A STUDY OF THE DEVELOPMENT OF PLANT COMMUNITY AND SOIL PROPERTIES IN MITIGATION WETLANDS CREATED IN THE VIRGINIA PIEDMONT, USA

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

A STUDY OF THE DEVELOPMENT OF PLANT COMMUNITY AND SOIL PROPERTIES IN MITIGATION WETLANDS CREATED IN THE VIRGINIA PIEDMONT, USA

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Investigating the progress of created mitigation wetlands can provide useful information on current and future wetland design and management efforts, including monitoring activities legally mandated to ensure ecosystem development to properly mitigate the loss of natural wetlands. The study investigated structural vegetative and soil properties along with functional vegetative measures in four non-tidal freshwater wetlands created in the Piedmont region of Virginia. During the 2009 growing season, vegetation and soil samples were collected from wetlands ranging in age from 3 to 10 years. Vegetation attributes included percent cover (i.e., total, seeded, volunteer, and non-native), richness (S), diversity (H´), floristic quality assessment index (FQAI), prevalence index (PI), and productivity (i.e., peak above- and below-ground biomass). Soil condition attributes included soil organic matter (SOM), total organic carbon (TOC), total nitrogen (TN), C:N ration, gravimetric soil moisture (GSM), pH, and bulk density (D_b). There were no significant differences in vegetation percent cover, S, H´, and FQAI by site. The lack of significant vegetation differences between sites was attributed to the abundance of a few common species, with the common soft rush, *Juncus effusus,* L., being the most dominant. However, significant site-based differences were detected for soil condition attributes ($p<0.001$), thus soil attributes were further analyzed using clustering statistics (60% dissimilarity applied), which resulted in four soil condition (SC) groups across the study sites. Vegetation data was then analyzed based on the SC groups. SC groups with greater SOM, lower D_b, more circumneutral pH, and higher GSM, all indicative of maturity in wetland ecosystem development, were associated with higher H´ and FQAI, and total and volunteer percent cover, and lower AGB, PI, and seeded percent cover. A significant predictive relationship was found between peak AGB and other attributes of vegetation and soils (standardized: AGB = 0.41H´+ 0.37PI - 0.29SOM - 0.24pH, $R^2=0.47$, $p<0.001$), which can be of use in assessment of the functional trajectory of the wetlands. The outcomes of the study suggest that the inclusion of soil attributes can significantly enhance understanding and prediction of plant community development in created mitigation wetlands.

Keywords: created wetlands, peak-biomass, plant development, productivity, soil properties, wetland mitigation, wetland monitoring

CHAPTER 1: INTRODUCTION

Wetland creation, restoration, and enhancement are required, under Section 404 of the Federal Clean Water Act (CWA), to provide compensatory mitigation when natural wetlands are lost as a result of construction projects (U.S. EPA 1990). Wetlands support environmental functions that sustain critical ecosystem services such as flood control, wildlife habitat, nutrient removal, and productivity (Cronk and Fennessy 2001, Mitsch and Gosselink 2007, Ramsar 2010). Compensatory wetland mitigation occurs either under a banking approach that anticipates future wetland loss or in direct response to specific loss (U.S. EPA 2008). The Army Corp of Engineers (ACOE) and Virginia Department of Environmental Quality (VDEQ) have jointly established minimum requirements for wetland mitigation monitoring in Virginia that are based on hydrology and wetland plant abundance (Norfolk 2004, U.S. EPA 1990).

While both structural and functional assessment of created wetlands is desirable, resource constraints have resulted in monitoring criteria which are only focused on structure (Andreas and others 2004, Nedland and others 2007). Plants are ideal subjects for mitigation monitoring because they are captive within the wetland and are responsive to natural and anthropogenic input, so vegetation surveys usually serve as surrogates for the functional development of created wetlands (Atkinson and others 2005, Balcombe and others 2005, Spieles 2005). Structural measures for vegetation, including species identification and percent cover, are relatively inexpensive to collect and are minimally intrusive to the wetland ecosystem; while many functional measures, including net primary productivity (e.g., above- and below-ground biomass per unit time) and biogeochemical cycling (e.g., plant tissue nutrient content and soil nutrient availability) require that both plants and soil be removed followed by resource intensive (i.e., labor and cost) laboratory analyses (Cronk and Fennessy 2001, Svengsouk and Mitsch 2001).

Vegetation development in created wetlands is heavily dependent on wetland hydrology and soil biogeochemisty (Ballantine and Schneider 2009, Bayley and Guimond 2009, Ehrenfeld and others 2005, Mitch and Gosselink 2007, Olde Venterink and others 2003). Comparative studies of created and natural wetland vegetation structure, often find that equivalence 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 development 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 freshwater wetlands have generally illustrated a lack of equivalence within the standard 5 to 10 year monitoring timeframe 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

2011b), 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 by establishing a framework that supports access to moisture and nutrients (Cronk and Fennessy 2001, Dwire and others 2006, Olde Venterink and others 2003). Soil structural attributes including bulk density, porosity, and texture support conditions that either enhance or diminish plant available nutrients (Mitsch and Gosselink 2007). Construction processes used to create wetlands often lead to severely disadvantaged soil structural states including high bulk density and reduced porosity caused by the crushing weight of earth moving equipment, in addition to practices that amalgamate in-situ subsoil and topsoil (Ballantine and Schneider 2009, Bruland and Richardson 2004, Hossler and Bouchard 2010). Created wetland designs, which usually incorporate low permeability subsoil layers that prevent access to ground water, and/or surrounding levees that limit connectivity to bank overflow, reduce periodic allochthonous nutrient input (Bayley and Guimond 2009, Cole and Brooks 2000, Shaffer and others 1999). The accumulation of moisture holding soil organic matter (i.e., nutrient pool) in created wetlands has an inverse relationship to bulk density, so challenges associated with poor soil structure and inhibition of natural nutrient replenishment processes can negatively affect the development of vegetation (Ballantine and Schneider 2009, Ehrenfeld and others 2005).

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, Svengsouk and Mitsch 2001), 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 existing sites (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, DeSteven and Sharitz 2007).

This study investigated plant community development and soil physicochemical condition in four relatively young 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. Are structural and functional attributes of vegetation and soils influenced by age of created mitigation wetlands?
2. Do soil physicochemical attributes affect vegetation development in created mitigation wetlands?
3. Is there a predictive relationship between wetland productivity (i.e., peak biomass) and structural vegetation and soil attributes?

CHAPTER 2: METHODS

2.1 Site descriptions

The study sites consisted of four created mitigation wetlands located in the Northern Virginia Piedmont in the 100-year floodplains of adjacent streams either in Prince William or Loudoun counties (Figure 1). At the time of the study in 2009, site ages varied from 3 to 10 years and could still be largely characterized as herbaceous, with a mix of open water, shrub-scrub, and young tree stands. Two different builders designed and created the sites, Wetland Studies and Solutions, Incorporated (WSSI) and Parsons Transportation Group (PTG). The builders incorporated shallow (i.e. <0.5 meters) perched, surface-driven water tables using low permeability subsoil layers and a mix of original and commercially available topsoil layers (Manassas 2009, WSSI 2009). All sites were disk tilled and hydroseeded with a combination of wetland and cover grass species, in addition to container-grown woody vegetation interspersed throughout.

The Loudoun County Mitigation Wetland Bank (LC 39º1′59″ N, 77º36′26″ W) was constructed in 2006 by WSSI in a rural suburban community. LC is composed of 32 acres of pre-existing and constructed palustrine-forested wetlands with an upland buffer complex in the 100-year floodplain of Goose Creek and its tributary, Big Branch (WSSI 2009). Study plots were established in two channel connected cells that were constructed

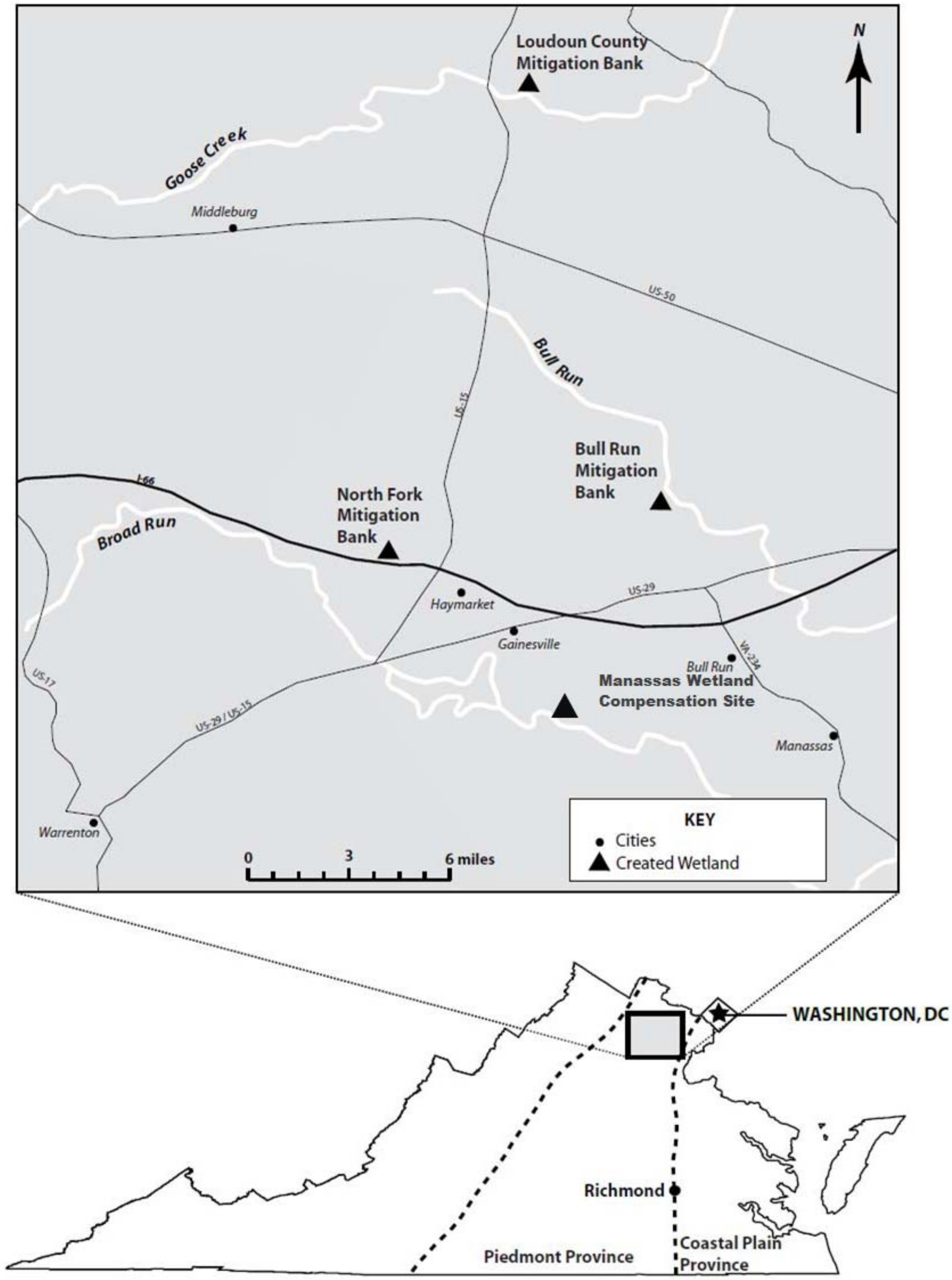

Figure 1. Created wetland study site locations (adapted from Wolf and others 2011a).

at different basin depths (i.e., 0.4 meter elevation difference) and separated by a berm (WSSI 2009). LC hydrology is primarily precipitation driven with surface water runoff from a housing development (i.e., <50 dwellings) and forested upland buffer, in addition to a small amount of groundwater from toe-slope intercept seepage (WSSI 2009). Water levels are maintained via overflow outlets to Big Branch.

The Bull Run Wetland Bank (BR 38º51′13″ N, 77º32.6′59" W), located in a rural area of Prince William County north of Manassas, Virginia was created by WSSI in 2002 (WSSI 2009). BR consists of almost 50 acres of upland buffer and created or restored riparian wetland including an open water pond. BR is connected to Bull Run via an AgriDrain structure that allows bi-directional flow and experiences annual overbank flooding. In addition, BR receives precipitation, sheet flow, and small amount of groundwater from toe-slope intercept seepage.

The North Fork Wetlands Bank (NF 38º49'32" N, 77º40′9″ W), located in Prince William County adjacent to interstate highway 66 west of Gainesville, was created by WSSI in 1999 (WSSI 2009). NF was previously a 125-acre pasture and includes a unique tiered design combining multiple wetlands, an open water pond, and an upland buffer complex. NF is hydrologically divided into four areas including a main pod connected to a tributary of the north fork of Broad Run which has been dammed to create the open water pond, an overbank flow area adjacent to the pond, vernal pools (VPs) fed exclusively by precipitation which are elevated from the main pod, and depressional wetlands fed primarily by precipitation with limited surface flow.

The Manassas Wetland Compensation Site (MW 38°43.3' N, 77°30.2' E), located where Broad Run and Cannon Branch converge just east of the Manassas Regional Airport, was created by PTG in 2000 under a Virginia Department of Transportation (VDOT) permit (Manassas 2009). MW consists of almost 40 acres 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 (Figure 1).

A total of 22 study plots (100 m^2), representative of site soil, hydrology, and vegetation, were selected for sampling across the four sites, including eight at Loudoun County (LC), five at Bull Run (BR), four at Manassas (MW), and five at North Fork (NF).

2.2 Field work

2.2.1 Vegetation survey and biomass sampling

Vegetation and soil sampling occurred in August and September 2009 including vegetative species identification, total percent cover, peak above- and below-ground biomass (i.e., AGB and BGB), and soil. A nested quadrat approach was used to collect four samples per plot for a total of 88 matched (i.e., collected within the same square meter) samples per attribute. A square meter quadrat was used for vegetation identification and cover samples, 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. Sampling locations were chosen by dividing plots into quadrants, then sub-quadrants were randomly selected within each quadrant, and the square meter quadrat randomly placed within the sub-quadrants.

Vegetation was identified to the species level and 10-level cover classes (Peet 1998) were used to estimate species percent cover based on a 100-cell string grid (i.e., 10 x 10 cm cells) embedded in the square meter quadrat. Herbarium specimens were created 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 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 grocery size 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.

2.2.2 *Hydrologic monitoring and soil sampling*

Precipitation data was 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 was 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. Field-wet mass was measured, samples dried at 105^{o} C for 48 hours, then gravimetric soil moisture calculated [(wet mass – dry mass)/ (dry mass) x 100] (Sparks 1996).

2.3 *Lab work*

2.3.1 *Above- and below-ground biomass*

AGB samples were dried at 48^{o} C (drying cabinet maximum temperature) until a constant mass was reached (< 5 gram difference). Thirteen samples from BR were weighed immediately after harvesting using a field scale (10 gram 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.

2.3.2 Soil physicochemical properties

Structural soil physicochemical 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) (Sparks 1996). SOM (%) was measured using weight loss on ignition method (Sparks 1996). Total C and N was determined by dry combustion of oven-dried, ground sub-samples from each core on a 2400 Series II CHN/O elemental analyzer (Perkin-Elmer, Waltham, Massachusetts).

2.4 *Data analysis*

Several plant community attributes were calculated, including percent cover (i.e., 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 Peets (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: 5-95%, 10:>95%) assigned to each species within the sample. Seeded, volunteer, and non-native percent cover values were calculated as a relative percentage of the total. H′ is a function of species richness (S) and distribution 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). Vegetative species IV was calculated for each species at each of the four sites to determine which five species had the largest influence on vegetative variables. IV is the sum of relative cover (RC), which was determined as the mean relative cover across all samples collected at each site, and mean relative frequency (RF), which is the percentage of total samples containing a given species *i*: $IV_i = RC_i + RF_i$ (Atkinson and Cairn 2005).

FQAI is a measure of natural character that is a function of the Coefficient of Conservation (C_n) for each species and the total number of native species present in a given sample or set of samples (Cronk and Fennessy 2001, Davis and Harold 2006). 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 (Cronk and Fennessy 2001). 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, EPA 2002a).

PI is a function of species wetland indicator status (WIS) (e.g., obligate, facultative wet, etc.) and proportional percent cover (Cronk and Fennessy 2001). WIS values range from one to five (1-5) 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).

Variable data sets were assessed for outliers, normality, and linearity. A combination of modifying outliers to mean plot values and the following data set 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 aid in selection of input variables for multi-regression. Euclidean clustering with average linkage was used on standardized soil attributes (i.e., plot means) to determine soil condition (SC) groups (i.e., plot combinations across sites with similar soil characteristics) (Zuur et al. 2007). Discriminant Analysis (DA) was conducted to test the accuracy of SC grouping using sample level data (Mertler and Vannatta 2010). Significant differences in vegetation and soil variables 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 sample sizes for site and soil condition groups were not equal, Tamehane T2 post-hoc evaluation was used to assess pairwise differences (SPSS 2010). Productivity (i.e., peak AGB) predictions were analyzed using least squares linear multi-regression with initial input variables including vegetative indices (i.e., S, H, FQAI, PI), percent cover, and soil properties. Predictor variables were limited to five to achieve a parsimonious solution, improve reliability (i.e., $n/k > 15/1$ where n=sample and k=predictor variables), and minimize the correlation ($r<0.3$) between predictors (Mertler and Vannatta 2010). All statistical analysis was done using IBM SPSS Statistics v19.0 (SPSS 2011).

CHAPTER 3: RESULTS

3.1 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 (Federal Interagency Committee for Wetland Delineation 1989, Norfolk 2004). Precipitation levels for 2009 were 17 centimeters above normal during the growing season (i.e. April through November) (National Weather Service 2010). During April through June 2009, 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 2009, NF was the only site that maintained water levels above -30 centimeters. Water levels (Mean ± SE) were not significantly different ($F_{3,75}$ = 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). Standing water days, where the water level was above the sediment surface, were also not significantly different ($F_{3,10}$ = 2.09, p=0.165) between sites (LC 113.0±7.2; BR 87.5±22.5; MW 117.5±13.2; NF 63.3±31.9). Overall, all study sites were under a similar hydrologic regime based on measurement of well water levels and standing water days.

3.2 Vegetation attributes

A total of 41 species were found in samples across the four sites, with no age-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). Seeding with a wetland mix had a continuing impact, accounting for close to 25% of the species found at each site. Hydrophytic vegetation that occurs at least 50% of the time in wetlands (i.e., facultative or wetter) represented 85% of the total species. Five species were dryer than facultative (FAC) 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*. Three of the sites (i.e. LC, MW, and NF) had plots that were monotypic for *Juncus effusus, Typha augustifolia,* or *Bidens aristosa* (Table 1).

Site percent cover ranged from a 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 2). Site indices ranged from 3.6 to 5.6 for S, 0.035 to 0.055 for H´, 5.9 to 7.4 for FQAI, and 1.2 to 1.8 for PI (Table 2). There were no

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

Scientific Name	Common name	Wetland[2] Indicator Status	Coefficient[2] of Conservatism	LC (3 years)	BR (7 years)	MW (9 years)	NF (10 years)
Alisma subcordatum Raf.	American water plantain	OBL	6	X	X	X	
Ambrosia trifada L.	Giant ragweed	FAC	3				X
Arthraxon hispidus Thunb.*	Small carpgrass	NI	0		X	X	X
Bidens aristosa Michx.	Bearded beggarticks	FACW	2	X[3]			X[4]
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	X	X		X
Carex tribuloides Wahlenb.	Blunt-broom sedge	FACW	3	X		X	X
Carex vulpinoidea Michx.	Fox sedge	OBL	3	X		X	X
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	X[4]	X	X[4]	X
Juncus tenuis Willd.	Poverty rush	FAC-	2	**X**	X	X	X
Leersia oryzoides L.	Rice cutgrass	OBL	4	X	X		X
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			X	
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	X		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		X		X
Scirpus cyperinus L.	Woolgrass	FACW+	3	X	X	X	X
Solidago rugosa Mill.	Wrinkled goldenrod	FAC	3				X
Symphyotrichum ericoides L.	White heath aster	FACU	1		X	X	
Typha augustifolia L.	Narrowleaf cattail	OBL	3		X	X	
Verbena hastata L.	Swamp verbena	FACW+	4		X		X
		Richness (S)		*19*	*22*	*20*	*27*

Notes: [1] *, 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.

[2] Wetland indicator status and coefficient of conservatism taken from the 2005 Virginia Wetland Plants C-Value List prepared by the Virginia FQAI Advisory Committee for the Virginia Department of Environmental Quality.

[3] Underline indicates species seeded at wetland creation.

[4] Monotypic in at least one study plot

significant 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 1970 $g \cdot m^{-2}$ and BGB ranged from 170 to 290 $g \cdot m^{-2}$ (Table 2). There were no significant differences between sites for BGB (p=0.871).

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

Vegetation[1]	LC (3 years)	BR (7 years)	MW (9 years)	NF (10 years)	$F_{3,84}$	p
Total cover, %[2]	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, %[3]	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[1]						
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

Notes: [1]ANOVA used to assess significant differences between sites at α=0.05, Tamehane T2 post-hoc.
[2] Due to multiple herbaceous canopy layers, the total cover estimates could exceed 100%.
[3] Non-native cover based on coefficient of conservatism=0, non-normal distribution (Kruskal-Wallace).
[4] * p<0.05, ** p<0.001
[5] 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)

NF, the oldest site, had the lowest AGB (p<0.001) and the highest PI (p<0.05) of the four sites (Table 2).

3.3 SC attributes

Soil moisture and nutrient attributes ranged from 24 to 32% for GSM, 3.9 to 6.7% for SOM, 1.5 to 2.3% for TOC, 0.14 to 0.20% for TN, and 10.4 to 11.7 for C:N (Table 2). 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 $g \cdot cm^{-3}$ (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).

3.4 SC groups across wetland sites

Ease of measurement was the primary consideration in selection of soil attributes used to determine soil condition (SC) groups. Four SC groups resulted from cluster analysis (60% dissimilarity applied) of SOM, pH, D_b, and GSM across the wetland sites (Table 3). Based on the four SC groups, Discriminant Analysis (DA) produced continuous discriminant function variables (i.e., F1 and F2) that were a linear combination of SC variables. The first two DA functions explained 99.5% of the variability in GSM, D_b, pH, and SOM (F1 70.0%: F2 29.5%). Based on standardized canonical discriminant function coefficients, function 1 was driven most positively by

SOM (F1 0.698: F2 -0.234) and pH (F1 0.974: F2 -0.175), and function 2 was affected most positively by GSM (F1 0.276: F2 0.799) and D_b (F1 0.049: F2 0.602). Samples from the original dataset (n=88) were correctly classified in 96.6% of the cases and 95.5% of the time during cross-validation, confirming the statistical validity of SC group classification.

Soil condition groups 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 (Table 3). 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).

3.5 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 two that were different previously 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

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

	SC1 (n=2 plots)	SC2 (n=12 plots)	SC3 (n=3 plots)	SC4 (n=5 plots)		
LC (3 years; 8 plots)		5 plots		3 plots		
BR (7 years; 5 plots)	1 plot	3 plots		1 plot		
MW (9 years; 4 plots)			3 plots	1 plot		
NF (10 years; 5 plots)	1 plot	4 plots				
					$F_{3,84}$ [1]	p [2]
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, % [3]	16±7a	16±3a	1±6b	8±5ab	11.745(t)	*
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

Notes: [1] ANOVA used to assess significant differences between soil condition groups at α=0.05, Tamehane T2 post-hoc.
[2] * p<0.05, ** p<0.001
[3] Kruskal-Wallace non-parametric test used to assess significant differences for non-native cover at α=0.05

higher in SC4 with both not significantly different from SC2 and SC3 (Table 3). AGB (1100-2290 $g \cdot m^{-2}$, p<0.001) was significantly higher in SC3 and SC4 groups, while BGB (130-360 $g \cdot m^{-2}$, p=0.064) differences were not significant (Table 3). Soil differences increased from four to seven by SC (p<0.001).

3.6 *Correlation between soil and vegetation attributes*

Seeded and volunteer percent cover were correlated ($p<0.01$) with all other vegetation attributes, except PI and BGB (Table 4). Seeded cover was associated with reduced FQAI and S, and volunteer cover with improved FQAI and S (Table 4). PI was negatively correlated with FQAI ($p<0.01$) and total cover ($p<0.05$) (Table 4). AGB was negatively correlated ($p<0.01$) with all vegetation indices. BGB was not correlated with any vegetation attribute (Table 4). AGB was negatively correlated with SOM and pH

Table 4**.** Pearson bi-variate correlation coefficient matrix for vegetation and soil attributes.

	Total	Seeded	Volunteer	NonNative	S	H´	FQAI	PI	AGB	BGB	GSM	SOM	TOC	TN	C:N	pH
Vegetative																
Total Cover, %																
Seeded Cover %	-0.210															
Volunteer Cover %	0.210	**-1.000**														
NonNative 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																
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

Note: 2-tailed, **Bolded** $p<0.01$, Underlined $p<0.05$

($p<0.01$), and BGB was negatively correlated with TOC and C:N (Table 4). PI was negatively correlated with soil nutrient attributes in addition to D_b ($p<0.01$) (Table 4).

Higher pH was correlated with greater total and volunteer percent cover, S, and H′, in addition to lower AGB (Table 4). Soil attributes were highly correlated with each other ($p<0.01$).

3.7 Plant productivity and its relationship with soil and vegetation attributes

Productivity (i.e. peak AGB) prediction using explanatory attributes of only vegetation, only soil, and combinations of vegetation and soil were assessed. Vegetation attributes were selected based on AGB prediction significance ($p<0.05$), while soil attributes were based on those used for SC groups. S, FQAI, and H′ were significantly correlated ($r>0.3$) with each other, so only one of these attributes in combination with PI was used per model (Table 4). SOM, GSM, and D_b were highly correlated ($r>0.3$) with each other, so only one of these attributes in combination with pH was used per model (Table 4). Predictive models that used only vegetation indices (AGB = 0.52 H′ + 0.31 PI, $F_{3,84}$=19.60, $p<0.001$, R^2=0.32) explained under 32% of the variation in AGB, while those that used only SC attributes (AGB = -0.23 SOM - 0.35 pH, $F_{3,84}$=11.80, $p<0.001$, R^2=0.22) explained under 22% of the AGB variation (Table 5). Vegetation and soil attribute alone models were highly significant ($p<0.001$, Table 5). Significant improvement was seen in explaining the variability in AGB (AGB = 0.41 H′ + 0.37 PI - 0.28 SOM - 0.24 pH, $F_{4,83}$=18.27, $p<0.001$, R^2=0.47), when both vegetation and soil condition attributes with the most powerful model including H′ and PI vegetation attributes, and SOM and pH soil attributes (Table 5).

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

R^2	S	FQAI	H´	PI	SOM	D_b	GSM	pH	F	p
Vegetation										
0.26	-0.42			0.29					14.60	**
0.25		-0.44		0.42					14.47	**
0.32			0.52	0.31					19.60	**
Soil										
0.22					-0.23			-0.35	11.80	**
0.17						-0.03		-0.41	8.71	**
0.21							-0.21	-0.48	11.22	**
Combined										
0.47			0.41	0.37	-0.28			-0.24	18.27	**

Notes: [1]NS-not significant, * p<0.05, ** p<0.001
[2]Regression on transformed variables per methods description

CHAPTER 4: DISCUSSION

4.1 Development of structural and functional attributes of vegetation and soils in created wetlands

To meet mitigation wetland hydrologic requirements in Virginia, a free water table must be continuously maintained above 30 centimeters below the sediment surface for at least 12.5% of the growing season (i.e., about 27 days) (Federal Interagency Committee for Wetland Delineation 1989, Norfolk 2004). During the 2009 growing season, mean water levels for wells closest to or within the study plots were well above minimum requirements at all four of the wetlands. Total and hydrophytic percent cover (i.e., herbaceous and scrub-shrub vegetation cover) must be greater than 80% and 50%, respectively, in Virginia (Federal Interagency Committee for Wetland Delineation 1989, Norfolk 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 (Norfolk 2004). The study wetlands were solidly in the obligate or facultative wet range, thus supporting wetland vegetation successfully (Table 2). Many previous studies have found that created freshwater wetlands achieve vegetative targets within the first decade (Balcombe and others 2005, Ravit and others. 2006, Spieles 2005). 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 2004).

Age of created wetlands has often been identified as an important factor for vegetation development (Atkinson and others 2005, Matthews and all 2010, Spieles 2005). Comparison of species with the five highest IVs (i.e., largest abundance and frequency at each site) provided possible clues behind the lack of significant vegetation differences between sites (Table 6). Several dominant species with low coefficients of conservatism (i.e., $C_n \leq 4$) were shared among sites (i.e., *J. effusus*, *Polygonum hydropiper*, *Scirpus cyperinus*, and *A. 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). MW had a broad area that was monotypic for T. *augustifolia*, which was captured in one plot (IV 54, 49% plot cover) (Table 6). In addition, the three WSSI 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). Shared species with high IVs in addition to low quality, combined to enhance equivalence between sites.

J. 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,* or common soft rush, is a hardy perennial classified as facultative wet plus (FACW+) in region 1. It can thrive in acidic soils under high pollution loads and extended standing water conditions (NRCS Plant Fact Sheet 2002, Magee and Kentula 2005). Even though *J. effusus* is native to Virginia, and can be beneficial as a wildlife habitat and for erosion control, it can also become invasive under the right conditions (NRCS Plant Fact Sheet 2002). In a two year study of the LC site, *J. effusus* expanded its coverage almost 40% in the lower elevation cell (Ahn and Dee 2011). Standing water conditions approaching 10 cm were maintained for the first four months of the growing season in both years, providing conditions that allowed J. effusus to out-compete other species (Ahn and Dee 2011). Thus, the intentional seeding element of wetland creation may contribute in unintended ways to limit vegetation development.

The invasive species, *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). The high IV of *M. keisak* increased non-native percent cover and contributed to reductions in S, H´, and FQAI (Tables 2 and 6). The introduction of *M. keisak* was likely associated with relatively high connectivity to the adjacent Bull Run stream. *M. keisak* is an annual herb 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). 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 (Brandt and Seabloom 2011, Davis and others 2011, Dunn and Sharitz 1990).

S and FQAI are usually determined based on species found in all samples collected across sites, which simplifies data collection and calculation (U.S. EPA 2002a). Objectives for our study required statistical assessment of significant differences and relationships between attributes in addition to identification of within-site developmental problem areas, which required use of matched sample level data. When whole site S

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

LC[2]						BR					
Species	WIS[1]	C_n	RC[3]	RF[3]	IV[3]	Species	WIS	C_n	RC	RF	IV
CARFRA	1	4	28	46	74	MURKEI	1	0	22	85	107
JUNEFF	1.5	3	30	43	73	JUNEFF	1.5	3	29	65	94
ECHCRU	4	0	13	50	63	SCICYP	1.5	3	11	60	71
BIDCER	1	4	17	33	50	POLHYD	1	4	21	50	71
POLHYD	1	4	9	25	34	ARTHIS	5	0	4	25	29
Mean C_n		**3**				Mean C_n		**2**			
MW						**NF**					
Species	WIS	C_n	RC	RF	IV	Species	WIS	C_n	RC	RF	IV
JUNEFF	1.5	3	38	69	107	JUNEFF	1.5	3	17	55	72
TYPAUG	1	3	17	37	54	LUDPAL	1	2	8	50	58
POLHYD	1	4	8	44	52	CARVUL	1	3	8	35	43
SCICYP	1.5	3	16	31	47	POLHYD	1	4	5	35	40
ALISUB	1	6	5	37	42	ARTHIS	5	0	10	30	40
Mean C_n		**3.8**				Mean C_n		**2.4**			

Notes: [1]Indicator Status1-Obligate, 2- Facultative Wet, 3- Facultative, 4- Facultative Upland, 5-Upland
[2]Based on site samples: LC (n=32), BR (n=20), MW (n=12), NF (n=20)
[3]RC-relative mean species cover, RF-relative mean species frequency, IV= RC+RF

(Table 1) and FQAI [LC 13.3, BR 15.9, MW 13.6, NF 18.8] were determined, both increased with age for the sites constructed by WSSI (e.g., statistical significance of differences can not be determined). Whole site S was comparable to that found in created wetlands in Virginia (S 19-21, Atkinson and others 2005) and West Virginia (S 13, Balcombe and others 2005). Atkinson and others (2005) also calculated sample (i.e., square meter) level S [3.9-4.6], which fell in a range equivalent to this study. Lopez and Fennessy (2002) established a significant correlation between disturbance ranking associated with adjacent land use (e.g., forested, agricultural, urban) and FQAI for depressional wetlands in Ohio ($r= -0.695$, $p<0.01$). Whole site FQAI was similar to that found in emergent and scrub-shrub wetlands that were highly disturbed (Lopez and Fennessy, 2002).

Diversity can be higher immediately after disturbance, such as construction, then stabilize to a lower level once the site has reached nominal climactic and hydrologic conditions (Nedland and others 2007, Odum 1969). Atkinson and others (2005) noted that 20-year old depressional wetlands had reached equilibrium defined by a transition from annual to predominantly perennial species, but there was little evidence to support succession to scrub-shrub wetlands. Odum (1969) characterized ecosystem stability as a state of maturity that supports inherent buffers to disturbance. Ahn and Dee (2011) found that S, H′, and FQAI all decreased significantly at the LC study site in the third year since creation, showing an early sign of plant community stabilization in response to nominal hydrology. Study H' was in the same range as created and reference sites in Virginia (e.g., included three main pod NF plots) (0.3-0.7, Moser and others 2007) but, slightly lower than natural and 4-20 year old created sites in West Virginia (0.6-0.8, Balcombe and others 2005). These young wetlands are populated by a mix of annual and perennial species, which indicates that they have not reached a truly stable state (Atkinson and others 2005). The dominance of *J. effusus* and preponderance of low quality vegetation contributed are causing decreased S, H′, and FQAI. The findings of this study reinforce those of several others that did not see a progressive linear trajectory toward a target asymptote in the first decade (Brown and Venemen 2001; Campbell and others 2002; Matthews and others 2009).

Unlike vegetative attributes, comparison of soil attributes illustrated several significant differences ($p<0.001$), with most between only two sites versus strictly following an age related trajectory (Table 2). The oldest site, NF, was an exception with the highest SOM, a key indicator of maturation in wetland soil development (Table 2). NF was the only site above -30 centimeters the entire growing season, which may have had an association with its higher GSM and SOM (Table 2). NF nutrient levels appear to have improved significantly since 2005 when TOC was 1.3% (2009 2.1±0.2%) and TN was 0.12% (2009 0.19±0.01%) (Moser and others 2008). SOM and D_b for all four sites were comparable to created wetlands under 20 years old in Pennsylvania (SOM 2.3-6.5%, Cole and others 2001), North Carolina (SOM 0.6-4.03, D_b 0.99-1.64 $g \cdot cm^{-3}$, Bruland and Richardson 2005), and New York (SOM 6.2%, Db 1.1 $g \cdot cm^{-3}$, Ballantine and Schneider 2009). Natural wetland soil characteristics for SOM were almost an order of magnitude larger, and D_b was about half what was seen at created sites in these same studies (Ballantine and Schneider 2010, Bruland and Richardson 2005, Cole and others 2001). As noted by Ballantine and Schneider (2010), several decades may be necessary for soil characteristics comparable to natural wetlands to develop in created sites. Overall, the relatively young sites in this study are effectively the same age from the perspective of their soil development.

4.2 Influences of soil condition attributes in vegetation development in created mitigation wetlands

S, H′, and FQAI all differed significantly ($p<0.05$) between plots (i.e., mosaic differences) within each site (Figure 2). Monotypic areas within each wetland had an impact on within site differences including *J. effusus* in MW and LC and *B. aristosa* in NF (Figure 2). Soil physical, biogeochemical, and microbial attributes all serve to support both positive and negative feedback in the establishment and development of wetland vegetation (Ehrenfeld and others 2005). Based on plant-soil feedback relationships and significant within site soil attribute differences ($p<0.001$), soil condition (SC) was assessed for its effect on vegetation development.

SC attribute selection (i.e., GSM, pH, SOM and D_b) was based on ease of measurement, in addition to high correlation with vegetation attributes (Table 4). SC attributes are interdependent with higher SOM displacing compacted soil and reducing D_b, in addition to providing an adsorptive substrate for water retention and thus increased GSM (Ballantine and Schneider 2009, Bruland and Richardson 2004, Ehrenfeld and others 2005, Reddy and DeLaune 2008). 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

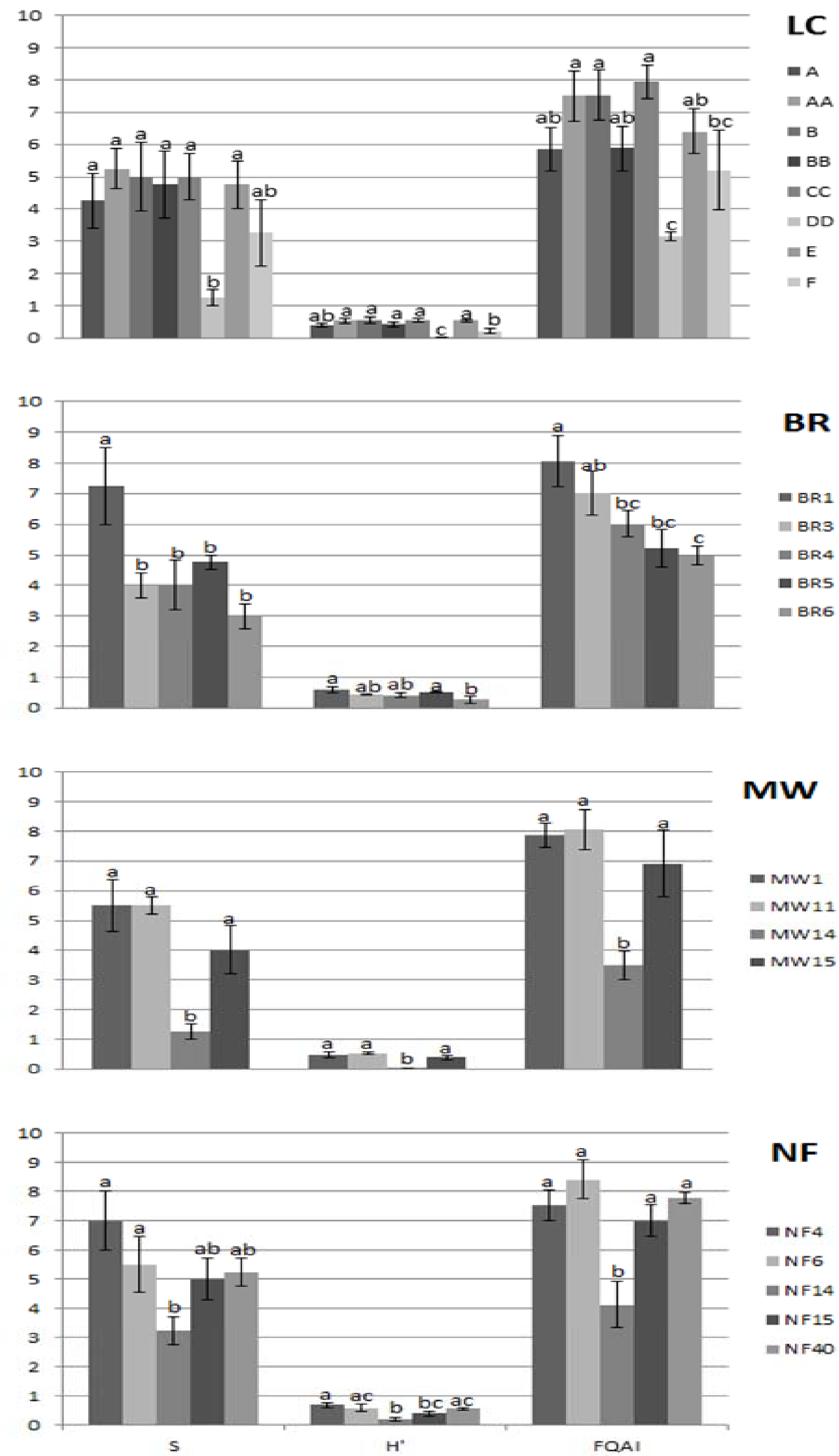

Figure 2: Within site vegetative index comparison illustrating heterogeneity between plots.

FQAI, and total and volunteer percent cover, and lower AGB, PI, and seeded percent cover (Table 3). Higher seeded percent cover was associated with reduced FQAI and S, and higher volunteer percent cover with improved FQAI and S (Table 4). A higher abundance of hydrophytic vegetation was related to increased total cover, improved FQAI, higher levels of soil nutrients (Table 4). SC groups can be viewed as a measure of developmental variation within a given created wetland, with some areas lagging others.

Autochthonous and allochthonous soil nutrients are made available to wetland plants from decomposing biomass, anthropogenic input such as fertilization run-off from residences and agricultural fields, bank overflow from adjacent streams, and atmospheric deposition (Bayley and Guimmond 2010, 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). Bayley and Guimmond (2009) found that both soil nutrient levels and above-ground biomass levels were significantly higher in wetlands connected directly to the Athabasca River in western Canada compared to those that had been impounded due to beavers and railroad construction.

Periodic nutrient replenishment from bank overflow was evident in three areas associated with different SC groups in three of the study wetlands, MW, NF, and BR. Even though MW (9 years) was almost the same age as the oldest site, NF (10 years), it rarely had comparable soil characteristics, but tended to be more like the two younger sites, only breaking out from all the WSSI sites with the lowest pH (Table 2). MW was the most disturbed of the four sites, with hydrology often dominated by storm drain run-off from an 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 (2120 ± 170 $g \cdot m^{-2}$), which should have supported SOM accumulation, but lower pH (4.3±0.01) and SOM (4.2 ± 0.3%) coupled with higher Db (1.22±0.04 $g \cdot cm^{-3}$), indicated that decomposition versus accumulation processes were dominating (Table 3). Overall, AGB was negatively correlated with SOM, so higher AGB did not 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. A BR and NF plot were in the more developed SC1 group. 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. The SC1 group plots are good examples of connected areas within NF and BR that have been positively influenced by external nutrient inputs, which have contributed to 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 $g \cdot cm^{-3}$).

Many studies have found that microtopography has a positive impact on the development of created wetland soils (Moser and others 2008), plant community diversity (Lawrence and Zedler 2011, Moser and others 2007), hydrology (Courtwright and Findlay 2010), nitrogen cycling (Wolf and others 2011a), and microbial community diversity (Ahn and Peralta 2009). Microtopography (i.e., hummocks and hollows) can be induced by disking at mitigation wetland creation then develops further through the maturation of tussock forming plants (Lawrence and Zedler 2011, Moser and others 2008). After only a few growing seasons, the direct effects of disking induced microtopography in created wetlands can wane, but autogenic development can quickly support similar healthy variation in sedimentation, nutrient cycling, and water flow (Ahn and Dee 2011, Lawrence and Zedler 2011, Moser and others 2007, Wolf and others 2011a). In addition to disking at creation, the study sites were host to a number of tussock forming wetland rushes (e.g., *J. effusus*) and sedges (e.g., *Carex* and *Scirpus spp.*) that likely contributed to SC group determination.

The finding that SC, based on easily measured soil attributes, 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. In this case, the areas where plots fell into SC3 and SC4 groups also contained the monotypic *J. effusus* plots, which without further design intervention have the potential to expand in coverage and degrade diverse plant community development.

4.3 Relationship between wetland productivity (i.e., peak above-ground biomass) and structural vegetation and soil attributes

Primary productivity is the lowest trophic level factory function in ecosystems, and is a measure of energy transferred and fixed by autotrophs in the form of carbon (Smith and Smith 2006). Net primary productivity is a control on heterotrophs (i.e., detritivores and herbivores) which utilize its energy for growth and maintenance, eventually making nutrients available to primary producers for their own growth and maintenance (EPA 2002b, Smith and Smith 2006, Reddy and DeLaune 2008). The allocation of carbon to above- and below-ground plant structures is dictated by local conditions including temperature, light, nutrients, and moisture, but in general, more carbon will be allocated to stems and leaves in response to higher moisture and nutrient levels (Smith and Smith 2006). Measures of net primary productivity are central to determination of many other important functions like nutrient use and resorption efficiency, nutrient availability, and carbon sequestration (EPA 2002b). Wetlands play a considerable role in shaping global carbon budgets due to their enhanced ability (i.e., due to anaerobic soil conditions) to sequester carbon (Reddy and DeLaune 2008). Soil organic carbon (SOC) represents about 50% of accumulated SOM, most of which is provided by in-situ litter (Mitsch and Gosselink 2007). Even though wetlands account for 6% of total terrestrial surface, it is estimated that they account for over 20% of stored terrestrial carbon (Reddy and Delaune 2008).

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). Younger ecosystems are usually typified by higher production, growth, and quantity, while mature systems are oriented toward processes that lead to stability and quality (Odum 1969). Wetlands often fall somewhere between youth and maturity due to periodic disturbance caused by pulsed flooding (Odum 1969). Peak AGB was significantly lower in the oldest created site, with increased AGB strongly negatively correlated with S, H′ and FQAI (Table 4). Lower diversity coupled with the dominance of the highly productive *J. effusus* was a strong gauge of increased AGB in this study. Findings were consistent with those of Olde Venterink and others (2003), who noted reduced above-ground biomass as richness increased also considering biomass nitrogen and phosphorus levels.

Measuring biomass through peak biomass methods typically underestimates net primary productivity (NPP) because it omits early growing season senesced plants and roots, in addition to excluding post-harvest growth (Cronk and Fennessy 2001). Site AGB was comparable to depressional freshwater wetlands in Southwestern Virginia (900-1200 $g \cdot m^{-2}$), Pennsylvania (520-1700 $g \cdot m^{-2}$), and Ohio (250–1500 $g \cdot m^{-2}$) (Atkinson and others 2010, Cole and others 2001, Lopez and Fennessy 2002). Site BGB was comparable to obligate wetlands in Southwestern Virginia (370 ± 100 $g \cdot m^{-2}$), but much lower than sites in Pennsylvania (1500-5000 $g \cdot m^{-2}$) and Ohio (≈ 1000 $g \cdot m^{-2}$) (Atkinson and others 2010, Cole and others 2001, Hernandez and others 2003). BGB can account for over 50% of net primary production in wetlands, but is even more of a challenge to measure than AGB due to sampling bias, root senescence over the growing season, inability to estimate peak growth, and variation in sampling depth (EPA 2002b, Gill and others 2002). Gill and others (2002) developed a total below-ground net primary productivity estimation technique that incorporated root turnover rate, mean annual temperature, and peak AGB, which may have application to wetlands.

This study assessed whether a vegetative function, productivity (i.e., peak AGB), could be predicted from vegetation (e.g., currently collected under mandated monitoring programs) soil (e.g., easily measured) physicochemical attributes. The combination of vegetation and SC attributes improved the predictive power of the model over soil or vegetation alone, increasing explained variability between 16 and 32% (Table 5). The best AGB predictions (R^2 =0.48) resulted from a model that used H´, PI, SOM, and pH. Explained variability could be improved through incorporation of other attributes known to have significant effects on productivity such as soil phosphorus, iron, and calcium (Uno and others 2001).

A similar approach could be used to predict other wetland functions, thus promoting a better understanding of created wetland developmental status. Prediction of selected wetland functions using existing vegetation monitoring measures coupled with the addition of SC measures will allow better tailoring of compensatory mitigation and modification of initial creation conditions. 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 disturbance tolerant species.

CHAPTER 5: CONCLUSIONS

Each site experienced varying environmental conditions including design elevation differences, induced and autogenic microtopography, water flow patterns, and flooding frequency that played roles in shaping soil and vegetation developmental states. Soil condition was a better indicator of ecosystem development or maturity *per se* across the study wetlands, with vegetation development following that of soil in a spatially heterogeneous manner within each site. The outcomes of the study suggest that the inclusion of soil attributes can significantly enhance understanding and prediction of plant community development for created mitigation wetlands. Therefore, the mandated inclusion of soil attributes in legal mitigation wetland monitoring programs is recommended to facilitate acceleration of soil property development and establishment of diverse plant communities, thus increasing the chance of success for 'functional mitigation'. Information garnered from this study will benefit state agencies like Department of Transportation, Department of Natural Resources or Environmental Quality, and other groups involved with wetland creation and restoration.

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