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SOIL DEVELOPMENT IN PHOSPHATE-MINED CREATED WETLANDS OF FLORIDA, USA

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Abstract: Soil characteristics of a wide variety of created wetlands were compared to those of native wetlands in phosphate-mined areas from central and north Florida, USA. Criteria selected for evaluation of soil samples from 184 sites included soil compaction, bulk density, organic matter (carbon) and nitrogen content, C:N ratio, and available and total nutrient contents. Organic matter accumulation, one of the indicators of a functional wetland, increased across transects going from uplands toward the center of the wetlands, and with wetland age. The organic matter accumulation rate in the AO and A1 horizons was 320 g m^2 yr^{-1}. Native wetlands had significantly greater organic matter accumulation, both in the litter and mineral soil surface. The C:N ratio of the soil organic matter decreased with created wetland age and approached values commonly found in wetland soils (15–25). Bulk density decreased with increasing organic matter content in the created wetlands, and low bulk density soils appeared to support better vegetative growth. Based on the above-mentioned parameters, reclaimed wetlands are slowly developing into ''typical'' wetlands; the rate of development could possibly be increased by minimizing soil compaction, incorporation of organic matter, or by fertilization.

Key Words: organic matter accumulation, C:N ratio, Mehlich 3 available nutrients, wetland age, soil compaction

INTRODUCTION

State laws passed in 1975 (Chapter 211, Florida Statutes) and 1978 (Chapter 378, Florida Statutes), require the Florida phosphate industry to replace mined native wetlands with wetlands of a similar nature. It seems that there is some reservation by agencies ''to approve impacts to any wetland type, especially forested wetland systems until restoration techniques have confirmed that the wetland type to be impacted can be recreated'' (Gaines et al. 2000).

Soils of created wetlands provide the substrate for aquatic flora and fauna to establish themselves and to flourish in a manner similar to natural wetlands and thus restore ecosystem integrity. Unlike wetlands created on ''normal'' landscapes, the mining process causes severe changes in the landscape, particularly soils, and ground- and surface-water hydrology. Therefore, information on soils of created wetlands is essential in order to re-establish native vegetation after phosphate mining. Some of the substrates used in constructing a wetland in phosphate-mined areas include overburden, sand tailings, and/or clay that provide both mechanical support and growth media for plants.

Eighty-three of 156 created wetlands on phosphate-mined lands, recently surveyed by a group of scientists, were created on graded overburden, while 38 sites were created on a mixture of overburden and sand tailings (Ervin et al. 1997). Wetlands created on sand tailings alone constituted eight sites, while four of the created sites used sand/clay as the substrate. Construction information on the remaining 12 wetlands in the survey was not available. They also found some information on created wetlands monitoring of vegetation (53 sites), water quality (20 sites), macroinvertibrates (15 sites), wildlife (12 sites), and hydrology (10 sites). Only four sites had some soils monitoring.

Characteristics of soils of created wetlands can influence the levels of available resources, which, in turn, will affect the composition and diversity of above-ground vegetation and soil microflora and fauna (Chambers et al. 1994). Wetland construction involves arranging water regimes with an appropriate hydroperiod, followed by seeding or planting seedlings (Odum et al. 1998). Lack of information on soils of created wetlands led us to evaluate the overall progression of a wide variety of created wetlands toward the properties of native wetlands in phosphate-mined

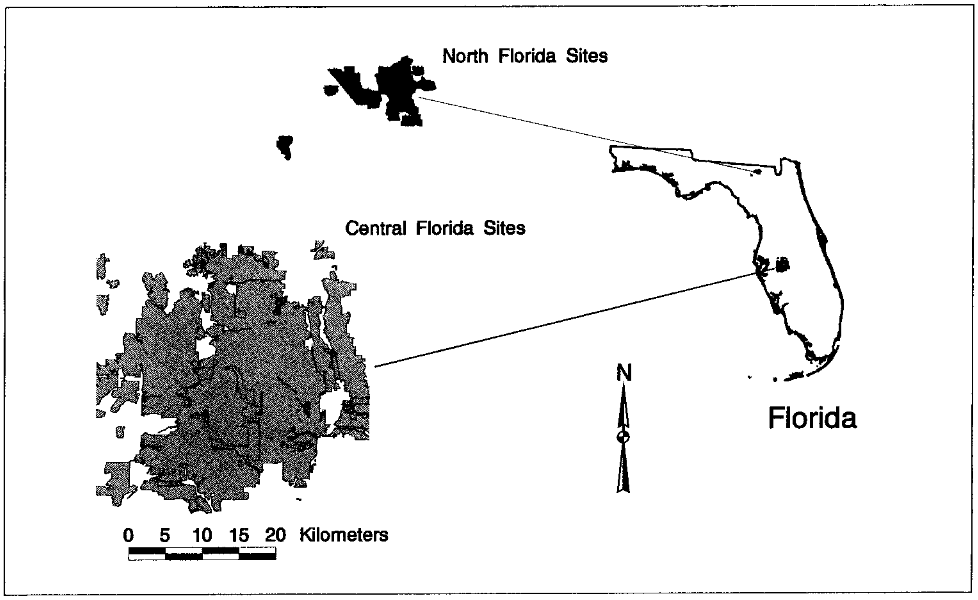

Figure 1. Location of mining sites in north and central Florida. For this study, 26 soil samples were collected from the north Florida sites and 151 soil samples from the central Florida sites.

areas in central and north Florida. The objectives of this study were i) to conduct a synoptic survey of soils in selected phosphate-reclaimed wetlands and ii) to determine successional changes in physico-chemical parameters of soils in created wetlands.

METHODS

Field Sampling

Field sampling was conducted at several central Florida, USA sites in February 1994 (Figure 1). To establish the soils-related criteria for successful progression of created wetlands, the following scenarios were included in the synoptic sampling: i) soil samples were taken along hydrologic gradients (upland to wetland), ii) samples were also taken from within a wetland site that showed substantial differences in plant growth and survival, iii) soil samples were taken from adjacent created and native wetlands of the same wetland type (wooded swamps), and iv) samples were taken from selected wetlands of different construction ages. Intact soil cores (ranging from 20- to 30-cm depth) were taken from these selected wetlands. Each core was sectioned into (i) AO ($\leq$10 cm depth) = organic/mineral layer with significant root mass, (ii) A1 = an intermediate organic/mineral layer with ''humus-type'' material below AO, (iii) B = an illuvial layer (when present), and (iv) C = the remaining subsoil. Organic litter accumulation was designated as ''O'' horizon material. The depth of the topsoil was visually determined based on low color value and chroma. There were a total of 151 soil samples. Details of all soil samples including location of soil sampling, layer designations, visual description, and depth of each layer are provided in Graetz et al. (1997). Soil samples were also collected from sites in north Florida in June 1994 (Figure 1). For north Florida sites, samples were collected from only two horizons: (i) surface organic and (ii) subsurface horizons. Since the organic layer was often small, composite samples were collected to ensure sufficient amounts of soil for laboratory analyses. Total number of soil samples collected was 26; their detailed description can be found in Graetz et al. (1997). The samples were placed in plastic bags, placed in a cooler, and brought to the laboratory for analyses. Soils from the north Florida sites were used primarily for soil compaction studies. Since information on comparison of created and native wetlands was lacking in the literature, we took advantage of our collected soils to obtain some basic comparison between soils of created and adjacently located native wetlands.

Soil Analyses

The total weight and volume of each soil sample was recorded for bulk density calculations. Subsamples from each of the soil samples were oven dried at 105°C for a minimum of 24 hours for moisture content determination. The bulk density for all the soil samples was then calculated based on the dry (oven-dried, 105°C) weight. The bulk samples were then air-dried, ground, passed through a 2-mm sieve, and analyzed for pH, total C and N, and available and total nutrients.

Soil samples were equilibrated with deionized water (1:2 soil:water) for one week (to simulate conditions in the wetland), and pH of the samples was determined. Total C and N was measured using a Carlo Erba CNS Analyzer (Carlo Erba, Milan, Italy).

Available P, K, Ca, Mg, Zn, Mn, Cu, and Fe were extracted using the Mehlich 3 procedure (Mehlich 1984). The extracting solution was ammonium nitrate in an ammonium fluoride/EDTA mixture and the resulting mixture was acidified with an acetic acid/nitric acid solution to maintain a pH of 2.5. The elements were analyzed using an inductively coupled argon plasma (ICAP) emission spectrometer.

Cation exchange capacity was determined on surface soils for the north Florida sites. The cation exchange sites of the soil were saturated with Na by equilibrating a subsample with 0.4 M NaOAc-0.1 M NaCl solution (pH 8.2) in 60% ethanol. The Na-saturated soil was then extracted with 0.5 M $MgNO_3$ solution (Rhoades 1982) to determine total exchangeable Na. Total Na in the extract, which represents cation exchange capacity of the soil, was analyzed using an atomic absorption spectrophotometer. Chloride in the extract was determined using a chloridometer for correction (Rhoads 1982).

Soil compaction was assessed for all north Florida sites in the field using a recording penetrometer (DELMI Machine and Instrument Co., 123 Shafter Ave., Schafter, CA 93263) with a penetrating point consisting of a 30-degree circular cone and a base area of 1.29 cm^2 (Vazquez et al. 1989).

RESULTS AND DISCUSSION

Organic Matter Accumulation and Nutrient Status of Soils

Organic matter is essential for improving structure and nutrient status of the soil. Based on the data obtained from all wetland sites sampled (herbaceous marshes or wooded swamps), bulk density of the soils decreased logarithmically with increasing total C (Figure 2). Based on analyses of the151 samples collected from the central Florida sites, total C reported in our current data had >95% organic C. Organic matter may be computed from organic C data using a multiplication factor of 1.724, based on the assumption that organic C constitutes 58% organic matter (Nelson and Sommers 1982). Figure 2 shows that soils with ≤2.5% (25 g kg^{-1}) total C were more compact (bulk densities >1.25 g cm^{-3}) than soils with >2.5% total C. Bulk densities of these soils are generally greater than those expected from mineral soils due to the great deal of compaction in the soils from the operation of heavy machinery during mining operations. Further, some of these soils included rock-type material brought to the surface during the mining process.

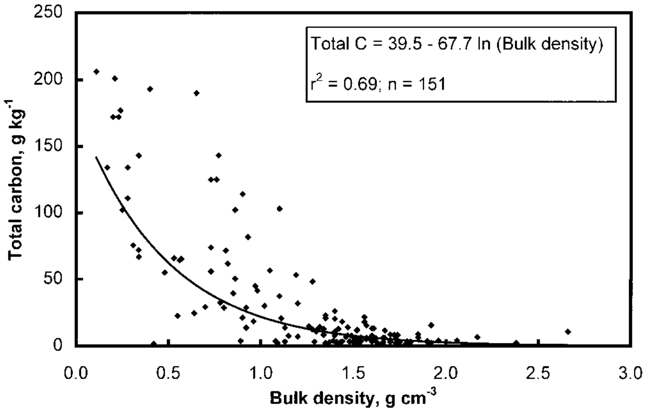

Figure 2. Relationship between total C and bulk density for all central Florida sites sampled.

The function of organic matter in improving soil nitrogen status is evident from the linear relationship between total C and N for all the central Florida sites sampled (Total N = −0.027 + 0.055 [Total C], r^2 = 0.92, n = 151). Results suggest that increases in total C can potentially increase the amount of N available to plants. This observation is of particular importance in productive wetlands. Both C and N progressively increased on surface soils from upland to wetland along an upland-wetland transect (Table 1). Available nutrients such as Fe, Cu, Zn, K, Ca, and Mg in surface soil (A horizons) also increased along the same transect. Available P, as determined by Mehlich 3 extractions, ranged from about 350 to 450 mg P kg^{-1} in surface soils and from 370 to 1020 mg P kg^{-1} at lower depths, showing considerable variation along the transect. Subsurface soils did not show any particular trend across the upland-to-wetland transect for total C and N nor for the available nutrients.

Organic Matter Accumulation Across an Upland-to-Wetland Transect

Accumulation of organic matter is an indication of a functional wetland (Ervin et al. 1997). An illustration of organic matter accumulation across a transect from an upland to a wetland area is given in Figure 3. Data presented in Figure 3 represent 13 years of net organic matter accumulation calculated from bulk density measurements and depth of the AO and A1 layers. Net accumulation at a given location along the hydrologic gradient was calculated by subtracting the carbon accumulation at that location from the carbon content in the upland soil. It was assumed that no net organic matter accumulation occurred in the upland area during the previous thirteen years. Accumulation rate of

Table 1. Concentration of total C and N and Mehlich 3 available nutrients across a transect from upland to wetland at a central Florida site.

Transect	Organic C	Total N	P	Ca	Mg	K	Zn	Cu	Mn	Fe
	g kg^{-1}	g kg^{-1}	mg kg^{-1}							
Surface†										
Upland	12	0.4	371	1080	230	12	1.1	<0.1	3.2	176
Intermediate Wetland 1	19	1.0	473	1519	365	6	1.2	<0.1	13.4	287
Intermediate Wetland 2	72	4.1	343	1954	707	88	1.6	0.4	4.7	353
Wetland	307	19.7	466	2853	1454	205	2.4	0.8	1.3	514
Subsurface†										
Upland	4	0.1	1020	2320	207	<0.1	1.4	<0.1	0.9	229
Intermediate Wetland 1	2	<0.1	373	3360	1670	<0.1	1.0	<0.1	2.5	301
Intermediate Wetland 2	2	0.1	663	1330	131	<0.1	1.0	<0.1	0.8	214
Wetland	2	0.1	629	1550	249	<0.1	0.8	<0.1	0.8	263

† Surface and subsurface samples at each site (upland, intermediate wetland 1, intermediate wetland 2, and wetland) were composite samples from four locations within the site.

organic C (AO and A1 layers) was 320 g m^{-2} yr^{-1}. This rate is comparable to that of the marshes (200–300 g C m^{-2} yr^{-1}) in Louisiana (Hatton 1982) and the Water Conservation Areas of the Everglades (86 to 387 g C m^{-2} yr^{-1}, Reddy et al. 1993).

Created *vs* Native Wetlands

Central Florida Sites. Soil cores from a 15-year-old created wetland and an adjacent native wetland (wooded swamps) were studied to compare the chemical characteristics of soils in created *vs* native wetlands. The created wetland was more acidic than the adjacent native wetland (Table 2). However, the pH of many of the created wetland soils in this survey was neutral (pH 6.0–7.4) to slightly alkaline (pH 7.5–8.0). Native wetland soils might be acidic or basic depending on location and other environmental conditions. Acidic pH may be attributed to rain-fed runoff and organic acid production during the decomposition of organic matter within the wetland, while pH of many alluvial wetlands could be near neutral due to flooding by river water with high Ca content.

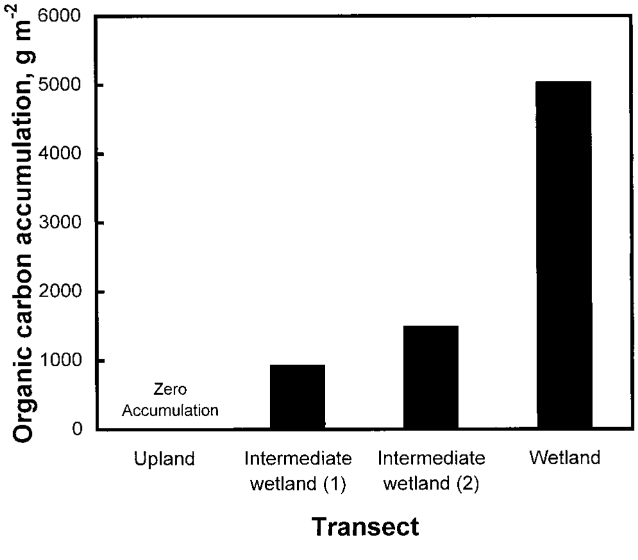

Figure 3. Organic carbon accumulation across an upland-to-wetland transect in central Florida. Note: Samples at each site (upland, intermediate wetland 1, intermediate wetland 2, and wetland) were composite samples from four locations within the site.

Bulk density was greater at all horizons for the created wetland compared to the native wetland. Total C content for the native wetland was about four times greater than that of the 15- year-old created wetland (Table 2). The native wetland had at least two times more total N than the created wetland. The two wetlands were found to have similar concentrations of available nutrients, although occasionally some of the values were marginally higher in the surface soils of the native wetland. Nutrient stability and equilibrium is apparent in the native wetland, based on C:N ratio. The created wetland soil maintained a C:N ratio between 20 and 23, indicating a well- balanced system with respect to mineralization and immobilization processes (Williams et al. 1968). The subsurface of the created wetland had a C:N ratio of 20 (Table 2), suggesting a developing horizon approaching that of the native wetland condition. The surface soil (AO and A1 layers) of the recreated wetland had narrow C:N ratios (about 15), which may favor N mineralization and, hence, nutrient availability. Some caution, however, must be exercised in using C:N ratio as one of the characteristic equilibrium values for soils. The C:N ratio, for example is less meaningful in wetlands where

Table 2. Physical and chemical characteristics† for created and native wetlands at a central Florida site.

Wetland	pH	BD‡ g cm^{-3}	Organic C g kg^{-1}	Total N g kg^{-1}	P	Ca	Mg	K	Zn	Cu	Mn	Fe
					Mehlich 3 nutrients, mg kg^{-1}							
Surface (A0 and A1)												
Created (A0)	5.94	0.70	56	4	239	3090	647	243	11.6	1.2	17.4	296
Native (A0)	6.15	0.40	193	9	213	5060	787	246	21.1	1.7	18.2	475
(A1)	6.30	0.90	50	2	543	3320	461	70	12.6	1.6	8.3	538
Subsurface												
Created	5.96	1.50	8	<0.1	560	2380	438	65	2.3	0.4	7.5	583
Native	6.17	1.00	41	2	895	2700	341	30	9.7	0.9	7.2	685

† Each sample (surface A0 and A1, and subsurface) of the created and native wetland was a composite sample from four locations.
‡ Bulk Density

substrates or soils have extremely low N (>0.01% total N) and total C. The Carlo Erba CNS Analyzer has a measuring range of 0.01 to 100% (N), with a 10% deviation from accuracy at 0.01% concentration (Carlo Erba Instruction Manual). The use of C:N ratio in evaluating progression of created wetlands requires due consideration of other indicators and parameters such as organic matter content and accumulation, soil development, and established vegetation. While soil properties have not been traditionally used as a measure of wetland restoration success, Whited et al. (1999) recently suggested that, in addition to return of hydrology, plant communities, and wildlife use, some soil properties could be used as criteria for assessing wetland restoration success.

North Florida Sites. Statistical comparison of surface soils of created and native wetlands (wooded swamps) in the north Florida region indicates that the total C, total N, and CEC of created wetlands were lower than those in an adjacent native wetland (Table 3). Mean values of total C for the native wetland were approximately 30 times the mean value of total C for created wetlands, while mean CEC values for the native wetlands were about 15 times those for the created wetlands. Since elevated values in these parameters are indicators of wetland progression, it appears that these one- and three-year-old created wetlands have not as yet made significant progression toward becoming functional wetlands. However, C:N ratios for the created and native wetlands appear to be similar.

Disturbances to the native soil have resulted in higher pH (>5.80) in the soils of created wetlands compared to those of the native wetlands (pH <4.20). Increases in pH of created wetlands may be attributed to increases in available Ca (Table 4). Some increases in available P were also noted in the created wetlands, although statistically, the native wetlands and the created wetlands had comparable K, Zn, Cu, Mn, and Fe. Brown and Tighe (1991) found that organic matter and available nutrients (Ca, Mg, Zn, Cu, and Na) for some created wetland sites varied widely among plant communities and wetland areas. They also reported that created wetlands have higher P, Ca, Fe, and Mn concentrations in soil than the native wetland communities. Some of their results differed from the statistical information obtained at the north Florida sites.

Effect of Age on Wetland Soil Characteristics

Five wetlands of different ages (1, 2, 4, 10, and 16 years) with the same general background (i.e., overburden matrix without mucking (without application of muck or organic wetland soil) in central Florida) were selected (Table 5) to evaluate changes in soil

Table 3. Comparison of pH, total C and N, C:N ratio, and cation exchange capacity (CEC) in surface soils of two created wetlands with a native wetland soil in north Florida.

Wetland Type	pH	Total C g kg^{-1}	Total N g kg^{-1}	C:N ratio	CEC cmol kg^{-1}
Native wetland	4.17 b†	310 a	12.7 a	25 a	145 a
Created wetland (one-year-old)	5.87 a	15 b	0.7 b	24 a	14 b
Created wetland (three-year-old)	5.84 a	6 b	0.3 b	29 a	6 b

† Statistical analyses are by the Waller Duncan procedure. Mean values of soil characteristics within a column followed by the same letter are not different ($P < 0.5$).

Table 4. Comparison of available nutrients in surface soils of two created wetlands with a native wetland soil in north Florida.

Wetland Type	P	Ca	Mg	K	Zn	Cu	Mn	Fe
	mg kg^{-1}							
Native wetland	45 b†	152 b	82 a	67 a	2.9 a	<0.1 a	1.6 a	76 a
Created wetland (one-year-old)	153 a	495 a	88 a	23 a	0.7 a	<0.1 a	0.8 a	40 a
Created wetland (three-year-old)	172 a	554 a	89 a	21 a	0.4 a	<0.1 a	1.3 a	55 a

† Statistical analyses are by the Waller Duncan procedure. Mean values of soil characteristics within a column followed by the same letter are not different ($P < 0.5$).

properties as a wetland becomes progressively more established. The two older wetlands (10 and 16 years old) had two clearly demarked organic surface horizons, and C accumulation was calculated as the sum of the two layers. Bulk density of the surface layer generally decreased with age (Table 5). This trend was also observed in the subsurface layer (data not shown), although to a lesser extent. This decreasing bulk density reflects the increasing amount of organic C accumulating in the soil (Table 5). Organic C, which is a measure of organic matter, increased from 3 g kg^{-1} in a new wetland to nearly 200 g kg^{-1} in a 16-year-old wetland. Organic C accumulation increased with age of wetland (Figure 4). Shaffer and Ernst (1999) found that soil organic matter was higher in naturally occurring wetlands than in mitigation wetlands but found no significant relationship between soil organic matter and wetland age.

Nitrogen concentration also increased with time but at a faster rate than carbon concentration. This is reflected in the C:N ratio, which is an indication of organic matter decomposition and stabilization. Wetland plants typically have a C:N ratio of >50. As the plant matter decays in the soil, CO_2 is evolved while N is retained. This results in a decreasing C:N ratio and suggests an increasing stabilization of the soil organic matter. Typical C:N ratios for stabilized soil organic matter are in the range of 15 to 25. We saw a progressive decrease in C:N ratio of soil organic matter with increasing age (Table 5). Thus, overall, we observed both an increase in the amount of organic matter accumulating and a decrease in the C:N ratio, which indicates that the wetlands are functioning as anticipated with regard to these parameters.

Soil Compaction in Created and Native Wetlands

Soils of created wetlands have varying degrees of compaction depending on the substrate used for construction (overburden, sand tailings, clay, and their mixtures) and/or due to the effects of heavy machinery. Soil strength and mechanical resistance, measured using a penetrometer, have been related to soil bulk density, compaction, and root penetration (Barley et al. 1965, Taylor et al. 1966). Blanchar et al. (1978) found that pea root growth in a B2 horizon (Hobson series) in a soil containing a fragipan was greatly restricted as probe resistance increased from 10 to 20 bars (or kg cm^{-2}); the authors reported that root growth stopped past 20 kg cm^{-2}. Similar observations were reported by Taylor et al. (1966), who found in soils varying in texture (loamy fine sand to loam) that cotton root elongation nearly ceased as probe resistance approached 20 kg cm^{-2}. Others have shown that pea root elongation in a clay soil essentially ceased at penetrometer readings >30 kg cm^{-2} (Gerard et al. 1972). Based on literature information, we may consider a penetrometer reading of 20 kg cm^{-2} as a critical value for root penetration and/or elongation in agricultural soils. However, we do not know if this would be an

Table 5. Selected surface soil characteristics for the wetlands used in the wetland age studies. All selected wetlands were on overburden matrix with no muck added.

	Site	Age Years	Depth† cm	Bulk Density† g cm^{-3}	Total C† g kg^{-1}	C:N
1	East Old Fort Green Road	1	10	1.5	3	65
2	Miles Grove	2	10	1.6	6	38
3	N. Hooker's Prairies Section 12	4	10	1.3	14	35
4	Tiger Bay 10	10	6	1.0	45	25
			12	1.5	4	
5	Parcel B	16	6	0.4	193	25
			10	0.9	51	

† The two older wetlands (10- and 16-year-old) had two distinct organic layers. Organic accumulation (Figure 4) was calculated by summing the accumulation within the two layers.

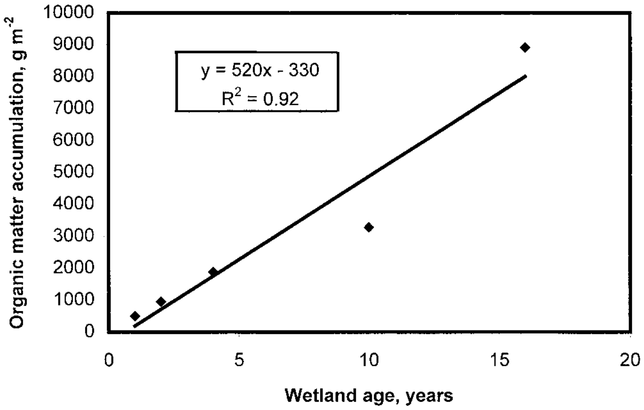

Figure 4. Organic matter accumulation with wetland age for wetlands on overburden matrix without mucking.

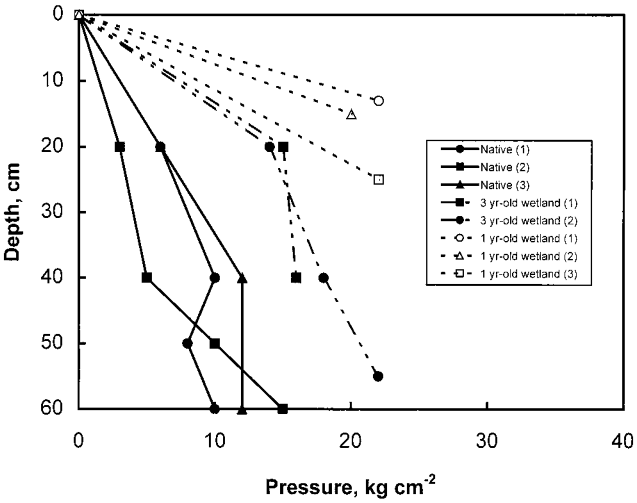

Figure 5. Penetrometer readings comparing soil compaction in native and created (three-year-old and one-year-old) wetlands in north Florida.

appropriate value for herbaceous and forested wetland soils.

Penetrometer readings recorded at the central Florida sites are given in Figure 5. Readings for each location within a site are means of three measurements taken within a radius of two meters. Native areas and the 3-year-old wetland had penetrometer readings <20 kg cm^{-2} at depths ≤ 50 cm. The newly created wetland was highly compacted at the 20-cm depth, yielding a penetrometer reading >20 kg cm^{-2} considered critical to root penetration (Taylor et al. 1966, Blanchar et al. 1978). High soil strength and mechanical resistance can be found in compact soils or substrates, overburden materials (Bradford et al. 1971), cemented or indurated horizons (Lutz 1952), and hardpans (Krusekopf 1942, Blanchar et al. 1978). At the time of sampling, the one-year-old wetland had sparse vegetation compared to the three-year-old created wetland and the native wetland.

CONCLUSIONS

Organic matter accumulation, one of the indicators of a productive wetland, increased with wetland age and across transects from uplands toward the center of the wetlands. Most created wetlands showed a definite increase in organic matter content in either the litter layer and/or the soil mineral layer with age. Extent of organic matter accumulation in the younger wetlands varied considerably, but nearly all showed some evidence of organic matter accumulation. Native wetlands generally had greater organic matter accumulation both in the litter and mineral soil surface. This is to be expected since native wetlands were in existence for a very long time. More importantly to the evaluation of created wetlands, nearly all showed evidence of organic matter accumulation, albeit at varying rates.

The C:N ratio of the soil organic matter decreased with wetland age and approached values commonly found in wetland soils (20–25). This indicates that not only is the amount of organic matter increasing in the created wetlands, but the quality of the organic matter is moving closer to that of a native wetland. The improvement in quality of organic matter was also indicated by its increased cation exchange capacity with age.

Bulk densities of the initial substrate material after placement in the created wetlands were often quite high due to the lack of organic matter and soil compaction due to the operation of heavy machinery. Incorporation of organic amendments and/or deep tillage subsequent to land-leveling activities could ameliorate this problem. Bulk density decreased with increasing organic matter content in the created wetland soils. Areas that had lower bulk density and higher organic matter content also appeared to support better vegetative growth.

The pH of the created wetland soils was near neutral (pH 6.0–7.4) to slightly alkaline (pH 7.5–8.0), reflecting the high pH of the initial substrate material. Many native wetlands have an acidic pH due to the input of rain-fed runoff and organic acid production during the decomposition of organic matter within the wetland. The created wetland soils showed evidence that high pH of the initial substrate materials was decreasing, particularly in the surface horizons and in the older wetlands.

Penetrometer measurements may be used as an *in situ* evaluation of overall soil compaction and an indication of compact layers within the soil horizon. Measurements showed distinct differences between native and created wetlands. The real value of the penetrometer may be to evaluate the degree of compaction during the wetland construction phase rather than changes in compaction with wetland progression. Preliminary soil penetrometer results suggest that penetrometer readings will be a useful parameter for relating compaction to vegetative growth in existing created wetlands.

Based on this synoptic survey, the soil-related criteria needed to adequately evaluate wetland performance and soil profile development in created wetlands on mined lands include compaction, organic matter accumulation, C:N ratio, available nutrients, and CEC. As a follow-up of this study, it is suggested that a systematic evaluation of wetland progression be done by careful selection of sites and sampling locations within sites to correlate vegetative growth and stand establishment with compaction (penetrometer measurements), bulk density and organic matter content, and substrate type (overburden, sand tailings, clay, or mixtures thereof). Vegetation nutrient concentrations may be correlated with soil parameters to establish recommendations for soil-amendments (organic and inorganic) and on substrate composition during wetland construction.

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