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# Effect of Water Management on Interannual Variation in Bulk Soil Properties from the Eastern Coastal Everglades

R. M. Chambers

*W. M. Keck Environmental Field Laboratory, College of William and Mary*


R. L. Hatch

*W. M. Keck Environmental Field Laboratory, College of William and Mary*

T. M. Russell

*W. M. Keck Environmental Field Laboratory, College of William and Mary*

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1 R. M. Chambers · R. L. Hatch · T. M. Russell

2

3 **Effect of Water Management on Interannual Variation in Bulk Soil Properties from the**  
4 **Eastern Coastal Everglades**

5

6 R. M. Chambers · R. L. Hatch · T. M. Russell

7 W. M. Keck Environmental Field Laboratory

8 College of William and Mary

9 Williamsburg, VA 23187, USA

10 Email: rmcham@wm.edu

11 Telephone: 757.221.2331

12 Fax: 757.221.5076

13

14 **Abstract** We examined interannual variation in soil properties from wetlands occurring in  
15 adjacent drainage basins from the southeastern Everglades. Triplicate 10-cm soil cores were  
16 collected, homogenized, and analyzed during the wet season 2006-2010 from five freshwater  
17 sawgrass wetland marshes and three estuarine mangrove forests. Soil bulk density from the  
18 Taylor Slough basin ranged from 0.15 to 0.5 gm-cm<sup>-3</sup>, was higher than from the Panhandle basin  
19 every year, and generally increased throughout the study period. Organic matter as a percent  
20 loss on ignition ranged from 7-12% from freshwater marshes and from 13-56% from estuarine  
21 mangroves. Extractable iron in soils was similar among drainage basins and wetland types,  
22 typically ranging from 0.6 to 2.0 g Fe kg<sup>-1</sup>. In contrast, inorganic sulfur was on average over  
23 four times higher from estuarine soils relative to freshwater, and was positively correlated with  
24 soil organic matter. Finally total soil phosphorus (P) was lower in freshwater soils relative to  
25 estuarine soils (84 ± 5 versus 326 ± 32 mg P kg<sup>-1</sup>). Total P from the freshwater marshes in the  
26 Panhandle basin rose throughout the study period from 54.7 ± 8.4 to 107 ± 17 mg P kg<sup>-1</sup>, a  
27 possible outcome of differences in water management between drainage basins.

28

29 **Keywords** Bulk Density · Organic Matter · Phosphorus · Sulfur · Southeastern Everglades

30

31 **Introduction**

32 The comprehensive Everglades restoration plan (CERP) is designed to restore and protect  
33 freshwater flows through wetlands of the southern Florida landscape while continuing to meet  
34 the water needs of and flood protection for the general public (US Congress 2000). The Florida  
35 Coastal Everglades Long-Term Ecological Research program was established in part to monitor  
36 and research the wetland responses associated with the proposed, enhanced freshwater flows. To  
37 date, however, political and financial hurdles have delayed many wetland restoration projects.  
38 Despite these temporal setbacks, coastal Everglades ecosystems still experience spatial and  
39 temporal variation in water flows driven by natural phenomena (i.e., hurricanes, El-Niño events,  
40 sea level rise) and by ongoing, smaller-scale water management decisions. These changes in  
41 water flows—although not part of CERP per se—can be used to examine ecosystem response  
42 patterns and to predict the ecological outcome of forthcoming restoration efforts.

43

44 Historical flows of freshwater to the Everglades have been reduced drastically. Much of  
45 the remaining water flow through the northern Everglades is enriched in phosphorus and other  
46 constituents derived from agricultural and urban non-point source runoff (Davis 1994), leading  
47 to shifts in plant community dominance from sawgrass (*Cladium jamaicense*) to cattail (*Typha*  
48 *sp.*) (Wu et al. 1997; Waters et al. 2012). When water flows are enhanced with restoration, one  
49 potential concern is the extent to which increased delivery of water farther south into  
50 oligotrophic portions of the Everglades will also carry more phosphorus (Noe et al. 2001).  
51 Childers et al. (2006b) documented vegetation changes in response to increased water depth and  
52 hydroperiod in a section of the southeastern Everglades with restored water flow. The soil  
53 response to hydrologic drivers in the oligohaline Everglades, however, has not been well-studied.

54 Recent studies of spatial variation in bulk soil properties of the southern Everglades have  
55 provided evidence of phosphorus enrichment (Osborne et al. 2011; this volume), but temporal  
56 variation in soil properties in this region must be examined in the context of hydrologic change.

57

58 Here, we provide a five-year time series documenting interannual variation in bulk soil  
59 properties from two adjacent drainage basins in the southeastern coastal Everglades that  
60 historically have experienced different water management and flow restoration regimes (Kotun  
61 and Renshaw this issue). One of the basins currently receives discharge from water detention  
62 areas and from pumping stations; the other basin had freshwater flow enhanced in 1997 by  
63 removing canal levees and allowing for more diffuse, overbank flooding. In the absence of any  
64 information on soil conditions in downstream wetlands pre-levee removal, we cannot calibrate  
65 the basins for a paired watershed experiment (EPA 1993). We can, however, compare the  
66 temporal patterns in soil properties and look for evidence of phosphorus enrichment and other  
67 potential changes in related, non-conservative soil constituents (bulk density, organic matter, soil  
68 sulfur and extractable iron) between basins within the context of recent changes in water  
69 management.

70

71

## 72 **Methods**

### 73 **Study Site**

74 The study was completed in the southeastern portion of the Everglades as part of the Florida  
75 Coastal Everglades Long-Term Ecological Research program. Two drainage basins underlain by  
76 limestone bedrock comprise this portion of the Everglades, including Taylor Slough (TS) and an

77 adjacent region called the Panhandle (Ph) (Fig. 1). Ecosystem structure of coastal Everglades  
78 wetlands is influenced strongly by hydrologic factors including water volume, source, and  
79 residence time (e.g., Ross et al., 2003). Freshwater runoff through canals, natural channels, and  
80 sheetflow drains into the coastal region where saltwater mixing from Florida Bay creates an  
81 estuarine environment. Whereas water delivery to the TS basin since 2000 has been dominated  
82 by directed flow through pump structures and associated detention areas to increase marsh  
83 hydroperiod (Kotun and Renshaw this issue), levee removal at the headwaters of the Ph basin (C-  
84 111 canal) in 1997 (Parker 2000) combined with lower elevation has led to more diffuse water  
85 delivery and a greater hydroperiod downstream relative to the TS basin (Childers et al. 2006b).  
86 In the TS basin, we sampled from three freshwater marshes dominated by sawgrass (*Cladium*  
87 *jamaicense*) and spikerush (*Eleocharis* sp.) and two estuarine mangrove forests dominated by  
88 scrub red mangrove (*Rhizophora mangle*). In the Ph basin, we sampled from two freshwater  
89 marshes and one estuarine mangrove forest dominated by the same species as in the TS basin.  
90 Relative to southwestern Everglades wetlands in the Shark River Slough basin, soils from the TS  
91 and Ph basins are more shallow and tend to have less peat and more marl deposits (Childers et  
92 al., 2003; Chambers and Pederson 2006).

93

#### 94 Soil Collection and Analysis

95 Because of field logistics, soil collections were completed in the wet season at the beginning of  
96 August for each of the five years of the study, at locations within the wetland vegetation, i.e., at  
97 least 50 m away from stream or canal channels. Between years, samples at each site were  
98 collected within 20 m of each other. From each of the eight sampling sites, surface periphyton  
99 and floc were cleared and three 60-ml syringe barrels were pushed into the soil to a depth a 10

100 cm while holding the plunger at the soil surface to minimize compaction. The syringe barrels  
101 were capped with butyl rubber stoppers and stored on ice for transport to the laboratory, where  
102 cores were refrigerated prior to analysis.

103

104         Soils were extruded and homogenized, then sub-sampled. Samples for bulk density, %  
105 organic matter, total phosphorus (P) and extractable iron (Fe) analyses were placed in tared vials,  
106 dried at 80°C and weighed to determine bulk density, then ashed at 450°C for four hours to  
107 determine weight loss on ignition. The ashed soils were then resuspended in 1N HCl to  
108 hydrolyze phosphate for total P analysis (Chambers and Fourqurean 1991) and to determine  
109 extractable iron using the ferrozine method (Stookey, 1970). Although the largest P pool in  
110 south Florida wetland soils is associated with calcium carbonate (Koch et al. 2001), recent  
111 studies suggest iron oxide coatings play a critical role in P exchange between sediment and water  
112 in calcareous systems (Huang and Zhang 2010).

113

114         Soil samples for total sulfide extraction were first suspended in 1N zinc acetate to  
115 precipitate any free sulfide in solution. Then, the samples were boiled for one hour in a  
116 concentrated HCl and 1M reduced chromium solution to liberate sulfur gas as H<sub>2</sub>S that was  
117 sequestered in a 1M NaOH trap. The trapped sulfide was fixed using Cline's reagent and  
118 analyzed colorimetrically (Cline 1969). Total sulfide includes free sulfide, iron monosulfide  
119 (FeS), polysulfides, and pyrite (FeS<sub>2</sub>) (Chambers and Pederson 2006) and is used here as a proxy  
120 for the relative amount of sulfate exposure in reduced wetland soils.

121

122 Soil measurement averages  $\pm$  standard errors were calculated by wetland type, by basin  
123 and by year. Data were summarized using factor analysis, and interannual variation in soil  
124 characteristics were examined graphically. Relationships between bulk density, organic matter  
125 and the concentration of non-conservative species (P, Fe, S) were investigated using multiple  
126 regression.

127

## 128 **Results**

129 Factor analysis of all soil parameters across years yielded three significant principal components  
130 accounting for 78% of the cumulative variation. The first principal component (PC1) had  
131 highest loadings for wetland type (freshwater marsh or mangrove forest), organic matter, and soil  
132 sulfide. PC2 had highest loadings for total P, extractable iron, and bulk density. Finally, PC3  
133 had the highest loading for basin. We view these groupings as a separation by wetland type for  
134 PC1, with the primary difference in freshwater and mangrove soils characterized by relative  
135 amounts of organic matter and inorganic sulfide. For PC2, the grouping reflects soil differences  
136 characterized by P abundance that is influenced by amounts of extractable iron and calcium  
137 carbonate (both components of bulk density). For PC3, the separation of basin as a single factor  
138 indicates differences in soil parameters between TS and Ph basins. Differences between basins,  
139 wetland types, and among sampling years are summarized below.

140

### 141 **Bulk Density**

142 From the freshwater marsh sites, average bulk density each year was higher from the TS basin  
143 relative to the Ph basin and generally rose between 2006 and 2009 (Fig. 2A). Likewise, average  
144 bulk density from the estuarine mangrove sites rose between 2006 and 2009, then dropped in

145 2010. The range in bulk density was from a low of  $0.119 \text{ g cm}^{-3}$  from the Ph estuarine site in  
146 2006 to a high of  $0.521 \text{ g cm}^{-3}$  from the TS freshwater sites in 2009.

147

#### 148 Organic Matter

149 From freshwater marsh sites, average soil organic matter (OM) ranged between 7.4 and 12.1%  
150 and each year was higher from the TS basin relative to the Ph basin (Fig. 2B). In contrast,  
151 average OM was lower from the TS estuarine mangrove sites and exhibited a much broader  
152 interannual range (between 12.6 and 55.6%). Whereas OM from the two freshwater sites from  
153 the TS basin rose slightly between 2006 and 2009, OM from both TS and Ph estuarine sites  
154 tended to fall over that same time frame. OM was 2-3 times higher from estuarine sites relative  
155 to freshwater sites.

156

#### 157 Total Phosphorus

158 Total P levels were comparably low from the five freshwater marsh sites in both TS and Ph  
159 basins (Fig 3), averaging less than  $100 \text{ mg kg}^{-1}$  over the five years sampled. Some interannual  
160 variation was noted in that total P from the two Ph marsh sites on average increased over the five  
161 years from  $54.7 \pm 8.4 \text{ mg kg}^{-1}$  in 2006 to  $107 \pm 17 \text{ mg kg}^{-1}$  in 2010. Total P levels were larger,  
162 more variable and exhibited no interannual pattern from the estuarine mangrove sites, although  
163 each year average total P was higher from the Ph site ( $410 \pm 21 \text{ mg kg}^{-1}$ ) relative to the TS sites  
164 ( $240 \pm 27 \text{ mg kg}^{-1}$ ) (Fig. 3). Stepwise, multiple regression of total P as a function of wetland  
165 type, bulk density, extractable iron and year yielded a significant correlation accounting for 48%  
166 of the variation in soil P ( $p < 0.001$ ).

167



168 Extractable Iron

169 Average extractable Fe varied between 0.62 and 1.27 g kg<sup>-1</sup> from freshwater marsh sites and  
170 between 0.82 and 9.05 g kg<sup>-1</sup> from estuarine sites (Fig. 4A). Wetland soils from the Ph basin  
171 were typically higher in extractable Fe, relative to wetland soils from the TS basin (excluding  
172 one outlier from the Ph basin in 2006, 1.4 ± 0.1 versus 1.0 ± 0.1 g kg<sup>-1</sup>). No interannual trends of  
173 increasing or decreasing Fe concentration were obvious. Stepwise, multiple regression of  
174 extractable iron as a function of total P, soil S, basin, and wetland type yielded a weak but  
175 significant correlation accounting for 23% of the variation in extractable iron (p < 0.001).

176

177 Total Sulfide

178 Reduced sulfur concentration was on average less than 1 mg kg<sup>-1</sup> from freshwater marsh soils  
179 (0.36 ± 0.08 g kg<sup>-1</sup>) and for most years greater than 1 from estuarine mangrove soils (2.41 ± 0.93  
180 mg kg<sup>-1</sup>) (Fig. 4B). Similar to the pattern observed for extractable Fe, in most years sulfur was  
181 higher in soils from the Ph basin relative to the TS basin. Multiple regression of soil S as a  
182 function of wetland type, percent organic matter, extractable iron, total P, and basin yielded a  
183 significant correlation accounting for 65% of the variation in soil S (p < 0.001).

184

185 **Discussion**

186 Soil characteristics are the integrated expression of a suite of physical and biogeochemical  
187 processes that take place over different spatial and temporal scales. For the coastal Everglades,  
188 the timing, volume, and quality of water flows through the landscape are principal factors  
189 influencing plant community structure (Ross 2003) and soil structure as well (Childers et al.  
190 2003). Since large-scale restoration plans proposed for the Everglades will include increases in

191 water flow, changes in soil properties may be expected. Here we present the results from  
192 adjacent drainage basins subjected to small-scale differences in water management, as a potential  
193 model system for determining the Everglades response to large-scale restoration. Superimposed  
194 upon water management differences between basins are potential differences in topography and  
195 other drivers of water movement, including sea level rise, acute storms and other meteorological  
196 phenomena that occur on regional scales. The two basins in the current study, however, are  
197 sufficiently close—similar to paired watersheds—that water management may account for the  
198 largest difference in water movements between basins.

199

200 Over the five-year time series of soil measurement, we observed no systematic changes in  
201 soil organic matter in either freshwater or estuarine wetland locations. Although percent organic  
202 matter was higher in estuarine mangrove forest soils relative to freshwater marsh soils, the  
203 patterns between basins were similar throughout the study, i.e., relative to the TS basin, organic  
204 matter from the Ph basin was lower every year in the freshwater marsh sites and higher in the  
205 estuarine forest sites from 2006-2010. Organic matter and bulk density typically are inversely  
206 related, but the small measured increase in organic matter (from 10% to 13%) when bulk density  
207 was also increasing (Fig. 2) could occur, for example, if organic density increased but inorganic  
208 density did not. A prior study reported values for organic matter averaged across all TS and Ph  
209 sites for 2003 that were higher for both freshwater and estuarine wetlands (14.4% and 35.8%,  
210 respectively) (Chambers and Pederson 2006). Given the range in organic matter from estuarine  
211 sites (Fig. 2A), we conclude that small-scale spatial variability of mangrove soils may limit our  
212 ability to detect interannual changes in OM associated with changes in water flow.

213

214 Soil bulk density differences among years were rather large, but consistent between  
215 basins and between wetland types. For both freshwater and estuarine soils, the average bulk  
216 density was always lower in the Ph basin relative to the TS basin, and all soils exhibited an  
217 average increase in bulk density 2006-2009, followed by a drop in 2010. All soils in the TS/Ph  
218 region are high in inorganic marl deposits (Childers et al. 2006a), although Osborne et al. (2011)  
219 found lower bulk density in the marl prairies typical of our Ph sites, relative to their TS sites.  
220 Rather than a response to water management, these discrepancies suggest that spatial variation  
221 among sites within a particular basin may be larger than temporal variation at the same site. This  
222 conclusion is consistent with the results of factor analysis that identified “basin” as a principal  
223 component (PC3) of variation among the data.

224

225 We measured substantial interannual variation in total soil phosphorus from estuarine  
226 mangrove sites (Fig. 3). Estuarine Everglades soils have more organic matter and thus store  
227 more P, as has been observed in prior studies (Koch and Reddy 1992; Childers et al. 2003;  
228 Chambers and Pederson 2006; Osborne et al. 2011). Soil P from the freshwater sites, in contrast,  
229 was less variable from year-to-year in our study, and low relative to prior years. Childers et al.  
230 (2003) collected soil in 1999 from the same three TS locations as our study and measured 142  
231 mg P kg<sup>-1</sup>, and Chambers and Pederson (2006) measured 220 mg kg<sup>-1</sup> in 2003, roughly double  
232 what we found in 2006. Although the use of water retention areas in the TS basin in 2000  
233 (Sullivan et al. this issue) and removal of canal levees in the Ph basin in 1997 changed water  
234 flows farther upstream (Kotun and Renshaw this issue), we view these soil differences as a  
235 reflection of spatial variation within sampling sites or the result of other factors besides water

236 management, such as hurricane-driven storm deposition (e.g., Castañeda-Moya et al. 2010), or  
237 interannual variation in rainfall patterns (Childers et al 2006a).

238

239 Total P from the freshwater marsh sites of the Ph basin, however, increased throughout  
240 the study period 2006-2010 (Fig. 3), unlike the pattern observed for any other soil property.  
241 Although a majority of soil P is organic (Scinto 1997), a significant fraction of Everglades soil P  
242 is carbonate-bound (Osborne et al. 2011), so soil P potentially could increase along with soil  
243 bulk density. Marsh soils from the Ph basin did exhibit increases in bulk density 2006-2009, but  
244 decreased in 2010. Further, increases in bulk density in the TS marsh soils were not matched by  
245 increases in total P, so we do not think the rise in soil P from the Ph marsh sites is due solely to  
246 increased P deposition with marl, the most common mode of P accumulation in Everglades soils  
247 (Noe and Childers 2007). Factor analysis identified a principal component (PC2) along an axis  
248 defined by variation in total P, extractable iron, and bulk density, suggesting an influence from  
249 iron oxides and perhaps other soil components in addition to carbonates.

250 Childers et al. (2006b) found that restoration of water flows in the Ph basin led to a  
251 decrease in primary production by sawgrass and a concomitant increase in spikerush (*Eleocharis*  
252 sp.) stem density. Shifts in plant community structure or algal production in the Ph marshes in  
253 response to increased water flow since 1997 could potentially shift the distribution and  
254 abundance of P in the soil, reflected in the observed increase in soil P 2006-2010 (Fig. 3). Plant  
255 root production and decomposition dynamics could change with the altered hydrology in the Ph  
256 basin. Alternately, the increased soil P could be a consequence of increased delivery of P along  
257 with the water (Rudnick et al. 1999), although Noe et al. (2002) found that experimental  
258 enrichment of Everglades water with P did not lead to increases in soil P after six months. More

259 recently, Noe et al. (2003) used a radiotracer study to show that 27% of P added to the  
260 Everglades water column could be incorporated into soil within 18 days, so perhaps the time  
261 frame for rapid soil processing of P (weeks) is much shorter than the time frame needed for  
262 detection of long-term P accumulation used in the current study (years).

263

264 Extractable iron as a proxy for reactive iron is a fraction of total soil iron that in  
265 Everglades soils averages roughly 10 g kg<sup>-1</sup> (Osborne et al. 2011). Because iron occurs in these  
266 biogenic carbonate soils in low concentration relative to terrigenous soils, the extent of various  
267 biogeochemical processes involving iron is diminished (Chambers et al. 2001). Soil phosphorus,  
268 for example, can sorb to reactive iron oxides, but prior studies have shown this is a minor  
269 fraction of the total P pool in carbonate sediment (Koch et al. 2001; Zhang et al. 2004). Reactive  
270 iron may be reduced under anaerobic conditions during the wet season in Everglades marsh soils,  
271 but during the dry season and water drawdown the iron may be re-oxidized. Thus, a seasonal  
272 sorption and release of P from iron still is plausible in carbonate soils (e.g., Huang and Zhang  
273 2010). In mangrove soils, extractable iron content is slightly higher than marsh soils, and some  
274 “reacted” iron has precipitated largely as iron sulfide in this estuarine environment. The source  
275 of most of the iron in the south Florida landscape is atmospheric deposition from African dust  
276 (Prospero et al. 2010), and deposition rates were fairly uniform spatially and not dramatically  
277 different over the five years of our study (J.M. Prospero, pers. comm.). Thus, the very high level  
278 of extractable iron in the Panhandle mangrove soil in 2008 cannot be the result of localized  
279 deposition of atmospheric iron, but may instead be a localized concentrated source of iron.

280

281           The distribution of total reduced sulfur (Fig 4B) and the results of factor analysis  
282 identifying a principal component (PC1) along an axis of variation defined by wetland type, soil  
283 organic matter and inorganic sulfide demonstrate how anaerobic sulfate reduction is driven by  
284 the availability of both organic matter as an energy source and sulfate as a terminal electron  
285 acceptor. The estuarine soils are higher in organic matter and seawater-derived sulfate; the  
286 mangrove forests also experience more prolonged flooding than the freshwater marshes. As a  
287 result, reduced sulfur compounds accumulate more extensively in the mangrove soils in both the  
288 TS and the Ph basins. Interestingly, sulfur content is higher in Ph marsh soils relative to TS,  
289 even though organic content is slightly lower (Fig 2A). To the extent that freshwater canals may  
290 operate to deliver elevated levels of sulfate derived from agriculture to the northern Everglades  
291 (EPA 2000; Gilmour et al. 2007), increased flows of water derived from canal discharge  
292 originating in agricultural and urbanized areas could be a source of sulfate that will increase  
293 sulfide deposition in southeastern Everglades marshes. We did not observe an increase in soil  
294 sulfide deposition in the Ph basin over the same time interval that soil P was increasing,  
295 however, suggesting either that S inputs were relatively constant or had equilibrated more  
296 rapidly, or that the availability of reactive iron limited sulfide deposition. Finally, Price et al.  
297 (2006) found evidence of greater saltwater intrusion of groundwater into the Ph freshwater basin  
298 relative to TS, so the elevated sulfide signature in Ph soils could be from seawater sulfate and not  
299 from freshwater canal discharge.

300

301           The ongoing objective of Everglades restoration initiatives is the enhancement and re-  
302 distribution of freshwater flows through the south Florida landscape (Perry 2004). As paired  
303 drainage areas, the TS and Ph basins currently differ with respect to freshwater management.

304 Since basin soils were not characterized prior to the recent “treatment” of increased water flow  
305 into the Ph basin in 1997 and inclusion of water detention areas in the TS basin in 2000,  
306 however, the possible causes of the differences in soil properties (rising levels of soil P; higher  
307 levels of reduced sulfur) are speculative. It is entirely possible that—in the absence of a  
308 calibration phase prior to 1997—soils in the two basins were different before the recent changes  
309 in flow. Nevertheless, our five-year time series provides a baseline against which future, post-  
310 restoration measurements can be compared.

311

312

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449 **Figure Legends**

450

451 Fig. 1 Site map of the eastern coastal Everglades, where water flows through freshwater  
452 marshes and estuarine mangrove forests before discharging to Florida Bay. Soils were collected  
453 from eight locations within the Taylor Slough (TS) and Panhandle (Ph) drainage basins

454

455 Fig. 2 A Soil bulk density 2006-2010 from freshwater marsh and estuarine mangrove  
456 locations. B Percent organic matter as weight loss on ignition (LOI)

457

458 Fig. 3 Soil total phosphorus 2006-2010 from freshwater marsh and estuarine mangrove  
459 locations. Freshwater P scale is one-fourth the estuarine P scale.

460

461 Fig. 4 A Soil extractable iron from freshwater marsh and estuarine mangrove locations. B  
462 Total inorganic sulfide

463