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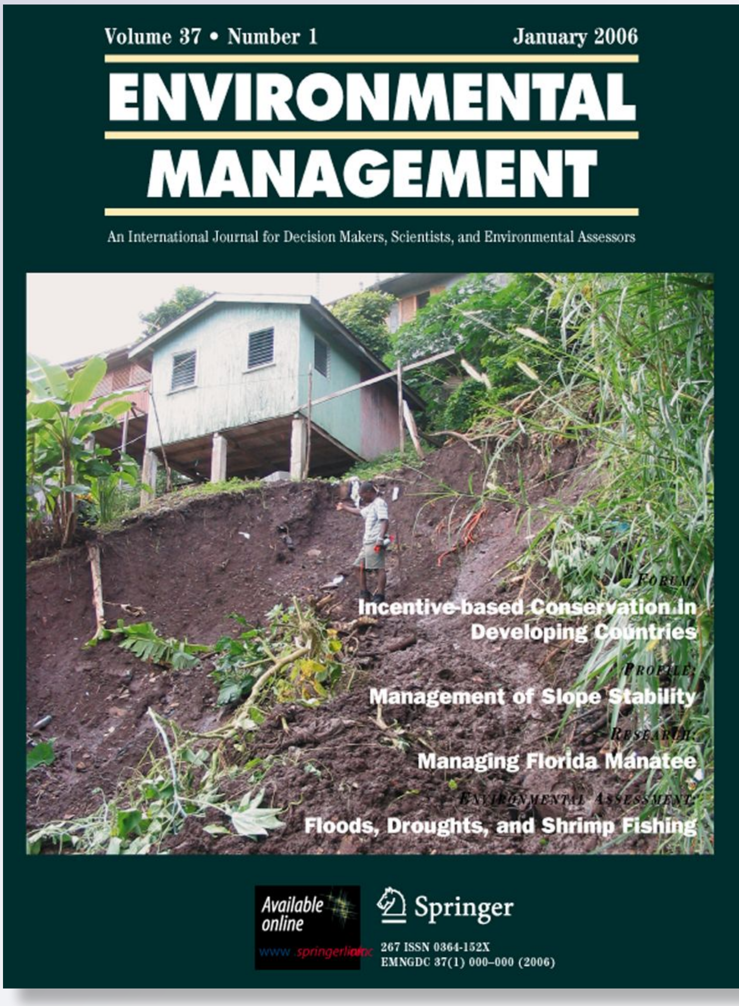

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Soil Properties Predict Plant Community Development of Mitigation Wetlands Created in the Virginia Piedmont, USA

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Abstract The study investigated vegetative and soil properties in four created mitigation wetlands, ranging in age from three to ten years, all created in the Virginia Piedmont. Vegetation attributes included percent cover, richness (S), diversity (H′), floristic quality assessment index (FQAI), prevalence index (PI), and productivity [i.e., peak above-ground biomass (AGB) and below-ground biomass]. Soil attributes included soil organic matter (SOM), gravimetric soil moisture (GSM), pH, and bulk density (D_b) for the top 10 cm. Species dominance (e.g., *Juncus effusus*, *Scirpus cyperinus*, *Arthraxon hispidus*) led to a lack of differences in vegetative attributes between sites. However, site-based differences were found for GSM, pH, and SOM ($P < 0.001$). Soil attributes were analyzed using Euclidean cluster analysis, resulting in four soil condition (SC) categories where plots were grouped based on common attribute levels (i.e., SC1 > SC2 > SC3 > SC4, trended more to less developed). When vegetation attributes were compared between SC groups, greater SOM, lower D_b, more circumneutral pH, and higher GSM, all indicative of maturation, were associated with higher H′ ($P < 0.05$), FQAI ($P < 0.05$), and total and volunteer percent cover ($P < 0.05$), and lower AGB ($P < 0.001$), PI ($P < 0.05$), and seeded percent cover ($P < 0.05$). The outcome of the study shows that site age does not necessarily equate with site development with soil and vegetation developmental rates varying both within and among sites. The inclusion of soil attributes in post-construction monitoring should be required to enhance our understanding and prediction of developmental trajectory of created mitigation wetlands.

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Introduction

Virginia has lost approximately 42 % of its original wetlands, and recent reports have documented continued annual losses of 970–1,200 hectares, mainly due to development (Chesapeake Bay Foundation 2010). These losses have continued despite Virginia's commitment with its Chesapeake Bay partner states to reach a "no net loss", and ultimately a "net gain" of wetlands in the Bay watershed. Since the 1977 amendments to the Clean Water Act, wetland creation and restoration have become common practices as compensation to mitigate losses (Zedler 1996, Brown and Venemen 2001, National Research Council 2001, Spieles 2005).

Vegetation measures are almost always used as performance standards in compensatory wetland mitigation, and in some cases, vegetation is the only performance standard (Spieles 2005; U.S. Environmental Protection Agency and Department of the Army 1990). The National Research Council (2001) has advised against the sole use of vegetation for performance monitoring based on a weak relationship to wetland function. The Army Corps of Engineers (ACOE) and Virginia Department of Environmental Quality (VDEQ) have jointly established minimum requirements for wetland mitigation monitoring in Virginia that are mostly based on wetland plant abundance along with meeting minimum hydrologic requirements (Norfolk

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District Corps and Virginia Department of Environmental Quality 2004). The goal of post-creation monitoring is often to determine if mitigation wetlands are successfully supporting native wetland vegetation. Plants are ideal subjects for mitigation monitoring because they are immobile and are responsive to natural and anthropogenic input (Atkinson and others 2005; Balcombe and others 2005; Spieles 2005). Structural measures of vegetation are relatively inexpensive to collect and are minimally intrusive to the wetland ecosystem; while many functional measures, including net primary productivity and biogeochemical cycling require that both plants and soil be removed followed by resource intensive (i.e., labor and cost) laboratory analyses (Cronk and Fennessy 2001). However, structural attributes of vegetation may not fully measure ecological functions that should be developing (National Research Council 2001).

Vegetation development in created wetlands is heavily dependent on wetland hydrology and soil physicochemisty (Ballantine and Schneider 2009; Bayley and Guimond 2009; Ehrenfeld and others 2005; Olde Venterink and others 2003). Comparative studies of structural vegetation attributes in both created and natural wetlands often find that equivalence between the two is achieved in terms of hydrophytic plant abundance, richness, and diversity in the first decade after creation (Balcombe and others 2005, Spieles 2005; Ravit and others 2006). However, vegetation developmental trends can stray significantly from paths leading to a targeted asymptote within a standard monitoring period, either regressing or on taking decades to reach an envisioned stable condition (Brown and Venemen 2001; Campbell and others 2002, Matthews and others 2009). Functional comparisons between created and natural wetlands have generally illustrated a lack of equivalence within the standard 5–10 year monitoring period for hydrology (Cole and Brooks 2000; Shaffer and others 1999), productivity (Fennessy and others 2008; Hossler and Bouchard 2010), decomposition rates and nutrient cycling (Atkinson and Cairns 2001; Fennessy and others 2008; Wolf and others 2011a, b), and soil characteristics (Ballantine and Schneider 2009; Campbell and others 2002; Hossler and Bouchard 2010; Nair and others 2001; Zedler and Callaway 1999).

Soil conditions influence the distribution, abundance, and productivity of wetland vegetation (Dick and Gilliam 2007; Dwire and others 2006; Olde Venterink and others 2003). Soil physicochemical attributes, including bulk density, porosity, moisture, organic matter content, and texture, are all inevitably linked to the development of the plant community in wetlands (Ballantine and Schneider 2009; Cronk and Fennessy 2001; Ehrenfeld and others 2005) and often heavily impacted by construction processes used in creating wetlands (Moser and others 2007). The use of heavy machinery for grading during wetland construction tends to reduce or eliminate microtopographic heterogeneity (Stolt and others 2000), and also leads to severely disadvantaged soil structures, including high bulk density and reduced porosity, all of which negatively influence plant community development (Bruland and Richardson 2004; Ballantine and Schneider 2009; Moser and others 2007, 2009; Hossler and Bouchard 2010). Soil properties are interdependent with higher SOM displacing compacted soil and reducing D_b, in addition to providing an absorptive substrate for water retention and thus increased soil moisture (Ballantine and Schneider 2009, Bruland and Richardson 2005, Ehrenfeld and others 2005, Reddy and DeLaune 2008). Created wetlands are also often found limited in soil nutrients and organic matter that are important to early development of plant community (Ballantine and Schneider 2009; Bruland and Richardson 2004; Hossler and Bouchard 2010).

A number of prior studies have assessed structural and/or functional developments in created wetlands (Ballantine and Schneider 2009; Cole and others 2001; Cook and Hauer 2007; Fennessy and others 2008; Lopez and Fennessy 2002; Matthews and others 2009; Moser and others 2007, 2009), but few have explored the relationship between structural and functional attributes of vegetation in conjunction with soil conditions. If functional levels could be reasonably predicted from structural measures, then gaps between predictions and goals could be better understood and addressed in future designs or through modification to current practices and monitoring (Gutrich and others 2008). Targeted compensatory refinement could take the form of one or a combination of strategies that resolve the potential causal issues including hydrologic adjustment, invasive species control, and soil nutrient augmentation (e.g., organic soil amendment) (Bruland and Richardson 2004; Bailey and others 2007; De Steven and Sharitz 2007).

This study investigated plant community development and soil properties in four created mitigation wetlands in the northern Virginia piedmont. The wetlands ranged in age from three to ten years. Vegetation indices (i.e., S, H′, FQAI, and PI), percent cover, biomass, and soil properties were examined. The study focused on the following research questions:

1. Do structural and functional attributes of vegetation and soils differ by site (i.e., age) among created mitigation wetlands?
2. Do soil attributes help explain the development of the vegetation community in created mitigation wetlands?
3. Is there a predictive relationship between plant productivity and vegetation and soil attributes?

Methods

Site Descriptions

The study sites consisted of four created mitigation wetlands located in the northern Virginia Piedmont physiographic province (i.e., underlain by igneous and metamorphic rock) in the 100-year floodplains of adjacent streams either in Prince William or Loudoun counties, which are part of the Potomac River watershed. At the time of the study in 2009, the wetland sites could still be largely characterized as herbaceous (e.g., *Juncus effusus*, *Scirpus cyperinus*, *Echinochloa crus-galli*) palustrine wetlands, with a mix of open water, shrub-scrub (e.g., *Ilex verticillata*, *Cornus amomum*, *Cephalanthus occidentalis)*, and young tree stands (e.g., *Salix nigra*, *Platanus occidentalis*, *Acer rubrum*). The wetlands were built with incorporated shallow (i.e., <0.5 m) perched, surface-driven water tables using low permeability subsoil layers and a mix of original and commercially available topsoil (i.e., silty loam or silty clay loam) layers (HDR 2009; WSSI 2009). Vegetation in the created wetlands is mostly herbaceous, interspersed with young tree saplings and shrubs in projected forested areas.

Loudoun County Mitigation Bank (LC) is a 12.9 ha wetland and upland buffer complex, constructed by Wetland Studies and Solutions, Inc. (WSSI) in the summer of 2006 in Loudoun County, Virginia (39°1′N, 77°36′W). LC receives surface water runoff from an upland housing development and forested buffer, as well as minor groundwater inputs from toe-slope intercept seepage. More details can be found in Ahn and Dee (2011).

Bull Run Wetland Bank (BR, 38°51′13N, 77°32.6′59″W) is a 20.2 ha wetland and upland buffer complex, constructed by WSSI in 2002 in Prince William County, Virginia (38°51′ N, 77°32′ W). The site is connected to Bull Run by design via a culvert structure that routes water to a central ditch through the wetland. Additionally, the site is subject to overbank flooding, during significant precipitation events, in the Northeast corner where Bull Run makes a sharp bend. The wetland receives limited surface water runoff from precipitation and negligible groundwater.

North Fork Wetlands Bank (NF) is a 50.6 ha wetland, constructed by WSSI in 1999 in Prince William County, Virginia (38°49′N, 77°40′W). With the exception of minor contributions from toe-slope intercept seepage, the site is disconnected from the groundwater by an underlying clay liner. Study plots were located in two created hydrologic regimes: main pod area – fed by upland surface water runoff and a tributary of the North Fork of Broad Run that is controlled by an artificial dam; and, vernal pool area – located in the southwest quadrant of the wetland and fed solely by precipitation.

Manassas Wetland Compensation Site (MW, 38°43.3′N, 77°30.2′E), located where Broad Run and Cannon Branch converge east of the Manassas Regional Airport, was created by Parsons Transportation Group (PTG) in 2000 under a Virginia Department of Transportation (VDOT) permit (HDR 2009). MW consists of almost 16.2 ha of diverse restored or created riparian wetland cells, including an open water pond and pre-existing wet woods. MW is intersected by a perennial stream, Cockrell Branch, and experiences overbank flooding from Cannon Branch and Broad Run during major precipitation events. MW also receives significant storm drain run-off from the adjacent airport industrial complex and highway.

A total of 22 study plots (10 × 10 m), representative of site hydrology, soil, and vegetation, were selected for sampling across the four sites (i.e., LC $n = 8$, BR $n = 5$, MW $n = 4$, NF $n = 5$). At LC, five plots in the higher elevation cell and three in the lower elevation cell were selected. Which indicated more variation between plots located in the higher elevation cell. At BR, five plots perpendicular to the overbank flowpath were selected. At MW, plots locations were based on design criteria (i.e., floodplain or wet woods), proximity to wells, non-interference with ongoing hydrologic remediation, and accessibility. At NF, three plots in the main pod area and two plots in the vernal pool area were selected.

Field Work

Vegetation and soil sampling occurred in August and September 2009 including vegetative species identification, species percent cover, peak above- and below-ground biomass (i.e., AGB and BGB), and soil. Sampling locations were chosen by dividing each of the 22 plots into quadrants, then sub-quadrants were randomly selected within each quadrant, and a square meter quadrat randomly placed within the selected sub-quadrants. A nested quadrat approach was used to collect four matched vegetation and soil samples per plot (i.e., $n = 88$ total per attribute for 16 different measured or calculated attributes). The square meter quadrat was used for vegetation identification and percent cover samples. Within the confines of the square meter quadrat, a 0.25 m^2 quadrat was used for AGB samples and a beveled soil auger with a removable aluminum liner (diameter = 4.7 cm, length = 10 cm) was used for BGB and soil samples. Vegetation was identified to the species level and 10-level cover classes (Peet et al. 1998) were used to estimate species percent cover based on a 100-cell string grid (i.e., 10 × 10 cm cells) embedded in the square meter quadrat. Herbarium specimens were collected for all species to more accurately support identification and for future use as a reference collection for the study sites. Species were identified using authoritative on-line sources (Tenaglia 2009; USDA NRCS 2009) and plant identification guides (Newcomb 1977; Strausbaugh and Core 1977; Tiner 1993).

AGB samples were collected within the square meter quadrat footprint using the peak biomass method (Cronk and Fennessy 2001). Standing litter and live AGB were clipped as close to the soil surface as possible then placed in pre-weighed paper bags (Cronk and Fennessy 2001). The soil auger used to collect BGB samples was hammered approximately 3 cm below the soil surface, the organic mat was removed, and then samples were extracted from the liner and placed into quart size plastic bags for transport back to the lab for drying.

Precipitation data were obtained from the National Weather Service for Dulles International Airport in Loudoun County, VA (National Weather Service 2010). Water level readings from several shallow wells, installed as part of legal mandatory monitoring by the builder (i.e., LC $n = 5$, BR $n = 2$, NF $n = 5$, MW $n = 4$), were measured weekly from March to June 2009, then on a monthly basis throughout the rest of the year. Water level data were obtained from WSSI and VDOT. Three soil cores (i.e., top 10 cm) were collected per plot monthly from August through October 2009 using a 1.8 cm diameter auger for soil moisture determination.

Lab Work

AGB samples were dried at 48 °C (drying cabinet maximum temperature) until a constant mass was reached (i.e., <5 g difference). Thirteen samples from BR were weighed immediately after harvesting using a field scale (10 g accuracy) then sub-sampled (i.e. 30–60 % wet sub-sample) due to large mass and volume, but the remaining 75 samples were dried in full without sub-sampling (Cronk and Fennessy 2001). BGB soil cores were air dried in the lab then large and fine roots were extracted using a sequential grinding and sieving process. A 2 mm mesh sieve was used to remove large roots then fine roots were separated via another cycle of grinding and sieving through a 0.5 mm mesh screen (Hernandez and others 2003). Root material was rinsed with tap water and air dried until reaching constant mass.

Soil attributes included bulk density (D_b), soil organic matter (SOM), total organic carbon and nitrogen (TOC/TN), soil pH, and gravimetric soil moisture (GSM). Prior to extracting BGB, dry mass was measured for calculation of soil bulk density (D_b), based on a total core volume of 173.5 cm^3 (Reddy and DeLaune 2008). Soil remaining after BGB separation and grinding was processed for SOM, TOC, TN, and pH. Soil pH was measured using a Hach meter (Hach Company, Loveland, Colorado) after mixing in a 1:1 ratio with deionized water and letting stand for 10 min (Thomas 1996). SOM (%) was measured using weight loss on ignition method (Wilson and Sanders 1996). Total C and N were determined by dry combustion of ground sub-samples from each core on a 2400 Series II CHN/O elemental analyzer (Perkin–Elmer, Waltham, Massachusetts). Field-wet mass was measured and soil moisture samples were dried at 105 °C for 48 h, then gravimetric soil moisture (GSM) was calculated as a percent [(wet mass − dry mass)/(dry mass) × 100] (Gardner 1986).

Data Analysis

Several plant community attributes were calculated, including percent cover (i.e., total, seeded, volunteer, and non-native), richness (S), Shannon–Weiner Diversity Index (H′), Importance Value (IV), Floristic Quality Assessment Index (FQAI), and Prevalence Index (PI).

Total percent cover was the total cover for each sample based on the mid-point of Peet et al.'s (1998) cover classes (i.e., 1:trace, 2:0–1 %, 3:1–2 %, 4:2–5 %, 5:5–10 %, 6:10–25 %, 7:25–50 %, 8:50–75 %, 9:75–95 %, 10:>95 %) assigned to each species within the sample. Seeded, volunteer, and non-native percent cover values were calculated as a proportional percentage of the total. H′ is a function of species richness (S) and evenness with the highest diversity values obtained under conditions where there are several species and their distribution is even (i.e., $H'_{max} = \log S$) :$H' = -\sum p_i \log p_i$, where p_i is the sample proportional percent cover of species i (Andreas and others 2004). Importance Values (IV; Atkinson and others 2005) were calculated for each species at each of the four sites to determine which five species had the largest influence on vegetation attributes. IV is the sum of relative cover (RC), which was determined as the mean relative cover across all samples collected at each site, and relative frequency (RF), which is the percentage of total samples containing a given species i: $IV_i = RC_i + RF_i$ (Atkinson and others 2005).

Floristic Quality Assessment Index (FQAI) is a measure of natural character calculated as a function of the Coefficient of Conservatism (C_n) for each species and the total number of native species present in a given sample or set of samples (Swink and Wilhelm 1979; Swink and Wilhelm 1994). C_n values range from 0 to 10 with 0 associated with non-native species adapted to disturbed conditions, and 10 to the most sensitive native species (Swink and Wilhelm 1979, 1994). C_n values assigned by a regional panel of experts in a 2006 study sponsored by the Virginia Department of Environmental Quality (VDEQ) were used to calculate FQAI: $I = \Sigma C_n/(N)^{1/2}$, where N is the total number of native species (Davis and Harold 2006, U.S. EPA 2002a). FQAI was calculated at the sample level (i.e., square meter quadrat samples) to facilitate use in comparative and predictive statistical analysis (i.e., ANOVA, regression, and correlation), and at the site level per standard practice.

Prevalence Index (PI) is a function of species wetland indicator status (WIS) and proportional percent cover (Cronk and Fennessy 2001). WIS values range from one to five (e.g., 1–Obligate, 1.5–Facultative Wet +, 2–Facultative Wet, 2.5–Facultative Wet-, 3–Facultative, 4–Facultative Upland, 5–Upland) with one being assigned to taxa found greater than 99 % of the time in wetlands and five assigned to taxa found less than 1 % of the time in wetlands (Cronk and Fennessy 2001). PI values less than three are reflective of an overall wetland status of Facultative to Obligate (i.e., majority of species are found in wetlands). PI was calculated using the equation: $PI = \sum A_i W_i / \sum A_i$, where A_i is the proportional percent cover of species i and W_i is the WIS of species i (Cronk and Fennessy 2001).

Attribute data sets (i.e., $n = 88$ per attribute) were assessed for outliers, normality, and linearity. A combination of modifying outliers to mean plot values and the following data transformations addressed most normality and linearity issues: Square root for AGB, BGB, TOC, and SOM; base 10 logarithm for GSM, inverse for PI and C:N ratio, reverse square root for H', and reverse base 10 logarithm for D_b (Mertler and Vannatta 2010). Percent non-native cover could not be normalized due to a high number of zero values.

Bi-variate Pearson correlation coefficients were calculated to determine the degree of correlation between variables, and to check the relationship between multi-regression predictors. Euclidean clustering with average linkage was used on standardized soil attributes (i.e., plot means, $n = 22$) to determine soil condition (SC) groups (i.e., plot combinations across sites with similar soil characteristics) (Zuur and others 2007). Significant differences in vegetation and soil attributes as affected by site and SC group were evaluated using General Linear Model (GLM) univariate Analysis of Variance (ANOVA) techniques (Mertler and Vannatta 2010). Since site and soil condition group sample sizes were not equal, Tamehane T2 post-hoc evaluation was used to assess pairwise differences (SPSS 2011). Stepwise multi-regression was used to determine which combinations of vegetation only, soil only, and vegetation and soil attributes were the best predictors of AGB. Constraints on multi-regression included limiting number of predictors to five to achieve a parsimonious solution and to improve reliability (i.e., $n/k > 15/1$ where $n =$ sample and $k =$ predictor variables where $88/5 = 17.6$) (Mertler and Vannatta 2010). All statistical analyses were done using IBM SPSS Statistics v19.0 (SPSS 2011).

Results

Hydrologic Regime

Growing season water levels in wells (i.e., water levels in relationship to the sediment surface), either co-located with or closest to the study plots, all met the Virginia legal criteria for jurisdictional wetland hydrology (i.e., above −30 cm for 12.5 % of the growing season) in 2009 (Norfolk District Corps and Virginia Department of Environmental Quality 2004). Precipitation levels for 2009 were 17 cm above normal during the growing season (i.e., April through November) (National Weather Service 2010). Water level readings from several shallow wells (i.e., LC $n = 5$, BR $n = 2$, MW $n = 4$, NF $n = 5$) were measured weekly from March to June, then on a monthly basis throughout the rest of the year (i.e., growing season mean water level readings LC $n = 21$, BR $n = 20$, MW $n = 17$, NF $n = 21$). During April through June, each of the sites experienced extended standing water conditions, with MW subjected to the deepest standing water at close to 20 cm for most of this period. During July through September, NF was the only site that maintained mean water levels above -30 cm. Water levels (Mean ± SE) were similar ($F_{3,75} = 0.898$, $P = 0.447$) between sites (LC −0.54 ± 3.45 cm; BR −4.47 ± 4.00 cm; MW 2.57 ± 5.60 cm; NF 3.48 ± 2.10 cm).

Vegetation Attributes

A total of 41 species were found in samples across the four sites, with no site-based trend noted in richness (S) (Table 1). Mean C_n ranged from 2.9 to 3.9, but was not significantly different between sites ($P = 0.765$). Seeded herbaceous species accounted for close to 25 % of the species found at each site. Hydrophytic vegetation that occurs at least 34 % of the time in wetlands (i.e., facultative or wetter) represented 85 % of the total species present. Five species were drier than facultative (FAC) or not indicated as a wetland species including *Arthraxon hispidus* (Not Indicated)*, Eupatorium serotinum* (FAC-), *Juncus tenuis* (FAC-), *Polygonum caespitosum* (FACU-), and *Symphyotrichum ericoides* (FACU) (Table 1). Species classified as invasive in Virginia included *A. hispidus*, *P. caespitosum*, and *Murdannia keisak*.

Site percent cover ranged from values for total of 99 to 106 %, seeded from 24 to 65 %, volunteer from 35 to 75 %, and non-native from 6 to 31 % (Table 2). There were no significant percent cover differences between sites for total ($P = 0.066$), seeded ($P = 0.227$), or volunteer percent cover ($P = 0.277$) (Table 2). Non-native percent cover was significantly higher ($P < 0.001$) in BR

Table 1 Plant species observed in created wetlands (LC, BR, MW, NF) during the 2009 growing season

Scientific Name	Common name	Wetland[1] indicator Status (WIS)	Coefficient[1] of conservatism (C_n)	LC (3 years)	BR (7 years)	MW (9 years)	NF (10 years)
Alisma subcordatum	Raf. American water plantain	OBL	6	X	X	X	
Ambrosia trifida L.	Giant ragweed	FAC	3				X
Arthraxon hispidus Thunb.*	Small carpgrass	NI	0		X	X	X
Bidens aristosa Michx.	Bearded beggarticks	FACW	2	<u>X</u>[2]			<u>X</u>
Bidens cernua L.	Nodding beggarticks	OBL	4	X			
Carex frankii Kunth.	Frank' sedge	OBL	4	X	X		X
Carex lurida Wahlenb.	Sallow sedge	OBL	4	<u>X</u>	<u>X</u>		<u>X</u>
Carex tribuloides Wahlenb.	Blunt-broom sedge	FACW	3	X		X	X
Carex vulpinoidea Michx.	Fox sedge	OBL	3	<u>X</u>		<u>X</u>	<u>X</u>
Cyperus strigosus L.	Strawcolored flatsedge	FACW	3	X	X		X
Echinochloa crusgalli L	Barnyard grass	FACW	0	X	X	X	X
Eclipta prostata L.	Yerba de Tajo	FAC	2	X			
Eleocharis obtusa Willd.	Blunt spikerush	OBL	2		X	X	X
Eleocharis tenuis Willd.	Slender spikerush	FACW+	6				X
Eupatorium serotinum Michx.	Late flowr. thoroughwort	FAC-	3		X	X	
Galium asprellum Michx	Rough bedstraw	OBL	7			X	X
Helenium autumnale L.	Common sneezeweed	FACW+	4			X	
Juncus effusus L.	Common rush	OBL	3	<u>X</u>	<u>X</u>	<u>X</u>	<u>X</u>
Juncus tenuis Willd.	Poverty rush	FAC-	2	X	X	X	X
Leersia oryzoides L.	Rice cutgrass	OBL	4	X	<u>X</u>		<u>X</u>
Lespedeza virginica L.	Slender lespedeza	UPL	3				X
Ludwigia alternifolia L.	Seedbox	FACW+	3				X
Ludwigia palustris L.	Marsh seedbox	OBL	2	X	X	X	X
Lycopus americanus Muhl.	Am. water horehound	OBL	4				X
Microstegium vimineum Trin.	Japanese stiltgrass	FAC	0			X	
Mimulus ringens L.	Monkey flower	OBL	5				X
Murdannia keisak Hassk.**	Marsh dewflower	OBL	0		X		
Panicum virgatum L.	Switchgrass	FAC	4			<u>X</u>	
Polygonum caespitosum Bl.**	Oriental ladysthumb	FACU-	0	X			
Polygonum hydropiper L.	Marshpepper knotweed	OBL	4	X	X	X	X
Polygonum hydropiperoides Michx.	Mild water pepper	OBL	4	X	X		X
Polygonum pennsylvanicum L.	Pennsylvania smartweed	FACW	2	<u>X</u>		X	
Polygonum punctatum Ell.	Dotted smartweed	OBL	4			X	X
Polygonum sagittatum L.	Arrowleaf tearthumb	OBL	5		X		
Schoenoplectus tabernaemontani Gmel.	Softstem bulrush	OBL	5		X		
Scirpus atrovirens Willd.	Green bulrush	OBL	5		<u>X</u>		<u>X</u>
Scirpus cyperinus L.	Woolgrass	FACW+	3	X	X	<u>X</u>	X
Solidago rugosa Mill.	Wrinkled goldenrod	FAC	3				X
Symphyotrichum ericoides L.	White heath aster	FACU	1		X	X	
Typha angustifolia L.	Narrowleaf cattail	OBL	3		X	X	
Verbena hastata L.	Swamp verbena	FACW+	4		<u>X</u>		<u>X</u>
		Richness (S)		19	22	20	27

*Moderately invasive species; **Highly invasive species taken from 2009 Invasive alien plant species of Virginia list prepared by the Virginia Department of Conservation and Recreation and the Virginia Native Plant Society

[1] 2005 Virginia wetland plants C-value list, prepared by the Virginia FQAI advisory committee for the Virginia Department of environmental quality

[2] Underline indicates species seeded at wetland creation

Table 2 Site-based differences for vegetation and soil attributes (mean ± standard error)

	LC	BR	MW	NF	$F_{3,84}$	P^2
Vegetation attributes						
Total cover, %[1]	113 ± 3a	113 ± 4a	103 ± 4a	103 ± 4a	2.489	NS
Seeded cover, %	49 ± 7a	32 ± 8a	56 ± 9a	47 ± 8a	1.477	NS
Volunteer cover, %	51 ± 7a	68 ± 8a	44 ± 9a	53 ± 8a	1.477	NS
Non-native cover, %	10 ± 4b	26 ± 5a	1 ± 5b	10 ± 5b	27.522	**
S	4.2 ± 0.4a	4.6 ± 0.4a	4.1 ± 0.5a	5.2 ± 0.4a	1.416	NS
H′	0.4 ± 0.04a	0.4 ± 0.05a	0.4 ± 0.05a	0.5 ± 0.05a	1.215	NS
FQAI	6.2 ± 0.3a	6.3 ± 0.4a	6.5 ± 0.5a	7.0 ± 0.4a	0.772	NS
PI	1.3 ± 0.1b	1.4 ± 0.1ab	1.6 ± 0.1ab	1.7 ± 0.1a	3.426	*
AGB ($g{\cdot}m^{-2}$)	1520 ± 100a	1640 ± 120a	1830 ± 140a	770 ± 120b	16.338	**
BGB ($g{\cdot}m^{-2}$)	250 ± 30a	250 ± 40a	210 ± 40a	240 ± 40a	0.236	NS
Soil attributes						
GSM, %	25 ± 0.6b	27 ± 0.8b	32 ± 0.9a	31 ± 0.8a	20.387	**
TOC, %	1.9 ± 0.1a	1.9 ± 0.2a	1.7 ± 0.2a	2.1 ± 0.2a	1.726	NS
TN, %	0.18 ± 0.01ab	0.16 ± 0.01ab	0.15 ± 0.01b	0.19 ± 0.01a	2.803	*
C:N	10.6 ± 0.2b	11.6 ± 0.3a	11.2 ± 0.2ab	11.5 ± 0.2a	6.616	**
SOM, %	4.6 ± 0.2b	4.6 ± 0.3b	4.2 ± 0.3b	6.4 ± 0.3a	11.072	**
pH	5.1 ± 0.1a	5.2 ± 0.1a	4.3 ± 0.1b	5.2 ± 0.1a	25.922	**
D_b ($g{\cdot}cm^{-3}$)	1.36 ± 0.03a	1.28 ± 0.04a	1.27 ± 0.05a	1.26 ± 0.04a	1.850	NS

[1] Due to multiple herbaceous canopy layers, the total cover estimates could exceed 100%

[2] *NS* Not significant, * $P < 0.05$, ** $P < 0.001$

Letters indicate significant differences between site attributes

Richness (S), Shannon–Weiner biodiversity index (H′), Floristic Quality Assessment Index (FQAI), prevalence index (PI), above ground biomass (AGB), below ground biomass (BGB), gravimetric soil moisture (GSM), soil organic matter (SOM), total (soil) organic carbon (TOC), total (soil) nitrogen (TN), soil C:N ratio, soil pH, and bulk density (D_b)

(Table 2). Site indices ranged from 3.6 to 5.6 for S, 0.35 to 0.55 for H′, 5.9 to 7.4 for FQAI, and 1.2–1.8 for PI (Table 2). There were no statistical difference in S ($P = 0.244$), H′ ($P = 0.309$), or FQAI ($P = 0.513$) between sites (Table 2). Peak AGB ranged from 650 to 1,970 $g{\bullet}m^{-2}$ and BGB ranged from 170 to 290 $g\ m^{-2}$ (Table 2). There were no significant differences between sites for BGB ($P = 0.871$). NF, the oldest site, had the lowest AGB ($P < 0.001$) and the highest PI ($P < 0.05$) of the four sites (Table 2).

Soil Attributes

Soil moisture and nutrient values ranged from 24 to 32% of dry weight for GSM, 3.9–6.7% for SOM, 1.5–2.3% for TOC, 0.14–0.20% for TN, and 10.4–11.7 for C:N (Table 2). The two older sites, MW and NF, had higher GSM ($P < 0.001$) than LC and BR (Table 2). SOM ($P < 0.001$) was highest at the oldest site, NF (Table 2). C:N ratio ($P < 0.001$) was lower at the youngest site, LC, and MW (Table 2). There were no significant differences in TOC ($P = 0.168$), but TN ($P = 0.045$) was marginally lower at BR and MW (Table 2). Soil pH ranged from 4.2 to 5.3 and D_b ranged from 1.22 to 1.39 $g\ cm^{-3}$ (Table 2). MW had the lowest soil pH ($P < 0.001$) with no difference between the WSSI sites, and there was no significant difference in D_b ($P = 0.144$, Table 2).

Soil Condition (SC) Groups Across Wetland Sites

Four SC groups resulted from cluster analysis (60% dissimilarity applied) of SOM, pH, D_b, and GSM across the wetland sites (Table 3). SC groups consisted of plots with common soil attribute levels, which trended from more to less developed from SC1 to SC4 (e.g., higher SOM, lower Db, higher GSM, etc.) with at least three different significance levels between SCs ($P < 0.001$) for each attribute. Three MW plots (SC3) grouped together (Table 3). LC broke into different groups with plots in the higher elevation cell in one group (SC2), and plots in the lower elevation cell in another group (SC4) (Table 3). BR plots distributed themselves among three groups, and NF plots were split between two groups (Table 3).

Table 3 Soil condition (SC) plot groups and vegetation attribute (mean ± standard error) differences

	SC1 ($n = 2$)	SC2 ($n = 12$)	SC3 ($n = 3$)	SC4 ($n = 5$)	$F_{3,84}$	*P*
LC		5 plots		3 plots		
BR	1 plot	3 plots		1 plot		
MW			3 plots	1 plot		
NF	1 plot	4 plots				
Total cover, %	128 ± 6a	108 ± 2b	102 ± 5b	107 ± 4b	4.386	*
Seeded cover, %	15 ± 12b	41 ± 5a	64 ± 10a	60 ± 8a	4.576	*
Volunteer cover, %	85 ± 12a	59 ± 5b	36 ± 10b	40 ± 8b	4.576	*
Non-native cover, %	16 ± 7a	16 ± 3a	1 ± 6b	8 ± 5ab	11.745	*
S	4.6 ± 0.7a	4.9 ± 0.3a	3.6 ± 0.6a	3.9 ± 0.4a	2.406	NS
H′	0.5 ± 0.08ab	0.5 ± 0.03a	0.3 ± 0.06b	0.4 ± 0.05ab	2.935	*
FQAI	7.4 ± 0.7a	6.7 ± 0.3ab	6.1 ± 0.5ab	5.5 ± 0.4b	2.987	*
PI	1.2 ± 0.2b	1.5 ± 0.1ab	1.3 ± 0.1ab	1.7 ± 0.1a	3.376	*
AGB ($g \cdot m^{-2}$)	1240 ± 200bc	1180 ± 80c	2120 ± 170a	1700 ± 130ab	10.200	**
BGB ($g \cdot m^{-2}$)	220 ± 60a	230 ± 20a	180 ± 50a	320 ± 40a	2.518	NS

NS Not significant, * $P < 0.05$, ** $P < 0.001$

Plant Community Development by SC Group

Plant community development showed more significant differences when analyzed by SC group. Eight of ten vegetative attributes were different by SC (Table 3), as opposed to only three that were different by site (Tables 2). Like soil, vegetation trended from more developed (i.e., higher H′, FQAI, total and volunteer cover) to less developed from SC1 to SC4. SC1 supported significantly higher total and volunteer percent cover (total 97–134%, volunteer 26–97%, $P < 0.05$), and lower seeded percent cover (3–74%, $P < 0.05$) than the other SC groups (Table 3). S was not significantly different between SC groups (3.0–5.3, $P = 0.073$). H′ and FQAI in SC1 and SC2 groups were higher than those in the other less developed SC3 and SC4 groups (H′ 0.2–0.6, FQAI 5.1-8.1, $P < 0.05$, Table 3). PI (1.0–1.8, $P < 0.05$) was lower in SC1 and higher in SC4 with both not significantly different for SC2 and SC3 (Table 3). AGB (1,100–2,290 g m^{-2}, $P < 0.001$) was significantly lower in SC1 and SC2 groups, while BGB (130–360 g m^{-2}, $P = 0.064$) differences were not significant (Table 3).

Correlation Between Soil and Vegetation Attributes

Seeded and volunteer percent cover were correlated ($P < 0.01$) with most other vegetation attributes, except PI and BGB (Table 4). Seeded cover was negatively correlated with S, H′, and FQAI, while volunteer cover was positively correlated ($P < 0.01$; Table 4). PI was negatively correlated with total cover and FQAI ($P < 0.01$; Table 4). AGB was negatively correlated ($P < 0.01$) with all vegetation indices and volunteer cover, but was positively correlated with seeded cover (Table 4). BGB was not correlated with any vegetation attribute (Table 4). S, H′, FQAI, and PI were largely uncorrelated with any of the soil attributes, with the exception of pH and SOM ($P < 0.01$) (Table 4). AGB was negatively correlated with SOM and pH ($P < 0.01$), and BGB was negatively correlated with TOC and C:N (Table 4). PI was negatively correlated with soil nutrient attributes ($P < 0.05$), but positively with D_b ($P < 0.01$) (Table 4). Soil pH was positively correlated with total and volunteer percent cover, S, and H′, but negatively with AGB (Table 4). All soil attributes were highly correlated with one another ($P < 0.01$), except pH, which was not correlated with either TOC or C:N (Table 4).

Plant Productivity and its Relations with Soil and Vegetation Attributes

Productivity (i.e., peak AGB) predictions, using vegetation attributes only, soil attributes only, and combinations of both vegetation and soil attributes, were assessed. Model selection was based on a combination of criteria including R^2 value, minimizing predictor number, and significance of the contribution of individual predictors ($P < 0.01$). The best predictive vegetation only attribute model used H and PI as predictors ($AGB' = 0.52\ H' + 0.31\ PI$, $F_{2,85} = 19.60$, $P < 0.001$, $R^2 = 0.32$), and explained 32% of the variation in AGB (Table 5). The best soil attribute only model used SOM, pH, and C:N ratio ($AGB' = -0.39$ SOM—0.33 pH—0.29 C:N, $F_{3,84} = 10.72$, $P < 0.001$, $R^2 = 0.28$), and explained 28% of the AGB variation

Table 4 Pearson correlation coefficient matrix for vegetation and soil attributes

	Total	Seeded	Volunteer	Non-native	S	H′	FQAI	PI	AGB	BGB	GSM	SOM	TOC	TN	C:N	pH
Vegetation attributes																
Seeded cover %	*−0.210*															
Volunteer cover %	*0.210*	**−1.000**														
Non−native cover, %	*0.215*	**−0.449**	**0.449**													
S	−0.095	**−0.343**	**0.343**	−0.046												
H′	0.077	**−0.481**	**0.481**	−0.030	**0.873**											
FQAI	0.001	**−0.474**	**0.474**	−0.081	**0.814**	**0.806**										
PI	**−0.274**	0.170	−0.170	0.182	−0.016	−0.154	**−0.314**									
AGB ($g \cdot m^{-2}$)	−0.022	**0.341**	**−0.341**	−0.094	**−0.416**	**−0.469**	**−0.312**	*−0.233*								
BGB ($g \cdot m^{-2}$)	0.092	−0.047	0.047	0.059	0.052	0.126	0.107	−0.061	0.051							
Soil attributes																
GSM, %	−0.046	0.129	−0.129	−0.144	−0.072	−0.108	0.057	−0.071	−0.062	−0.209						
SOM, %	0.061	*−0.240*	*0.240*	0.040	−0.091	0.128	*0.211*	−0.207	**−0.317**	−0.202	**0.441**					
TOC, %	0.132	*0.233*	*−0.233*	0.041	−0.026	0.085	0.145	**−0.373**	−0.128	*−0.214*	**0.349**	**0.824**				
TN, %	0.157	−0.178	0.178	0.005	0.049	0.100	0.151	**−0.355**	−0.169	−0.159	**0.294**	**0.791**	**0.951**			
C:N	0.026	*−0.219*	*0.219*	0.093	−0.013	0.034	0.136	*−0.222*	0.070	*−0.250*	**0.411**	**0.525**	**0.623**	**0.399**		
pH	*0.237*	**−0.279**	**0.279**	*0.223*	*0.271*	**0.320**	0.192	−0.078	**−0.411**	−0.031	**−0.311**	*0.255*	0.196	*0.219*	0.049	
D_b($g \cdot cm^{-3}$)	0.103	*−0.220*	*0.220*	−0.025	0.008	−0.067	−0.168	**0.267**	0.031	0.062	**−0.457**	**−0.628**	**−0.687**	**−0.622**	**−0.528**	0.007

Bolded, $P < 0.01$; Italics, $P < 0.05$

Table 5 Multi-regression models for above−ground biomass (AGB) using vegetation and soil attributes

Standardized Coefficients	H′	PI	pH	SOM	C:N	F	*P*	R^2
Vegetation								
	0.47					24.25	**	0.22
	0.52	0.31				19.60	**	0.32
Soil								
	−0.41					17.48	**	0.16
	−0.35	−0.23				11.80	**	0.22
	−0.33	−0.39	−0.29			10.72	**	0.28
Combined								
	0.49	0.38	−0.33			20.38	**	0.42
	0.42	0.37	−0.24	−0.28		18.27	**	0.47
	0.41	0.35	−0.22	−0.40	−0.23	16.73	**	0.51

** $P < 0.001$; Blanks indicate attributes not used in model/associated row

(Table 5). The best combined vegetation and soil attribute model included H′, PI, SOM, and pH (AGB = 0.42 H′ + 0.37 PI—0.24 SOM—0.28 pH, $F_{4,83} = 18.27$, $P < 0.001$, $R^2 = 0.47$), and explained 47% of the AGB variation (Table 5). The selected combined model excluded C:N because the significance of its contribution was <0.01.

Discussion

Site Hydrology and Characteristics of Vegetation Attributes

Overall, all study wetlands seemed to succeed in meeting their hydrologic and vegetation targets, satisfying established structural goals for mitigation of impacted natural wetlands (Norfolk District Corps and Virginia Department of Environmental Quality 2004). Both total (Table 2) and facultative or wetter percent cover [LC 107 ± 4; BR 106 ± 7; MW 94 ± 7; NF 96 ± 9] were substantially above minimum permit requirements in Virginia (i.e., 80 and 50%) (Norfolk District Corps and Virginia Department of Environmental Quality 2004). The study wetlands were solidly in the obligate or facultative wet range, thus supporting wetland vegetation successfully (Table 2). Additionally, mean water levels for wells closest to or within the study plots were well above minimum requirements at all four of the wetlands with no difference between sites.

Age related vegetation development in created wetlands is often reported (Atkinson and others 2005; Matthews and Endress 2010; Noon 1996; Spieles 2005), yet we did not see maturation in terms of improved percent cover, S, H′, or FQAI across an age trajectory for our study sites (Table 2). Comparison of species with the five highest importance values (IV) (i.e., largest abundance and frequency at each site) provided possible clues behind the lack of significant vegetation differences between sites (Table 6). Importance values (IV) for the five most dominant species at each site illustrated several shared dominant species including *Juncus effusus*, *Polygonum hydropiper*, *Scirpus cyperinus*, and an invasive, *Arthraxon hispidus* (Table 6). Three of the sites had one plot that was monotypic including *J. effusus* at both LC (IV 73, 100 % plot cover) and MW (IV 107, 90 % plot cover), and *B. aristosa* at NF (IV 37, 99 % plot cover) (Table 6). Additionally, MW had a broad area that was monotypic for *T. angustifolia*, which was captured in one plot (IV 54, 49 % plot cover) (Table 6). In addition, LC, BR, and NF sites had at least one species with a C_n value of zero in the top five [LC *Echinochloa crus-galli*; BR *M. keisak* and *A. hispidus*; NF *A. hispidus*] (Table 6). Because several dominant (i.e., high IV) species were common to each of the four sites, indices and percent cover attributes were equalized. Additionally, dominant species with low C_n values, even if not common between sites, contributed to equivalence in FQAI.

Juncus effusus was seeded at all four sites and had the highest or second highest IV across the sites [LC 73; BR 94; MW 107; NF 72] (Table 6). *J. effusus* is a hardy perennial classified as facultative wet plus (FACW+) in Virginia (USDA NRCS 2002). It can thrive in acidic soils under high pollution loads and extended standing water conditions (USDA NRCS 2002; Magee and Kentula 2005). It is native to Virginia, and can be beneficial as a wildlife habitat and for erosion control, but it can also become invasive under the right conditions (USDA NRCS 2002). In a 2 year study of the LC wetland, *J. effusus* expanded its coverage almost 40% in the lower elevation cell (Ahn and Dee 2011). Standing water conditions approaching 10 cm were maintained in the lower elevation cell for the first four

Table 6 Vegetation importance values (IV) for the top five species at each wetland site

Species	WIS	C_n	RC	RF	IV	Species	WIS	C_n	RC	RF	IV
LC						**BR**					
CAFR	1	4	28	46	74	MUKE	1	0	22	85	107
JUEF	1.5	3	30	43	73	JUEF	1.5	3	29	65	94
ECCR	4	0	13	50	63	SCCY	1.5	3	11	60	71
BICE	1	4	17	33	50	POHY	1	4	21	50	71
POLY	1	4	9	25	34	ARHI	NI	0	4	25	29
Mean C_n		**3**				Mean C_n		**2**			
MW						**NF**					
JUEF	1.5	3	38	69	107	JUEF	1.5	3	17	55	72
TYAU	1	3	17	37	54	LUPA	1	2	8	50	58
POHY	1	4	8	44	52	CAVU	1	3	8	35	43
SCCY	1.5	3	16	31	47	POHY	1	4	5	35	40
ALSU	1	6	5	37	42	ARHI	NI	0	10	30	40
Mean C_n		**3.8**				Mean C_n		**2.4**			

*RC R*elative mean species cover, *RF* relative mean species frequency, IV = RC + RF

months of the growing season in both years, providing hydrologic conditions that allowed *J. effusus* to out-compete other species (Ahn and Dee 2011). Thus, pre-seeding coupled with hydrologic design elements of wetland creation may contribute to unintended limitations on diverse plant community development.

Invasive species can change or control the structure and function of wetlands, thus affecting early plant community development in created wetlands (Galatowitsch and others 1999; Kercher and Zedler 2004). *M. keisak* is an annual herb that was introduced from Asia in the 1920s as a result of rice cultivation in Louisiana, and spread to Virginia by the 1950s (Dunn and Sharitz 1990). *M. keisak* had the highest IV at BR (107) and was found in virtually every sample with a mean percent cover of 31% for the 20 samples collected (Table 6). *M. keisak* dominance in BR increased non-native percent cover and contributed to reductions in S, H′, and FQAI (Tables 2, 6). The introduction of *M. keisak* was likely associated with relatively high connectivity to the adjacent Bull Run stream. Recent studies suggest that exotic species should be evaluated based on their ecosystem impact and ability to coexist spatially and temporally with native species (Brandt and Seabloom 2011; Davis and others 2011). *M. keisak* can produce thousands of seeds per square meter so should be carefully monitored in BR for tendencies to coexist or outcompete higher quality wetland plants.

Plant community richness, diversity, productivity, and quality indices in our study were similar to other studies of depressional created and natural wetlands (Cole and others 2001; Lopez and Fennessy 2002; Atkinson and others 2005, 2010; Balcombe and others 2005; Moser and others 2007). Diversity can be higher immediately after disturbance, such as wetland construction, then stabilize to a lower level once typical climactic and hydrologic conditions are reached (Nedland and others 2007; Noon 1996; Odum 1969). Ahn and Dee (2011) found that S, H′, and FQAI all decreased significantly at the LC study site in the third year since creation, illustrating early signs of plant community stabilization in response to normal hydrology. S and FQAI are usually determined based on species found in all samples collected across sites (U.S. Environmental Protection Agency 2002a). Site S (Table 1) was comparable to that found in created wetlands in Virginia (Atkinson and others 2005) and West Virginia (Balcombe and others 2005). Site FQAI [LC 13.3, BR 15.9, MW 13.6, NF 18.8] values were similar to those found in emergent and scrub-shrub wetlands that were highly disturbed (Lopez and Fennessy 2002).

Characteristics of Soil Condition (SC) Attributes

Unlike vegetative attributes, comparison of soil attributes illustrated several significant differences by site ($P < 0.001$), seemingly following an age-related trajectory (Table 2). The oldest site, NF, had the highest SOM, a key indicator of maturation in wetland soil development (Table 2). NF also had higher GSM that may have been associated with the higher SOM (Tables 2, 4). Carbon and nitrogen levels at NF appear to have improved significantly since 2005 with TOC increasing from 1.3% in 2005 to 2.1 ± 0.2% in this study, and TN increasing from 0.12% in 2005 to 0.19 ± 0.01% in this study (Table 2) (Moser and others 2007). Study SOM and D_b levels were comparable to created wetlands under 20 years old in Pennsylvania (Cole and others 2001), North Carolina (Bruland and

Richardson 2005), and New York (Ballantine and Schneider 2009).

Vegetation Development by SC Groups and Spatial Heterogeneity

Most vegetation and soil attributes differed significantly ($P < 0.05$) between plots within each site (Table 7). This shows that site age does not necessarily equate with site development since soil and vegetation developmental rates varied more within than among sites (Table 7). Dick and Gilliam (2007) also observed significant spatial variability on a scale less than four meters for both soil condition (e.g., SOM, pH, N mineralization) and vegetation (e.g., S, H′, percent cover) attributes in a seasonal riverine wetland. Based on many highly significant within-site soil attribute differences ($P < 0.001$) in our study, soil condition (SC) was assessed for its effects on plant community development (Table 7). SC attributes recruited in this study (i.e., GSM, pH, SOM and D_b) are easily measurable, thus do not require intensive lab procedures.

SC groups reflected similar plots across the sites with directionality from more to less developed (i.e., SC1 > SC2 > SC3 > SC4). SC groups with greater SOM, lower D_b, more circumneutral pH, and higher GSM, all indicative of maturity in ecosystem development, were associated with higher H′ and FQAI, and total and volunteer percent cover, and lower AGB, PI, and seeded percent cover (Table 3). Seeded species, including *J. effusus* and *S. cyperinus*, were more productive (i.e., higher AGB) than volunteer species and tended to dominate areas with lower SOM accumulation and higher D_b (i.e., SC3 and SC4) in each wetland. Wetland areas with higher SOM accumulation and lower D_b, had higher plant community diversity and quality, which in turn was associated with an increased abundance of volunteer species. SC groups can be viewed as a measure of soil developmental variation within a created wetland, with some groups lagging others and thus maturing at different rates. Because plant community development was strongly related to key indicators of soil maturity in created wetlands (i.e., higher SOM and lower Db), an age-trajectory of vegetation development "as determined" by soil condition was reflected.

Table 7 Within site differences for vegetation and soil attributes (*P*-values)

	LC	BR	MW	NF
Vegetation attributes				
Total cover	NS	*	NS	*
Seeded cover	*	*	*	*
Volunteer cover	*	*	*	*
Non-native cover	*	NS	NS	NS
S	*	*	*	*
H′	**	NS	*	*
FQAI	*	*	*	*
PI	NS	*	**	*
AGB	*	NS	*	NS
BGB	NS	*	NS	NS
Soil attributes				
GSM	*	**	**	**
TOC	**	**	*	*
TN	**	**	*	*
C:N	NS	**	*	NS
SOM	**	**	*	NS
pH	**	**	**	*
D_b	*	**	*	*

NS-Not Significant, * $P < 0.05$, ** $P < 0.001$

Autochthonous and allochthonous soil nutrients are made available to wetland plants from decomposing biomass, anthropogenic inputs from residences and agricultural fields, bank overflow from adjacent streams, and atmospheric deposition (Bayley and Guimond 2009; Fennessy and others 2008; Olde Venterink and others 2003). The degree to which a wetland is connected to adjacent streams can have a significant effect on productivity and diversity by promoting frequent flood pulses which import nutrients, sediment, and volunteer plant species (Bayley and Guimond 2009; Fennessy and Mitsch 2001). Periodic nutrient replenishment from bank overflow was suspected in three areas associated with different SC groups in three of the study wetlands, MW, NF, and BR. Even though MW and NF were created within a year of each other, MW rarely had comparable soil characteristics, but tended to be more like the two younger sites (Table 2). MW was the most anthropogenically impacted of the four sites, with hydrology often dominated by storm drain runoff from the adjacent airport industrial zone and highway. Cockrell Branch (i.e., intersecting stream) supported frequent flooding pulses in the immediate riparian area where the three MW plots that comprised SC3 were located. SC3 had higher AGB (2,120 ± 170 g m^{-2}), which should have supported increased SOM accumulation, but lower pH (4.3 ± 0.01) and SOM (4.2 ± 0.3%) coupled with higher Db (1.22 ± 0.04 g cm^{-3}) indicated that accumulation processes were weak (Table 3). SC3 represents an area within MW where external inputs may have negatively influenced plant community and soil development. Overall, AGB was negatively correlated with SOM, so higher AGB did not appear to support greater SOM accumulation across the four sites (Table 4).

BR and NF are located in rural settings that include both wooded and pasture areas. The more developed SC1 group consisted of a BR and NF plot. The SC1 BR plot is the frequent recipient of bank overflow nutrients from the southeast corner of the wetland where Bull Run turns sharply 90 degrees. The SC1 NF plot is located on the banks of the NF wetland pond, which is directly influenced by nutrient input during flooding from the North fork of Broad Run. SC1 plots had more developed soil conditions with the highest SOM (7.3 ± 0.4%), TOC (3.0 ± 0.2%), TN (0.23 ± 0.01%), and C:N (12.8 ± 0.3%), and the lowest D_b (0.97 ± 0.05 g cm^{-3}). SC1 represents areas within NF and BR that have been positively influenced by external nutrient inputs resulting from floodplain connectivity to adjacent streams.

The finding that SC can be used to more accurately assess significant differences in vegetation attributes has potential application for future monitoring, created wetland design, and post-creation refinement. SC information can help distinguish problem areas and potential causes for underperforming zones within a created mitigation wetland. Areas in our study where plots fell into less mature SC3 and SC4 groups included monotypic *J. effusus* plots, which without further design intervention have the potential to expand in coverage and hamper diverse plant community development. Areas in SC1 and SC2 groups supported more developed plant communities and soil conditions, even though, in the case of BR, there was a higher abundance of the invasive *M. keisak*.

Relationship Between Function (i.e., Plant Productivity) and Structure (i.e., Vegetation and Soil Attributes)

Many studies comparing productivity in created and natural wetlands have found that natural sites have significantly higher productivity, leading to a conclusion that older, more developed created sites might also trend toward increasing productivity (Fennessy and others 2008, Hoeltje and Cole 2009; Hossler and Bouchard 2010). Peak AGB was significantly lower in our oldest created site, NF, contrary to other studies (Table 2). In fact, AGB was negatively correlated with S, H′ and FQAI, indicating that more developed plant communities were not as productive (Table 4). Lower diversity driven in part by the dominance of the highly productive *J. effusus* was a strong gauge of increased AGB in this study. Our findings were consistent with those of Olde Venterink and others (2003), who noted reduced AGB as richness increased and Lopez and Fennessy (2002), who saw increases in FQAI with reduction in AGB.

This study assessed whether a vegetative function, productivity (i.e., peak AGB), could be predicted from structural vegetation and soil attributes. The combination of vegetation and soil attributes improved the predictive power of the model over soil or vegetation alone, increasing explained variability by 15–19% over just vegetation or soil attributes (Table 5). The best AGB predictions ($R^2 = 0.47$) resulted from a model that used H′, PI, SOM, and pH, (Table 5). A similar approach could be used to enhance our understanding of the functional developmental trajectory of created wetlands. Comprehensive assessment of vegetation and soil properties can support improvements to wetland design and management activities, including practices that reduce bulk density, increase accumulation of soil organic matter, and reduce the dominance of invasive species.

Conclusions

The study investigated vegetative and soil properties in four mitigation wetlands in the Piedmont region of Virginia. Soil condition attributes such as SOM, D_b, pH, and GSM, all related to the maturation of a created wetland, were associated with the development of structural and functional vegetation attributes in a spatially heterogeneous manner within each wetland illustrating that site age site age does not necessarily equate with overall site maturity. A significant predictive relationship was also found between peak AGB and attributes of vegetation and soils, which can be of use in assessment of the functional trajectory of the wetlands. The inclusion of soil attributes in post-construction monitoring should be required to enhance our understanding and prediction of developmental trajectory, both structural and functional, of created mitigation wetlands. Information garnered from this study may benefit state agencies and other groups involved with wetland creation and restoration to mitigate the loss of natural wetlands.

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