generally measured in wetland
79 monitoring studies, and as such, understanding P availability contributes to interpreting overall
80 health and functioning of a wetland system. Deltaic wetlands have P associated with both
81 riverine sediment and highly organic peat soil (Reddy and DeLaune 2008). Organic P (OP)
82 forms by the conversion of dissolved inorganic P immobilized into organic matter (OM) by
83 either microbes or plants. Up to 80% of bioavailable P removal can be performed by plants
84 depending on the productivity of the system (Reddy et al. 1995; Reddy et al., 1998). Inorganic P
85 (IP) in a river system is present either in the form of dissolved inorganic phosphate (PO_4^-) in

86 river water or more substantially as ortho-phosphate minerals associated with iron (Fe) and
87 aluminum (Al) (Zhang et al., 2012).

88 A critical baseline wetland soil study in the Davis Pond diversion wetland in 2007 by
89 Kral et al. (2012) did not demonstrate a strong spatial component driving the distribution of total
90 P before full river reconnection began, likely due to the low volume operation of the diversion up
91 to that point. Kral et al. (2012) found that total P distribution was weakly correlated to any other
92 organic or inorganic soil parameter and this has been shown by others (Rivero et al., 2007;
93 Tipping et al., 2016; Adams et al., 2018). Analysis of inorganic and organic soil P fractions may
94 help identify drivers of spatial variability in P availability and can be used to delineate areas of
95 river influence in wetlands. In the years following initial sampling, the wetland has accreted 0.59
96 to 1.03 cm yr⁻¹ of new soil each year (DeLaune et al., 2013). A resampling effort of the newly
97 accreted 0-10 cm soil layer was conducted in 2018 to document the ~11-year record of
98 hydrologic restoration on the soils of this coastal, deltaic freshwater wetland. We hypothesize
99 that the relative contribution of Mississippi River sediments and associated metal bound P to the
100 Davis Pond wetland has significantly increased soil P stocks over time and should provide a
101 spatial indication of river influence. These changes may be linked to increased nutrient
102 availability and ecosystem productivity.

103 **2. Materials and Methods**

104 *Study Site*

105 The Davis Pond Mississippi River Diversion discharges into a fresh water wetland ponding area
106 located in northern Barataria Basin, Louisiana, USA (Figure 1). The diversion structure is
107 approximately 19 km upstream the Mississippi River and on the opposite bank from the city of
108 New Orleans. At maximum flow, the diversion delivers up to 300 m³ s⁻¹ of water into the 37.6

109 km² ponding area, however operation of the diversion is limited by Mississippi River stage
110 because water is redirected passively by 14 ft box culverts. Since 2007, average diversion
111 discharge was 58 m³s⁻¹ with a median discharge of 36 m³s⁻¹, and diversion operation was
112 negligible on an average of 44 days each year (USGS, 2018). The ponding area is surrounded by
113 levees on the northern, western and eastern sides directing flow to the southeastern boundary.
114 That boundary is composed of a low rock weir cut with several outflow canals, allowing water to
115 enter into Lake Cataouache and then Lake Salvador eventually entering Barataria Bay further
116 south. The Davis Pond Freshwater diversion was built in 2002, however, water flow issues
117 prevented operation of the diversion at full capacity before 2009, once modifications to the flow
118 path and upgrades to the levees were completed (Chuck Villarubia, per. comm).

119 *2.1. Sampling*

120 The sampling locations were identified using spatial simulated annealing (SSA) (van Groenigen
121 et al., 1999) approach (Kral et al., 2012). At these locations push core samples of the top 10 cm
122 of soil were collected at 140 stations in May through July 2007 and May through June 2018.
123 Dried, ground archived soils samples from 2007 were used for phosphorus fractionation and
124 metals analyses.

125 *2.2. Soil physiochemical properties*

126 Soil moisture and bulk density (BD) were determined by drying field moist sub-samples at 70°C
127 until at constant weight. Total P was separated into total inorganic P (IP) and total organic P
128 (OP). For IP extraction, 0.5 g of dried ground samples were shaken for 3 hours on longitudinal
129 shaker with 25 mL of 1M HCl, followed by 10-minute centrifugation at 4000 g. The supernatant
130 fluid was filtered through a 0.45-µm membrane filter and stored at 4°C (Reddy 1998; Reddy and
131 DeLaune, 2008). Dried ground sub samples were combusted at 550°C for 4 hours in a muffle

132 furnace for loss-on-ignition method of organic matter (OM) (Sparks, 1996) and ash content
133 determination, from here ash content is referred to as mineral content (MC). After combustions,
134 ashed samples were digested with 6 N HCl, then filtered for total P analysis (Andersen 1976).
135 Total P and total IP were determined with an AQ2 Automated Discrete Analyzer (SEAL
136 Analytical, West Sussex, England), using US EPA ascorbic acid automated colorimetric
137 procedure (Method 353.2; US EPA). Total organic P was determined by the difference (TP-IP).
138 Total metals (Fe, Al, Ca, and Mg) were analyzed on 40 randomly selected 2018 samples from
139 the 6 N HCl digestion with inductively coupled plasma atomic emission spectroscopy (Hitachi
140 High-Technologies America, Schaumburg, IL, USA).

141 *2.3. Statistical analysis workflow*

142 This study used geostatistical means to identify spatial and temporal patterns in the distribution
143 of soil phosphorus fractions in the Davis Pond wetland. The work flow consisted of (1)
144 univariate analysis of between year measured site P data; (2) visualization of patterns in spatial
145 distribution of soil P fractions across the wetland and over time by modeling soil variables
146 through spatial auto-correlation; (3) creating a new dataset from modeled data in order to make
147 univariate and multivariate comparisons between years and between distinct areas of the
148 wetland.

149 *2.4. Univariate Analysis*

150 Paired t-tests were conducted in order to evaluate how soil characteristics changed at each site
151 between sampling years. *P* values < 0.05 were considered significant at an α of 0.05.

152 *2.5. Geostatistical Analysis*

153 A geostatistical approach was used to describe the spatial variability in soil characteristics across
154 the Davis Pond wetland from archived 2007 data and analysis from 2018. This analysis assumes

155 that the observed variation in soil properties is a result of a random function that determines the
156 value of a variable of interest, Z , at any given region. A linear model of describing Z at location x
157 is formulated as $Z(x) = \mu + \varepsilon(\mathbf{x})$ where μ is the unknown and invariant mean and $\varepsilon(\mathbf{x})$ is the
158 stochastic spatially autocorrelated component and the stochastic spatially uncorrelated variation
159 drawn from a normal distribution with mean zero.

160 Assuming the assumption of first order stationarity, then models of the spatially
161 dependent variance are the same over the entire sampled area and are represented with
162 semivariance ($\gamma(\mathbf{h})$) (Eq. 1) in variable Z at separating, or lag, vector \mathbf{h} .

$$163 \quad \gamma(\mathbf{h}) = \frac{1}{2} E \{ [Z(x) - Z(x + \mathbf{h})]^2 \} \quad (\text{Eq. 1})$$

164 Construction of experimental variograms and fitting of variogram models was performed
165 using R (R Core Team, 2014) within RStudio (RStudio Team, 2015). Classical Matheron's
166 method of moments variogram estimator (Kral et al., 2012) was used for least squares fitting,
167 weighted by the number of sites separated by vector \mathbf{h} . Authorized models such as the
168 exponential and spherical models were used for variogram fitting (Grunwald et al, 2006; Webster
169 and Oliver, 2007). Final model selection was based on minimization of weighted sum of squares.

170 Variogram models were used for spatial autocorrelation by ordinary kriging in R with
171 global neighborhood (Ribeiro and Diggle, 2001) to produce predictions of physiochemical
172 properties for ~660,000 100 m² grid cells across the study area. Final map layouts were
173 produced in ArcMap 10.6.1 (ESRI, 2018).

174 *2.6. Soil Nutrient Stock Estimations*

175 Soil nutrient stocks in the 0-10 cm soil layers from each sampling year were estimated using the
176 methodology outlined by Veronesi et al. (2014). Soil total P, IP and OP depth-integrated

177 volumetric content (g P m⁻²), from here referred to as stocks, and mineral density (g cm⁻³) was
 178 calculated using spatially autocorrelated surfaces with the following equations:

$$179 \quad \text{Mineral Density} = \text{MC}_i \cdot \text{BD}_i \quad (\text{Eq.2})$$

$$180 \quad \text{Organic Matter Density} = \text{OM}_i \cdot \text{BD}_i \quad (\text{Eq.3})$$

$$181 \quad \text{P Stock} = \text{TP}_i \cdot \text{BD}_i \cdot d \quad (\text{Eq.4})$$

$$182 \quad \text{IP Stock} = \text{TIP}_i \cdot \text{BD}_i \cdot \text{MC}_i \cdot d \quad (\text{Eq.5})$$

$$183 \quad \text{OP Stock} = \text{TOP}_i \cdot \text{BD}_i \cdot \text{OM}_i \cdot d \quad (\text{Eq.6})$$

184 Total P (TP_i) concentration and inorganic phosphorous concentration (TIP_i) were
 185 normalized with bulk soil density (g cm⁻³), mineral density (g cm⁻³), and organic matter density
 186 (g cm⁻³) respectively. The depth of the soil layer (d = 10 cm) was used to produce estimates of
 187 depth-integrated P stocks (g P m⁻²).

188 2.7. Nutrient Stock Variation Estimations

189 Error propagation in mineral density and the P, OP and IP fractions stock estimations was
 190 addressed by assessing uncertainty associated with each variable. Estimation of variance of the
 191 P, IP, and OP stock in each predicted grid cell were computed with the following equations,
 192 adapted from Goidts et al. (2009) and Schrumpf et al. (2011):

$$193 \quad \text{Var (P Stock)} = (\text{P Stock})^2 \cdot \left(\frac{\sigma_{\text{TP}}^2}{\text{TP}^2} + \frac{\sigma_{\text{BD}}^2}{\text{BD}^2} + 2 \frac{\sigma_{\text{TP-BD}}}{\text{TP} \cdot \text{BD}} \right) \quad (\text{Eq.7})$$

$$194 \quad \text{Var (IP Stock)} = (\text{IP Stock})^2 \cdot \left(\frac{\sigma_{\text{TIP}}^2}{\text{TIP}^2} + \frac{\sigma_{\text{BD}}^2}{\text{BD}^2} + \frac{\sigma_{\text{MC}}^2}{\text{MC}^2} + 2 \frac{\sigma_{\text{TIP-BD}}}{\text{TIP} \cdot \text{BD}} + 2 \frac{\sigma_{\text{MC-BD}}}{\text{MC} \cdot \text{BD}} + 2 \frac{\sigma_{\text{TIP-MC}}}{\text{TIP} \cdot \text{MC}} \right) \quad (\text{Eq.8})$$

$$196 \quad \text{Var (OP Stock)} = (\text{OP Stock})^2 \cdot \left(\frac{\sigma_{\text{TOP}}^2}{\text{TOP}^2} + \frac{\sigma_{\text{BD}}^2}{\text{BD}^2} + \frac{\sigma_{\text{OM}}^2}{\text{OM}^2} + 2 \frac{\sigma_{\text{TOP-BD}}}{\text{TOP} \cdot \text{BD}} + 2 \frac{\sigma_{\text{OM-BD}}}{\text{OM} \cdot \text{BD}} + 2 \frac{\sigma_{\text{TOP-OM}}}{\text{TOP} \cdot \text{OM}} \right) \quad (\text{Eq.9})$$

198 Where Var (P Stock) in each grid cell is the error associated with the P stock prediction
199 in g m^{-2} . σ_{TP} , σ_{TIP} , σ_{MC} , σ_{OM} , and σ_{BD} are the standard deviation of TP, TIP concentration, MC,
200 OM, and BD. Covariance (σ) of TP, TIP, MC, OM, and BD which were calculated from the raw
201 dataset.

202 2.8. Significant change determination

203 Variance maps from each year for mineral content, IP and OP density were used to find ΔVar
204 ($\Delta\sigma^2$), or the difference in variance value at each site between years, for each grid cell. In order
205 to determine significance of difference in soil parameter between years (ΔIP) the 95%
206 confidence interval around zero for change in each grid cell for IP density was calculated:

$$207 \quad \pm 1.96 \cdot \sqrt{\Delta\text{Var}_i(\text{IP})} \quad (\text{Eq.9})$$

208 Where $\Delta\text{Var}_i(\text{IP})$ is the difference in uncertainty calculations each year at location i . A grid cell
209 with ΔIP Density value within this confidence interval around zero would signify no significant
210 change; those outside were considered significant for our analysis.

211 2.9 Mixture Model for defining area of diversion influence

212 Mixture distributions are commonly used to model a population composed of two or
213 more sub-populations and have been applied in a variety of disciplines (Everitt & Hand, 1981;
214 Lo et al., 2001; Everitt, 2014). An expectation-maximization (EM) algorithm was used to fit a
215 normal mixture model to the mineral content (%) dataset using the mixtools package in R
216 (Benaglia et al. 2009).

217 3. Results and Discussion

218 *Sedimentation from diversion influence*

219 Mineral density is a measure of the mass of mineral material present in a given volume of
220 wetland soil, in this case, related to fine grained Mississippi River sediment delivered through

221 the river diversion. Although the Davis Pond freshwater diversion was not specifically designed
222 to bring sediment from the river into the ponding areas, spatial distribution of mineral density (g
223 cm^{-3}) demonstrates that fine-grained mineral sediment has settled out from diverted river water
224 and became incorporated into the organic soils as they accrued (Figure 2). Net contribution of
225 mineral materials is more pronounced throughout the wetland with a 58% increase in average
226 BD and 100% increase in mineral density since the 2007 sampling (Table 1). As expected, soils
227 with high mineral density occur closest to the diversion inflow and mineral density decreases
228 with distance from the river (Day et al., 2009). In 2007, highly mineral soils are limited to
229 northern areas of the wetland which experienced direct impact from preliminary operation of the
230 diversion. After approximately 11 years of diversion operation, however, there is increased
231 mineral density throughout the surface wetland soil, especially down the central preferential flow
232 path.

233 In order to more accurately define the sediment-influence zones, an expectation-
234 maximization (EM) algorithm was used to fit a normal mixture model to the mineral content (%)
235 dataset (Figure 3). The model identified a bimodal distribution with two distinct components, the
236 low mineral content component (mean = 48.4%, SD=12.94) and high mineral content component
237 (mean = 74.5%, SD= 7.99). We estimated the break point between these populations in the
238 dataset as the approximate overlap of the modelled distribution curves. This process indicated
239 that a soil mineral content threshold of 65% by weight could be used to divide the modelled soil
240 property estimations into two groups with significantly different sediment enrichment. In 2007,
241 this sediment-influenced area was 4.8 km^2 (480 ha), in 2018 that area was over 3 times larger at
242 15.1 km^2 (1510 ha) (Figure 4). This finding is particularly noteworthy as it was hypothesized by
243 the designers that these diversions would not add appreciable sediment to the wetlands.

244 Keogh et al. (2019) found that the Davis Pond freshwater diversion effectively captures
245 fine-grained sediment, demonstrating that during moderate and low flow conditions in the
246 summer and fall the sediment retention rate is up to 81%. Increased soil mineral content and
247 consolidation of deposited muddy sediment has been shown to reduce vulnerability of
248 Mississippi River Delta freshwater wetlands to impacts from erosive forces, sea level rise and
249 subsidence (Morris et al. 2013; Graham and Mendelsohn, 2013; Slocum et al. 2005, Xu et al.,
250 2019), especially when that sediment is accompanied by increased OM accumulation. Root
251 systems of wetland plant communities are an important structural component for highly organic
252 soils (DeLaune and White, 2012). Soils rich with organic material tend to have higher buoyancy
253 and are less resistant to physical stress such as storms (Turner et al., 2009; Jafari et al., 2019).
254 However, soils which receive fine-grained mineral sediment will have increased bulk density
255 (Poormahdi et al. 2018) and will be less susceptible to erosion from wind waves (Sapkota and
256 White, 2019) or storms (Howes et al., 2010). In addition, regular mineral sediment supply can
257 improve growing conditions for wetland vegetation by increasing elevation, relieving flood
258 stress, and introducing new substrate into which vegetation can grow (Graham and Mendelsohn
259 2016; Mendelsohn and Kuhn, 2003). Finally, riverine sediments commonly have associations
260 with nutrients, like particulate inorganic P, which can become available after deposition. The
261 remainder of this discussion will focus on the impacts of sedimentation on soil P stocks in the
262 Davis Pond wetland system.

263 *P Dynamics*

264 Differences in total P, OP and IP stocks (g P m^2) between years were significant at the 140
265 measured sites ($p < 0.0001$) as well as for the means from modeled data (Table 1). Total P stock
266 is greater in 2018, driven by significant gains in IP and a decrease in total OP (Table 1). A large

267 portion of the study area (29% of the total wetland area), mainly located in the diversion
268 influenced zone, switched dominant P form from OP in 2007 to IP in 2018. Allochthonous
269 sources of P are mainly inorganic particulate P or ortho-phosphates associated with mineral
270 sediments from the river. The most abundant P associated metals in Mississippi River sediments
271 are Fe and Al (Sutula et al., 2004). In 2018, the Davis Pond wetland soil Fe and Al
272 concentrations are equally positively correlated with log(mineral density) ($R=0.54$, $p=0.0003$).
273 The presence of IP has a positive relationship with mineral density and bulk density of the soil
274 ($R=0.93$ and 0.88 , respectively, $p < 0.0001$), demonstrating that IP loading is closely related to
275 deposition of river sediment. Fe and Al form complexes with IP, and can form minerals,
276 providing long-term P storage (Malecki-Brown, et al., 2007). Under flooded or anoxic
277 conditions, however, Fe will become reduced and dissolved IP may be released into the pore
278 water (Zhang et al., 2012; Adhikari et al., 2015). As mineral sediments are the major driver for
279 IP stock in the soils, then areas of the wetland with significant sedimentation should have greater
280 stocks of inorganic P, a portion of which can be released from the sediment under low redox
281 conditions, contributing to organic matter accumulation through plant uptake (White et al, 2006;
282 Zhang et al., 2012).

283 *Spatial P distribution*

284 Sediment influence zones approximated with soil mineral content by percent allowed us to
285 identify how P dynamics differ between areas influenced by the diversion and areas where no
286 effective river reconnection occurs. River influenced regions in 2007 and 2018 have more than
287 two times higher mean total P stock, and IP stocks are almost nine times larger than non-
288 diversion-influenced soils (Table 2, Figure 5). Almost all sites that experience a statistically
289 significant increase in IP content between years are located within the area of significant mineral

290 sedimentation (Figure 6 a). Delivery of sediments brings large stocks of potentially bioavailable
291 P, associated with Fe and Al (Ghaisas et al. 2019).

292 In contrast, the spatial distribution of soils with significant changes in OP has a less
293 distinct pattern related to the diversion flow path. A majority of the sites with OP loss are located
294 outside the sedimentation zone (Figure 6 b) and total OP stocks are decreasing with continued
295 isolation from river influence over time (Table 2). Mean OP stocks, however, in the sediment
296 influenced zone did not significantly decrease over time. This pattern is especially important
297 because OP can act as a long-term P storage mechanism and reconnecting coastal freshwater
298 wetlands to river influence aids in maintaining organic material and associated OP accretion.
299 Losses to OM accrual in wetland soils can reduce nutrient storage functions, wetland soil
300 stability, and carbon sequestration (Turner et al., 2009).

301 River diversion projects receive varying degrees of support from the scientific
302 community because of large uncertainties in predicting impacts from river diversion derived
303 sediment and nutrient enrichment (Quirk et al., 2019; White et al., 2019; Jafari et al., 2019). This
304 study provided the first significant spatial data set covering over a decade of time as an
305 opportunity to define river reconnection influence on receiving wetland soils. Coastal managers
306 can use the results of this study to understand potential effects from the currently planned large
307 sediment diversions. Introduction of riverine materials through Mississippi River diversions
308 dramatically alters soil conditions in wetland systems due to introduction of fine-grained
309 sediments and potentially bioavailable forms of P. Overall, we identified positive impacts from
310 nearly continuous diversion influence on freshwater wetland soil structure, nutrient status, and
311 organic matter accumulation.

312 Significant river influence in this wetland occurred down a central preferential flow path
313 that is likely driven by elevation within the basin. Designs for larger sediment diversions should
314 allow dispersion of diverted materials across larger areas of receiving basins while also
315 considering the importance of small-grained sediments for land building and marsh nourishment.
316 P dynamics in active deltaic systems are difficult to track over time due to interactions between P
317 forms and environmental conditions which drive P cycling (Adams, et al., 2018). Previous to this
318 study, the long-term impacts of lower Mississippi River hydrologic restoration projects had yet
319 to be statistically quantified due to little or no pre-sampling. This is the first study to describe and
320 model changes of soil characteristics in a river diversion restoration wetland over space and time
321 for use in identifying the extent and intensity of river diversion influence. Determining the
322 effectiveness of freshwater diversions will ensure their continued use not only as examples for
323 other diversions, but as effective restoration tools which can contribute to regional scale coastal
324 restoration goals.

Table 1. Summary of Soil Physiochemical Properties ^a

	Bulk Density (g/cm ³)	Mineral Density (g/cm ³)	Organic Matter Density (g/cm ³)	Phosphorus (g/m ²)	Inorganic P (g/m ²)	Organic P (g/m ²)
Measured 2007	0.12 ± 0.010	0.07 ± 0.004	0.049 ± 0.02	10.2 ± 3.2	3.28 ± 0.002	3.03 ± 0.27
Measured 2018	0.21 ± 0.012	0.14 ± 0.005	0.047 ± 0.01	15.3 ± 3.2	7.43 ± 0.04	2.30 ± 0.35
Paired t-test <i>p</i> ^b	<i>p</i> < 0.0001	<i>p</i> < 0.0001	<i>p</i> = 0.64	<i>p</i> < 0.0001	<i>p</i> < 0.0001	<i>p</i> < 0.0001
Predicted 2007	0.093 ± 0.038	0.060 ± 0.0002	0.059 ± 0.003	10.5 ± 0.12	2.2 ± 0.19	3.7 ± 0.05
Predicted 2018	0.147 ± 0.065	0.120 ± 0.0003	0.062 ± 0.004	15.1 ± 0.20	5.3 ± 0.35	3.0 ± 0.05

^a Data from 140 measured sites and predicted dataset for 100 m² grid cells, presented with standard error. Bold signifies significant difference between years.

^b Results from paired t-tests are for data from measured sites only.

Table 2. Mean P stock by year of each soil P fraction inside and outside of the sediment influenced area. ^a

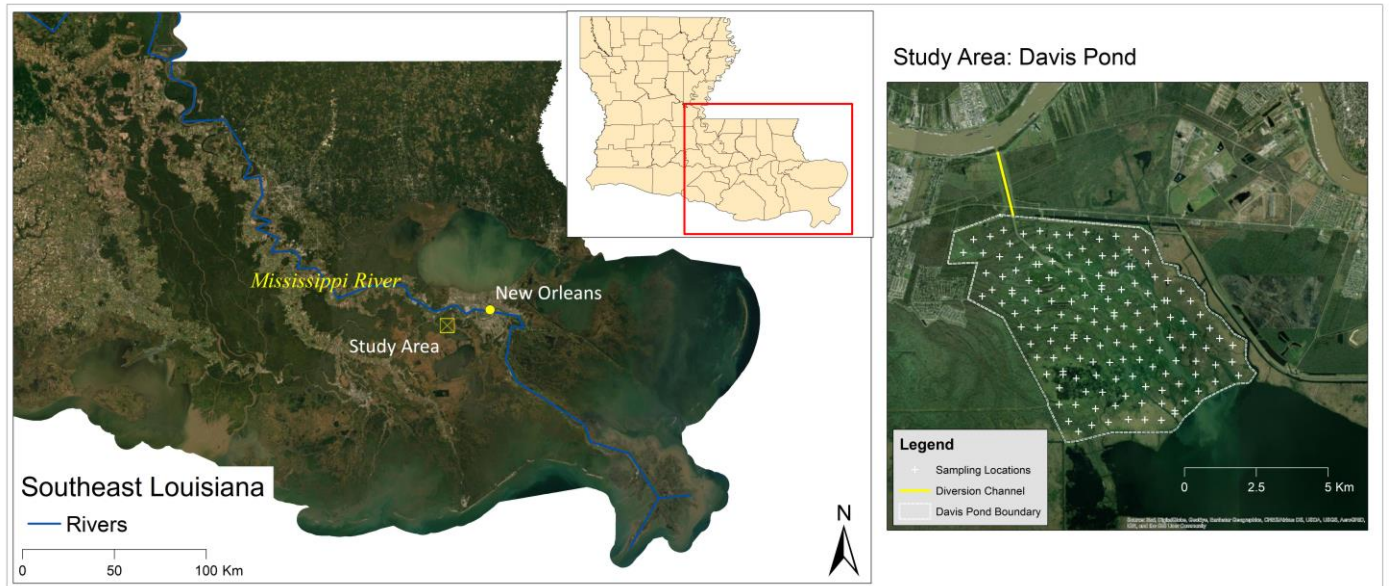
P Fraction	Year	River influenced (g P m ⁻²)	Non-River Influenced (g P m ⁻²)
Total P	2007	10.98 ± 0.92 *	6.21 ± 0.01 *
	2018	8.67 ± 0.54 *	7.16 ± 0.02 *
Inorganic P	2007	11.03 ± 0.9 *	0.91 ± 0.01 *
	2018	10.83 ± 0.6*	1.64 ± 0.03 *
Organic P	2007	2.32 ± 0.8*	3.95 ± 0.05 *
	2018	2.08 ± 0.3*	3.66 ± 0.10 *

^a Organic P was found by normalizing concentration with organic matter density, inorganic P was found using mineral density. Bold indicates significant difference between years.

* Indicates significant difference between wetland areas.

330
331

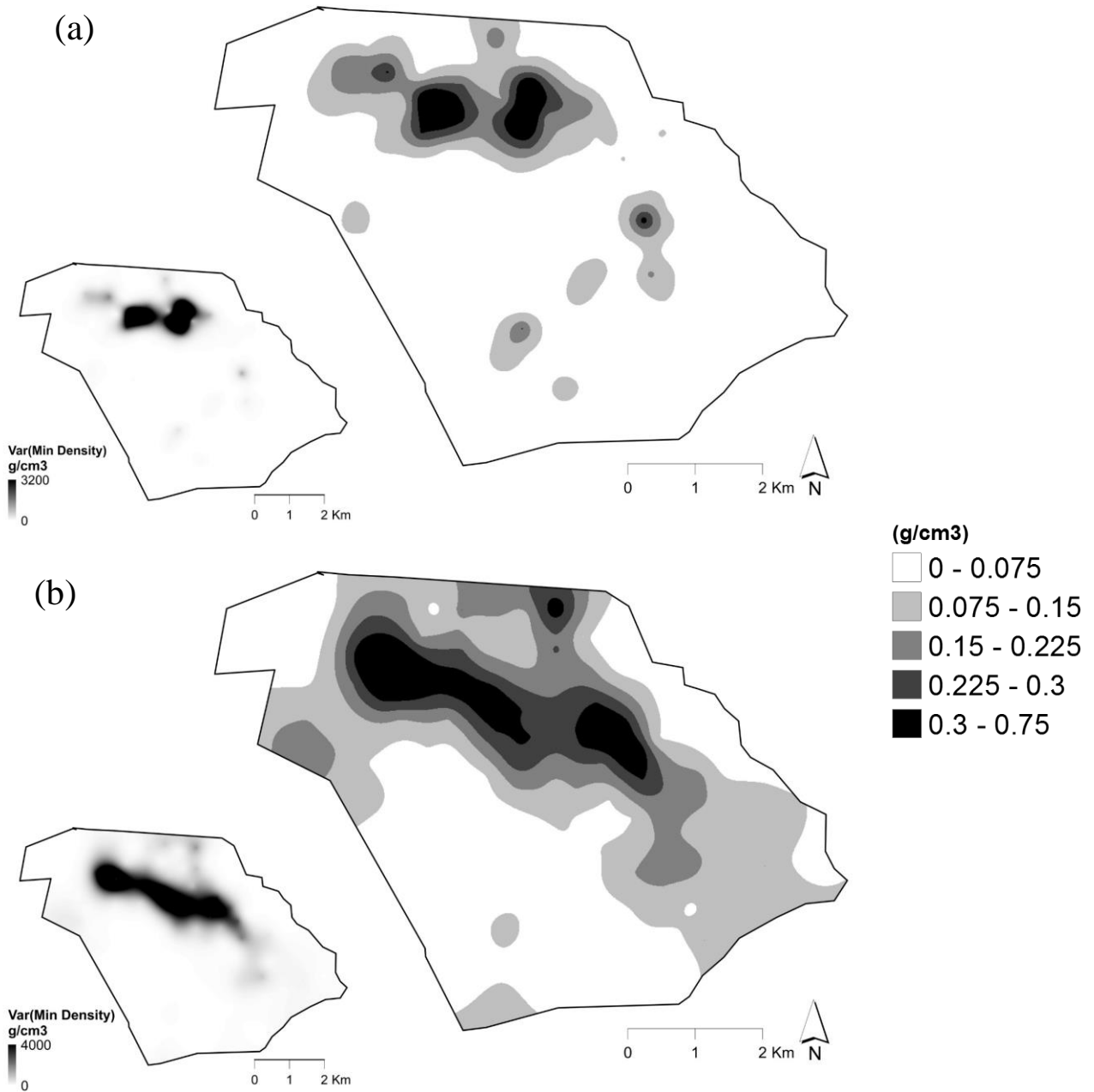
Figures



332
333
334
335
336

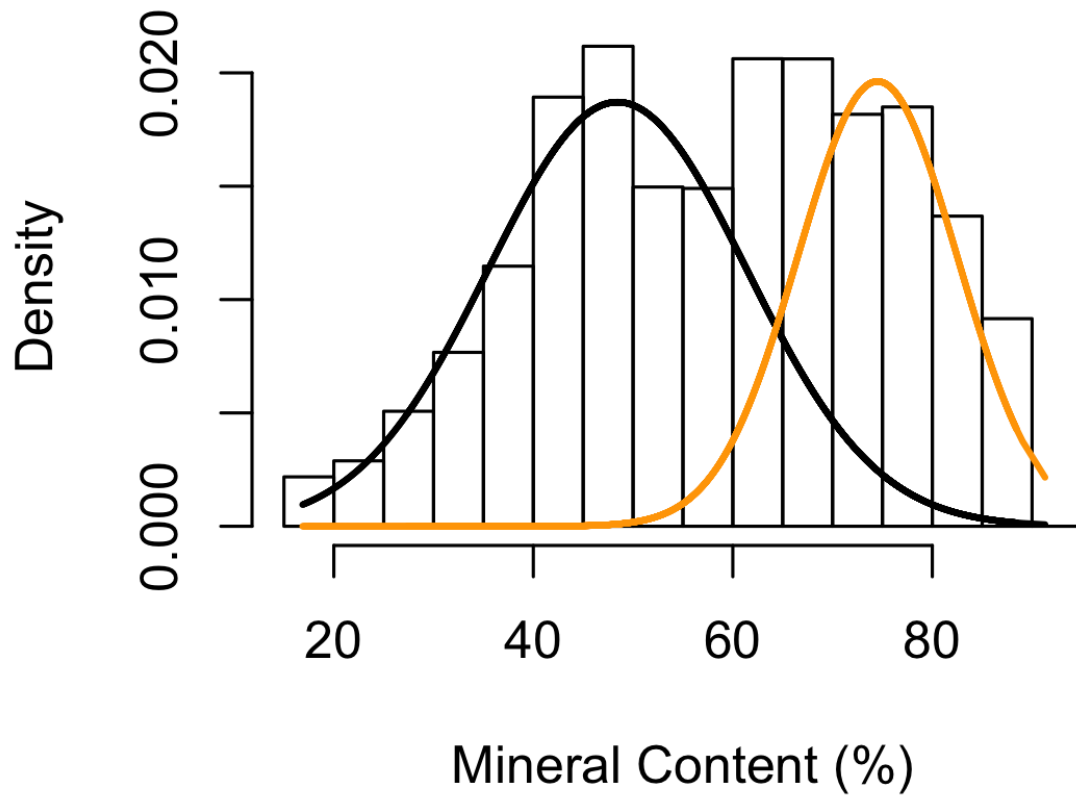
Figure 1. (a) Satellite image of southeastern Louisiana, the study area is located southwest of New Orleans. (b) Satellite image of study wetland area, Davis Pond, with 140 sampled stations. Adapted from GoogleEarth imagery.

337

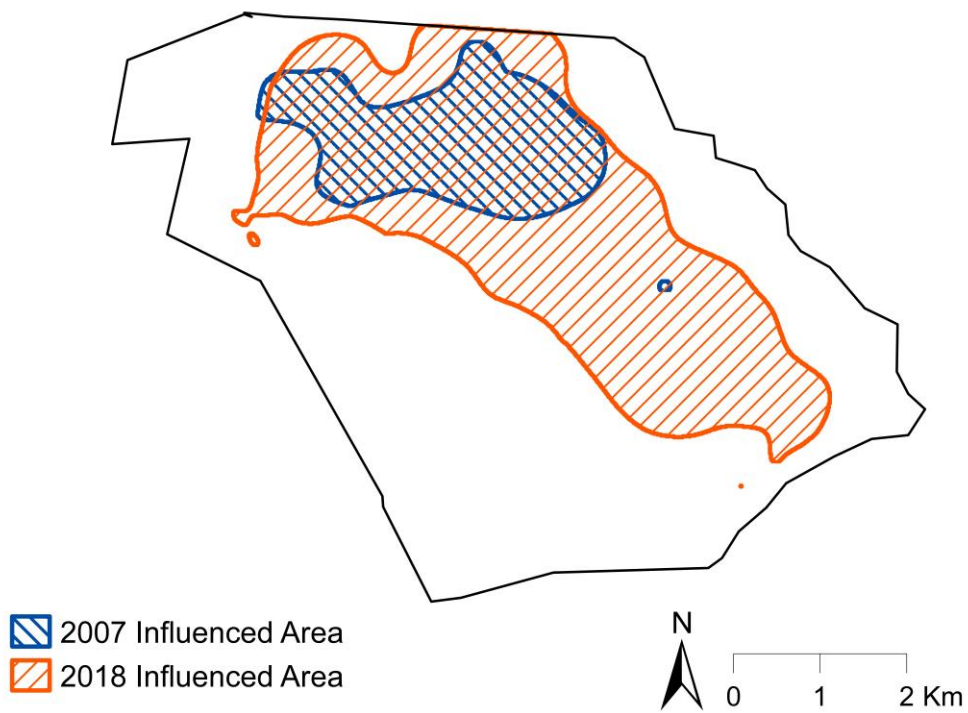


338
339
340
341
342
343
344
345
346
347
348
349

Figure 2. Maps of mineral density (g cm^{-3}) in 0-10 cm soil layer in (a) 2007 and (b) 2018. Small adjacent maps represent associated variance values across the wetland for each prediction.



351
 352 **Figure 3.** Density plot with modelled component distributions calculated from the EM
 353 Algorithm mixture model of the 2018 mineral content (%) data. Low mineral content component
 354 in black, high mineral content component is orange.
 355



356
357
358
359
360

Figure 4. Map of sediment influenced zone from 2007 (blue, back facing shading) and 2018 (orange, forward facing shading) defined by mixture model from mineral content (%) dataset.

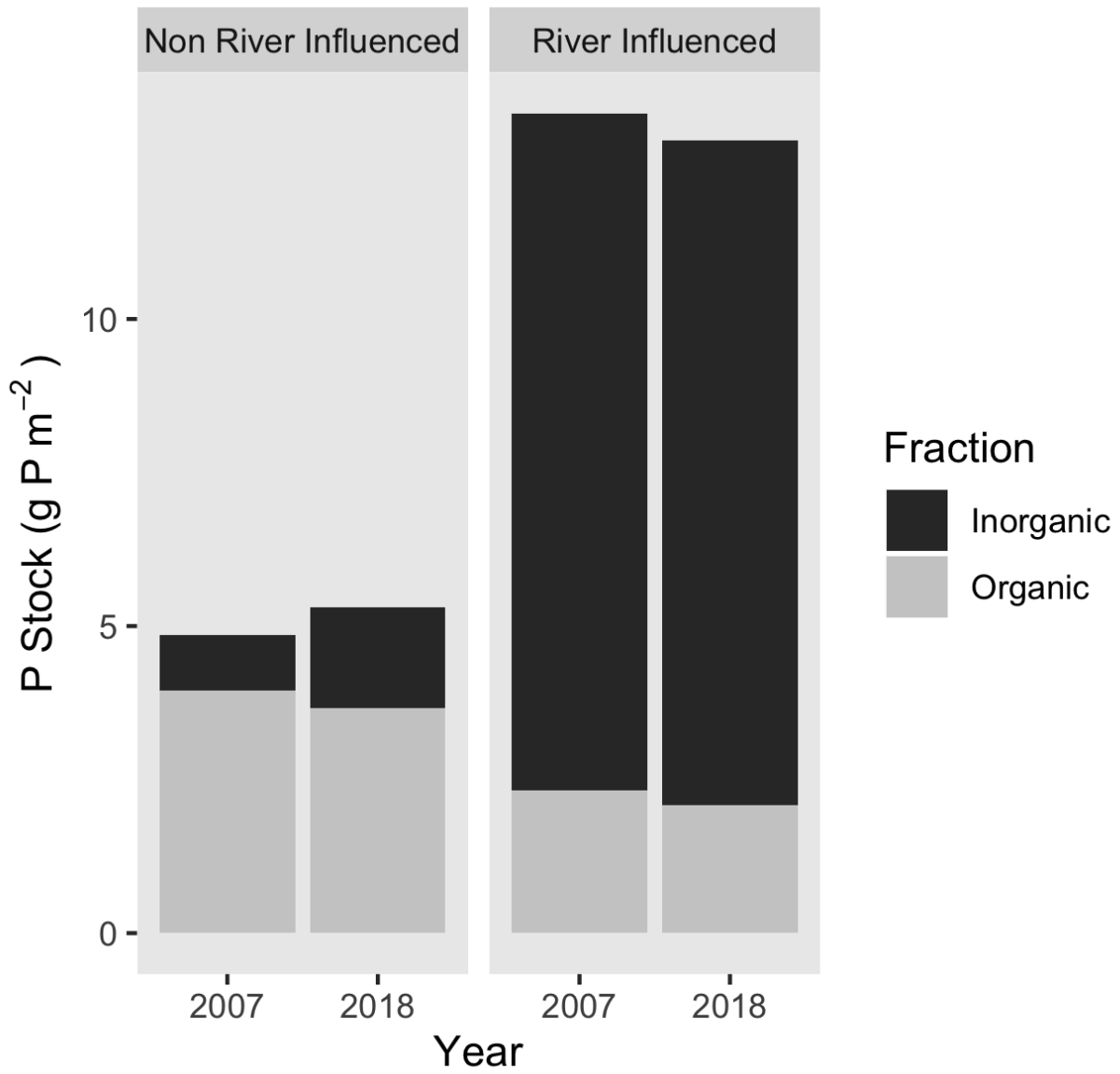
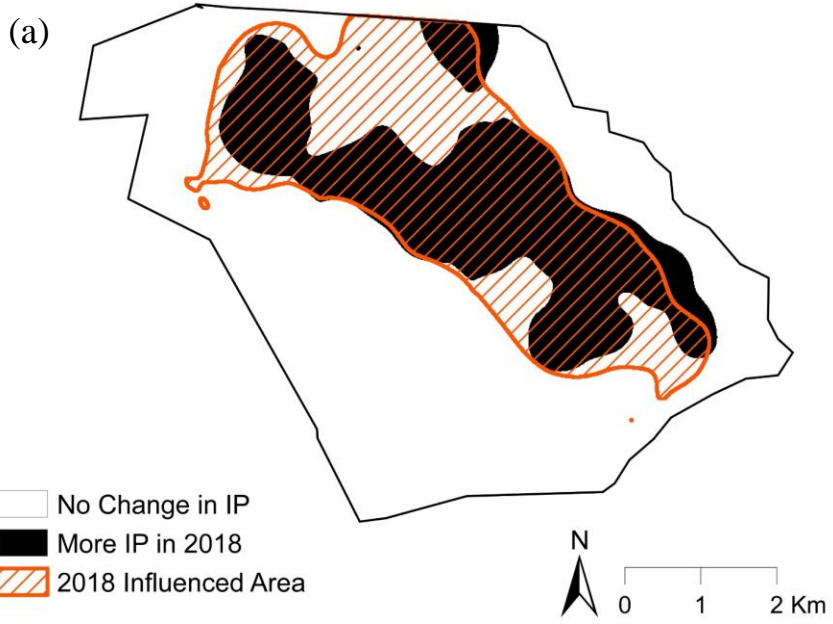


Figure 5. Contribution of P stock for each soil P fraction by year in the diversion sediment influenced zone and the non-influenced zone.

361
362
363
364
365
366
367
368
369



370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397

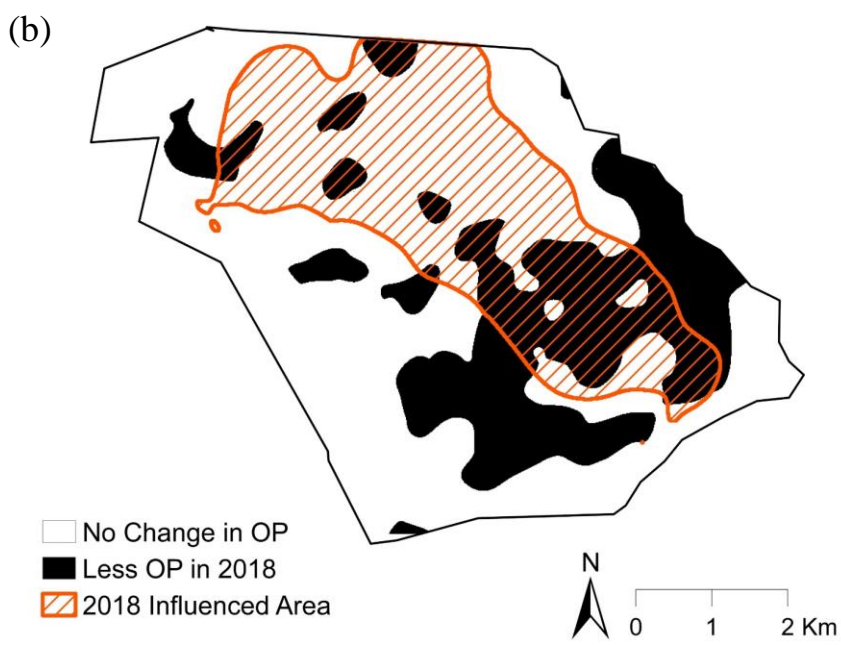


Figure 6. Davis Pond map, black area demarcates where between years new soils had (a) an increase in IP stock or (b) a decrease in OP stock that was outside the 95% confidence interval for change in each variable. Orange shaded area is diversion sediment impact zone in 2018 (mineral content > 65%).

398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432

Table Captions

Table 1. Mean bulk density, mineral and organic matter density, and P stock for each fraction at 140 measured sites and from predicted dataset presented with standard error. Results from paired t-tests are for data from measured sites. Bold signifies significant difference between years.

Table 2. Mean content stocks by year of each soil P fraction inside and outside of the sediment influenced area. Organic P stock was found by normalizing concentration with organic matter density, inorganic P stock was found using mineral density. Bold indicates significant difference between years. ^a indicates significant difference between wetland areas.

Figure Captions

Figure 1. (a) Satellite image of southeastern Louisiana, the study area is located southwest of New Orleans. (b) Satellite image of study wetland area, Davis Pond, with 140 sampled stations. Adapted from GoogleEarth imagery.

Figure 2. Maps of mineral density (g cm^{-3}) in 0-10 cm soil layer in (a) 2007 and (b) 2018. Small maps represent associated variance values across the wetland for each prediction.

Figure 3. Density plot with modelled component distributions calculated from the EM Algorithm mixture model of the 2018 mineral content (%) data. Low mineral content component in black, high mineral content component is orange.

Figure 4. Map of sediment influenced zone from 2007 (blue, back facing shading) and 2018 (orange, front facing shading) defined by mixture model from mineral content (%) dataset.

Figure 5. Contribution of stock for each soil P fraction by year in the diversion sediment influenced zone and the non-influenced zone.

Figure 6. Davis Pond map, black area demarcates where between years new soils had (a) an increase in IP stock or (b) a decrease in OP stock that was outside the 95% confidence interval for change in each variable. Orange shaded area is diversion sediment impact zone in 2018 (mineral content > 65%).

433
434
435
436
437
438
439
440
441
442
443
444
445

Acknowledgements

The 2018 sampling and subsequent analysis was funded by The Water Institute of the Gulf under project award number 2000249131. This project was paid for with federal funding from the Department of the Treasury through the Louisiana Coastal Protection and Restoration Authority’s Center of Excellence Research Grants Program under the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act of 2012 (RESTORE Act). The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of the Department of the Treasury, CPRA or The Water Institute of the Gulf. Additional support was provided by the Society of Wetland Scientists. We also acknowledge Michael P. Hayes, Joanna Zawadzka, Ean Hill, Peter Mates, and Thomas Blanchard for their contribution to this research. The authors would also like to acknowledge Dr. Ben Merchant for his role in designing the original sampling scheme.

- 447 Adams, J. L., Tipping, E., Thacker, S. A., & Quinton, J. N. 2018. An investigation of the
448 distribution of phosphorus between free and mineral associated soil organic matter, using
449 density fractionation. *Plant and Soil*, 427(1–2), 139–148.
- 450 Adhikari, P. L., White, J. R., Maiti, K., & Nguyen, N. 2015. Phosphorus speciation and
451 sedimentary phosphorus release from the Gulf of Mexico sediments: Implication for
452 hypoxia. *Estuarine, Coastal and Shelf Science*, 164, 77–85.
- 453 Anisfeld, S.C. & Hill, T.D. (2012). Fertilization Effects on Elevation Change and Belowground
454 Carbon Balance in a Long Island Sound Tidal Marsh. *Estuaries and Coasts* 35: 201.
- 455 Bargu, S., D. Justic, J.R. White, R. Lane, J. Day, H. Paerl, R. Raynie. 2019. Mississippi River
456 Diversions and Phytoplankton Dynamics in Deltaic, Gulf of Mexico Estuaries: A
457 Review. *Estuarine, Coastal and Shelf Science*. 221:39-52.
- 458 Barras, J., Beville, S., Britsch, D., Hartley, S., Hawes, S., Johnston, J., Kemp, P., Kinler, Q.,
459 Martucci, A., Porthouse, J., Reed, D., Roy, K., Sapkota, S., and Suhayda, J. (2003).
460 Historical and projected coastal Louisiana land changes: 1978–2050: USGS Open File
461 Report 03– 334, 39 p. (Revised January 2004).
- 462 Benaglia T, Chauveau D, Hunter DR, Young D 2009. “mixtools: An R Package for Analyzing
463 Finite Mixture Models.” *Journal of Statistical Software*, 32(6), 1–29.
464 <http://www.jstatsoft.org/v32/i06/>.
465
- 466 Blinn, C. R., and M. A. Kilgore. 2001. “Riparian Management Practices: A Summary of State
467 Guidelines.” *Journal of Forestry* 99 (8): 11–17. <https://doi.org/10.1093/jof/99.8.11>.
468
- 469 Chesney, E. J, Baltz, D. M, & Thomas, R. Glenn. (2000). Louisiana estuarine and coastal
470 fisheries and habitats: perspectives from a fish's eye view. *Ecological applications*, 10,
471 350-366.
- 472 Coastal Protection and Restoration Authority of Louisiana (CPRA). 2017. Louisiana’s
473 Comprehensive Master Plan for a Sustainable Coast. Coastal Protection and Restoration
474 Authority of Louisiana. Baton Rouge, LA.
- 475 Jr. Cowan, J. H., L.A. Deegan, and J.W. Day. 2014. “Fisheries in a Changing Delta.” In
476 Perspectives on the Restoration of the Mississippi Delta, edited by John W. Day, G. Paul
477 Kemp, Angelina M. Freeman, and David P. Muth, 99–109. Dordrecht: Springer
478 Netherlands.
- 479 Darby, F. A., & Turner, R. E. 2008. Below- and Aboveground Biomass of *Spartina alterniflora*:
480 Response to Nutrient Addition in a Louisiana Salt Marsh. *Estuaries and Coasts*, 31(2),
481 326–334.

- 482 Day, J. W., D. F. Boesch, E. J. Clairain, G. P. Kemp, S. B. Laska, W. J. Mitsch, K. Orth, et al.
 483 2007. "Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita."
 484 *Science* 315 (5819): 1679–84.
- 485 Day, J. W., Cable, J. E., Cowan, J. H., DeLaune, R., de Mutsert, K., Fry, B., Wissel, B. 2009.
 486 The Impacts of Pulsed Reintroduction of River Water on a Mississippi Delta Coastal
 487 Basin. *Journal of Coastal Research*, 10054, 225–243.
- 488 Day, J. W., Agboola, J., Chen, Z., D'Elia, C., Forbes, D. L., Giosan, L., Yañez-Arancibia, A.
 489 2016. Approaches to defining deltaic sustainability in the 21st century. *Estuarine,
 490 Coastal and Shelf Science*, 183, 275–291.
- 491 Day, JW., DeLaune, R.D, J.R. White, R.R. Lane, G.P. Shaffer, R. Hunger. 2018. Can
 492 Denitrification Explain Coastal Wetland Loss: A Review of Case Studies in the
 493 Mississippi Delta and New England. *Estuarine, Coastal and Shelf Science*.
- 494 Delaune, R. D., Lindau, C. W., & Jugsujinda, A. 2008. Indicators for evaluating the influence of
 495 diverted mississippi river water on louisiana coastal marsh. *Journal of Freshwater
 496 Ecology*, 23(3), 475–477.
- 497 DeLaune, R. D., & White, J. R. 2012. Will coastal wetlands continue to sequester carbon in
 498 response to an increase in global sea level? : A case study of the rapidly subsiding
 499 Mississippi river deltaic plain. *Climatic Change*, 110(1–2), 297–314.
- 500 DeLaune, R. D., Kongchum, M., White, J. R., & Jugsujinda, A. 2013. Freshwater diversions as
 501 an ecosystem management tool for maintaining soil organic matter accretion in coastal
 502 marshes. *Catena*, 107, 139–144.
- 503 DeLaune, R. D., Sasser, C. E., Evers-Hebert, E., White, J. R., & Roberts, H. H. 2016. Influence
 504 of the Wax Lake Delta sediment diversion on aboveground plant productivity and carbon
 505 storage in deltaic island and mainland coastal marshes. *Estuarine, Coastal and Shelf
 506 Science*, 177, 83–89.
- 507 Ducey, T. F., J. O. Miller, M. W. Lang, A. A. Szogi, P. G. Hunt, D. E. Fenstermacher, M. C.
 508 Rabenhorst, and G. W. McCarty. 2015. Soil Physicochemical Conditions, Denitrification
 509 Rates, and NosZ Abundance in North Carolina Coastal Plain Restored Wetlands. *Journal
 510 of Environmental Quality* 44 (3): 1011–22.
- 511 Everitt, Brian, and D. J. Hand. 1981. Finite Mixture Distributions. Monographs on Applied
 512 Probability and Statistics. London ; New York: Chapman and Hall.
- 513 Everitt, Brian S. 2014. Finite Mixture Distributions. In Wiley StatsRef: Statistics Reference
 514 Online. American Cancer Society.

- 515 Evers, D.E., J.G. Gosselink, C.E. Sasser, and J.M. Hill. (1992). Wetland loss dynamics in
516 southwestern Barataria basin, Louisiana (USA), 1945–1985. *Wetlands Ecol. Manage.*
517 2:103–118.
- 518 ESRI 2018. ArcGIS Desktop: Release 10.6.1 Redlands, CA: Environmental Systems Research
519 Institute.
- 520 Ghaisas, K. Maiti, J.R. White. 2019. Coupled Iron and Phosphorus Release From Seasonally
521 Hypoxic Louisiana Shelf Sediments. *Estuarine, Coastal and Shelf Science*. 219:81-89.
- 522 Gilliam, J. W. 1994. Riparian Wetlands and Water Quality. *Journal of Environmental Quality* 23
523 (5): 896–900.
- 524 Goidts, E., Van Wesemael, B. and Crucifix, M. 2009, Magnitude and sources of uncertainties in
525 soil organic carbon (SOC) stock assessments at various scales. *European Journal of Soil*
526 *Science*, 60: 723-739.
- 527 Goolsby, D. A., Battaglin, W. A., Aulenbach, B. T., & Hooper, R. P. 2000. Nitrogen flux and
528 sources in the Mississippi River Basin. *Science of The Total Environment*, 248(2–3), 75–
529 86.
- 530 Graham, S.A., and I.A. Mendelsohn. 2013. Functional assessment of differential sediment
531 slurry applications in a deteriorating brackish marsh. *Ecological Engineering* 51: 264–
532 274.
- 533 Graham, S. A., & Mendelsohn, I. A. 2016. Contrasting effects of nutrient enrichment on below-
534 ground biomass in coastal wetlands. *Journal of Ecology*, 104(1), 249–260.
- 535 Grunwald, S., R. Corstanje, B.E. Weinrich, and K.R. Reddy. 2006. Spatial patterns of labile
536 forms of phosphorus in a subtropical wetland. *J. Environ. Qual.* 35:378–389.
- 537 Howes, N. C., FitzGerald, D. M., Hughes, Z. J., Georgiou, I. Y., Kulp, M. A., Miner, M. D.,
538 Barras, J. A. 2010. Hurricane-induced failure of low salinity wetlands. *Proceedings of the*
539 *National Academy of Sciences*, 107(32), 14014–14019.
- 540 Jafari, N. H., Day, J. W., Wigand, C., Freeman, A., Sharp, L. A., Pahl, J., Lane, R. R. 2019.
541 Wetland Soil Strength with Emphasis on the Impacts of Nutrients and Sediments. *Estuarine,*
542 *Coastal and Shelf Science*, 225.
- 543 Keogh, M. E., Kolker, A. S., Snedden, G. A., & Renfro, A. A. 2019. Hydrodynamic controls on
544 sediment retention in an emerging diversion-fed delta. *Geomorphology*, 332, 100–111.
- 545 Kral, F., Corstanje, R., White, J. R., & Veronesi, F. 2012. A Geostatistical Analysis of Soil
546 Properties in the Davis Pond Mississippi Freshwater Diversion. *Soil Science Society of*
547 *America Journal*, 76(3), 1107.

- 548 Lo, Y., N.R. Mendell, and D.B. Rubin. 2001. Testing the Number of Components in a Normal
549 Mixture. *Biometrika* 88(3): 767–78.
- 550 Lopez, J. A., Henkel, T. K., Moshogianis, A. M., Baker, A. D., Boyd, E. C., Hillmann, E. R.,
551 Baker, D. B. 2014. Examination of Deltaic Processes of Mississippi River Outlets—
552 Caernarvon Delta and Bohemia Spillway in Southeastern Louisiana. *GCAGS Journal*.
553 Vol 64: 707-708.
- 554 Malecki-Brown, L. M., J. R. White, and K. R. Reddy. 2007. Soil Biogeochemical Characteristics
555 Influenced by Alum Application in a Municipal Wastewater Treatment Wetland. *J.*
556 *Environ. Qual.* 36:1904-1913.
- 557 McAlpin, T. O., Letter, J. V, & Martin, S. K. (2008). *A Hydrodynamic Study of Davis Pond,*
558 *Near New Orleans, LA.* Report from the Coastal and Hydraulics Laboratory, U.S. Army
559 Engineer Research and Development Center. ERDC/CHL TR-08-11.
- 560 Mendelsohn, I.A., and N.L. Kuhn. 2003. Sediment subsidy: Effects on soil–plant responses in a
561 rapidly submerging coastal salt marsh. *Ecological Engineering* 21 (2-3): 115–128.
- 562 Morris, J.T., G.P. Shaffer, and J.A. Nyman. 2013. Brinson review: Perspectives on the influence
563 of nutrients on the sustainability of coastal wetlands. *Wetlands* 33 (6): 975–988.
- 564 Poormahdi, S., Graham, S. A., & Mendelsohn, I. A. 2018. Wetland Plant Community
565 Responses to the Interactive Effects of Simulated Nutrient and Sediment Loading:
566 Implications for Coastal Restoration Using Mississippi River Diversions. *Estuaries and*
567 *Coasts*, 41(6), 1679–1698.
- 568 R Core Team 2014. R: A language and environment for statistical computing. R Foundation for
569 Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>.
- 570 RStudio Team 2015. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA
571 URL <http://www.rstudio.com/>.
- 572 Ribeiro, P.J., Jr., and P.J. Diggle. 2001. GeoR: A package for geostatistical analysis. *R-NEWS*
573 1(2):15–18.
- 574 Rivero, R. G., Grunwald, S., Osborne, T. Z., Reddy, K. R., & Newman, S. 2007.
575 Characterization of The Spatial Distribution of Soil Properties in Water Conservation Area
576 2a, Everglades, Florida. *Soil Science*, 172(2), 149–166.
- 577 Reddy, K. R., Diaz, O. A., Scinto, L. J., & Agami, M. 1995. Phosphorus dynamics in selected
578 wetlands and streams of the lake Okeechobee Basin. *Ecological Engineering*, 5(2–3),
579 183–207.

- 580 Reddy, K. R., Wang, Y., Debusk, W. F., Fisher, M. M., & Newman, S. 1998. Forms of Soil
581 Phosphorus in Selected Hydrologic Units of the Florida Everglades. *Soil Science Society*
582 *of America Journal*, 62, 1134–1147.
- 583 Reddy, K.R. and Delaune, R.D. 2008 *Biogeochemistry of Wetlands: Science and Applications*.
584 CRC Press, Boca Raton.
- 585 Sapkota, Y., & White, J. R. 2019. Marsh edge erosion and associated carbon dynamics in coastal
586 Louisiana: A proxy for future wetland-dominated coastlines world-wide. *Estuarine,*
587 *Coastal and Shelf Science*, 226, 106289.
- 588 Schrumpf, M., Schulze, E. D., Kaiser, K., & Schumacher, J. 2011. How accurately can soil
589 organic carbon stocks and stock changes be quantified by soil inventories?
590 *Biogeosciences*, 8 (5), 1193-1212.
- 591 Slocum, M.G., I.A. Mendelsohn, and N.L. Kuhn. 2005. Effects of sediment slurry enrichment
592 on salt marsh rehabilitation: Plant and soil responses over seven years. *Estuaries* 28 (4):
593 519–528.
- 594 Snedden, G.A., J.E. Cable, C. Swarzenski, and E. Swenson. 2007. Sediment discharge into a
595 subsiding Louisiana deltaic estuary through a Mississippi River diversion. *Estuarine*
596 *Coastal and Shelf Science* 71 (1-2): 181–193.
- 597 Sutula, M., Bianchi, T. S., & McKee, B. A. 2004. Effect of seasonal sediment storage in the
598 lower Mississippi River on the flux of reactive particulate phosphorus to the Gulf of
599 Mexico. *Limnology and Oceanography*, 49(6), 2223–2235.
- 600 Swarzenski, C. M., Doyle, T. W., Fry, B., & Hargis, T. G. 2008. Biogeochemical response of
601 organic-rich freshwater marshes in the Louisiana delta plain to chronic river water influx.
602 *Biogeochemistry*, 90(1), 49–63.
- 603
604 Sparks, D (Ed.) 1996, *Methods of Soil Analysis. Part 3. Chemical Methods*, Book Ser, vol. 5,
605 SSSA, Madison
- 606 Tipping, E., Somerville, C. J., & Luster, J. 2016. The C:N:P:S stoichiometry of soil organic
607 matter. *Biogeochemistry*, 130(1–2), 117–131.
- 608 Turner, R. E., Howes, B. L., Teal, J. M., Milan, C. S., Swenson, E. M., & Goehring-Toner, D.
609 D. 2009. Salt marshes and eutrophication: An unsustainable outcome. *Limnology and*
610 *Oceanography*, 54(5), 1634–1642.
- 611 Turner, R. E., M.Layne, Y. Mo, and E.M. Swenson. 2019. Net Land Gain or Loss for Two
612 Mississippi River Diversions: Caernarvon and Davis Pond. *Restoration Ecology* 27 (6):
613 1231–40.

- 614 van Groenigen, J. W., Siderius, W., & Stein, A. 1999. Constrained optimisation of soil sampling
615 for minimisation of the kriging variance. *Geoderma*, 87(3–4), 239–259.
- 616 Veronesi, F., Corstanje, R., & Mayr, T. 2014. Landscape scale estimation of soil carbon stock
617 using 3D modelling. *Science of The Total Environment*, 487, 578–586.
- 618 White, J. R., Reddy, K. R., & Majer-Newman, J. 2006. Hydrologic and Vegetation Effects on
619 Water Column Phosphorus in Wetland Mesocosms. *Soil Science Society of America*
620 *Journal*, 70(4), 1242.
- 621 White, J. R., R. D. DeLaune, D. Justic, J.W. Day, J Pahl, R. R. Lane, W. R. Boynton, and R. R.
622 Twilley. 2019. Consequences of Mississippi River Diversions on Nutrient Dynamics of
623 Coastal Wetland Soils and Estuarine Sediments: A Review. *Estuarine, Coastal and Shelf*
624 *Science* 224: 209–16.
- 625 Webster, R. and Oliver, M.A. 2007. *Geostatistics for Environmental Scientists*. John Wiley &
626 Sons, Chichester.
- 627 Xu, K., Bentley, S. J., Day, J. W., & Freeman, A. M. 2019. A review of sediment diversion in the
628 Mississippi River Deltaic Plain. *Estuarine, Coastal and Shelf Science*, 225, 106241.
- 629 Zedler, J. B., & Kercher, S. 2005. Wetland Resources: Status, Trends, Ecosystem Services, and
630 Restorability. *Annual Review of Environment and Resources*, 30(1), 39–74.
- 631 Zhang, W., White, J. R., & DeLaune, R. D. 2012. Diverted Mississippi River sediment as a
632 potential phosphorus source affecting coastal Louisiana water quality. *Journal of*
633 *Freshwater Ecology*, 27(4), 575–586.