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Plant tissue nutrients as a descriptor of plant productivity of created mitigation wetlands

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ABSTRACT

The study investigated vegetative nutrient levels and ratios, net primary productivity, and soil physicochemical conditions in four created mitigation wetlands, ranging in age from 3 to 10 years, all created in the Virginia Piedmont. Plant tissue nutrients from peak above-ground biomass samples included macronutrients (i.e., C, N, P, K, Ca, Mg, S) and micronutrients (i.e., Mn, Fe, Cu, B, Zn, Al). Ratios of major elements were calculated including C:N, N:P, K:P, and N:K. Four soil condition (SC) groups were developed based on soil organic matter (SOM), gravimetric soil moisture (GSM), pH, and bulk density (D_b), where study plots were grouped across the wetland sites based on common attribute levels (i.e., SC1 > SC2 > SC3 > SC4, trended more to less successionally developed). There was a lack of wetland site based differences in plant tissue macronutrient (i.e., N, P, K, and S) levels and ratios (i.e., C:N, N:P, N:K, K:P), but differences were seen for all micronutrients ($P < 0.005$). When plant tissue macronutrient levels were compared between SC groups, greater SOM, lower D_b, more circumneutral pH, and higher GSM, all indicative of wetland soil maturation, were associated with higher tissue macronutrient levels for C, N, K, Ca, and Mg ($P < 0.005$), and higher micronutrient levels for Fe, Cu, B, and Al ($P < 0.005$) in plant tissues. A significant predictive relationship was found between plant productivity (i.e., peak AGB) and plant tissue boron and aluminum (i.e., $AGB = -0.54B + 0.2Al - 0.38$, $F_{4,83} = 24.7$, $P < 0.001$, $R^2 = 0.47$). The results of this study show that plant tissue concentrations of macro- and micronutrients are associated with the physicochemical maturity of soils and can be used to estimate functional development (e.g., plant biomass production) in created mitigation wetlands.

1. Introduction

Wetland vegetation diversity and productivity are principally determined by hydrology, soil physicochemistry, and light regime (Ballantine and Schneider, 2009; Boutin and Keddy, 1993; Dee and Ahn, 2012; Ehrenfeld et al., 2005; Olde Venterink et al., 2003). Soil attributes including bulk density, porosity, organic matter, pH, texture, and moisture content affect chemical and microbial decomposition processes, which are the principle means by which nutrients essential to the development of wetland vegetation are made available (Angeloni et al., 2006; Cronk and Fennessy, 2001; Ehrenfeld et al., 2005; Yu and Ehrenfeld, 2010). Decomposition of organic matter replenishes bioavailable nutrients that are often lacking in created wetlands compared to their natural counterparts (Bayley and Guimond, 2009; Dee and Ahn, 2012; Hogan and Walbridge, 2007; Wolf et al., 2011). Created and restored wetlands are born from construction practices that cause high bulk densities and reduced porosities, which leads to multi-decadal soil development timelines (Ballantine and Schneider, 2009). Created wetland maturation is often a spatially heterogeneous process with variation across a site affected by topographical and hydrologic design features (Ahn and Dee, 2011; Bruland and Richardson, 2005; Dee and Ahn, 2012; Moser et al., 2009). Extended and highly variable soil development in created wetlands limits early development of diverse plant communities (Hossler and Bouchard, 2010; Hossler et al., 2011; Matthews et al., 2009; Dee and Ahn, 2012), thus delaying realization of functionality equivalent to that of natural wetlands.

A dearth of plant available nutrients in created wetlands, when compared to natural wetlands, can result in the lack of sufficient nutrient cycling functionality for carbon, nitrogen, and phosphorus (Fennessy et al., 2008; Hossler et al., 2011; Wolf et al., 2011). Wetland plants have evolved unique adaptations to address low oxygen, decomposition-limiting conditions in the root zone (i.e., saturated or inundated soils), including symbiotic or mutualistic relationships with nitrogen-fixing bacteria and

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fungal mycorrhiza, solubilizing phosphate root exudates, and oxygenated rhizospheres, in addition to root depth, density, and size adaptations (Angeloni et al., 2006; Cronk and Fennessy, 2001; Deng et al., 2009; Snowden and Wheeler, 1995; Verhoeven et al., 1996). More diverse wetlands tend to be lower in productivity (i.e., above ground biomass levels < 400 g m^{-2}), which has been linked to interspecific competition for low levels of plant available nutrients leading to populations of species with special adaptations to deal with specific limitations (Bedford et al., 1999; Svengsouk and Mitsch, 2000; Verhoeven et al., 1996). Highly productive herbaceous wetlands (i.e., above ground biomass > 1000 g m^{-2}) tend to be monotypic, in most case consisting of interstitial reed and clonal species, which has been attributed more to light limitation and to a lesser degree elevated nutrient levels (Angeloni et al., 2006; Bedford et al., 1999; Farrar and Goldberg, 2009; Verhoeven et al., 1996; Olde Venterink et al., 2003).

Macronutrients (i.e., carbon, nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur) are responsible for plant development and growth through control of enzyme activation for the synthesis of proteins, nucleotides, and chlorophyll (Cronk and Fennessy, 2001; Uno et al., 2001). Plant tissues macronutrient ratios (i.e., N:P, N:K, and K:P) below critical levels are symptomatic of nutrient limitation or co-limitation, which can affect wetland productivity and richness-productivity patterns (Bedford et al., 1999; Koerselman and Meuleman, 1996; Olde Venterink et al., 2003; Verhoeven et al.,1996). Critical N:P ratios in wetland vegetation and soils have been extensively studied by Koerselman and Meuleman (1996) with ratios below about 14 indicative of nitrogen limitation, ratios above 16 indicative of phosphorus limitation, and ratios between 14 and 16 being N and P co-limited. Olde Venterink et al. (2003) further refined critical nutrient ratios based on European wetland and grassland fertilization studies to include potassium (i.e., N:K and K:P) as a factor in determination of N, P, or K limitation or co-limitation.

Micronutrients (i.e., manganese, zinc, copper, iron, and boron) are only needed by plants in trace amounts (i.e., 0.01% or less) with zinc and boron instrumental in pollen and pollen tube formation, manganese in photosynthetic electron transfer, copper in plastid pigments and lignin, and iron in chlorophyll production (Cronk and Fennessy, 2001; Uno et al., 2001). Micronutrients, especially the reduced form of iron (Fe^{2+}) and manganese (Mn^{2+}), can be present at toxic levels in saturated wetland soils, but rhizospheric oxygenation and the ability to store excess micronutrients in vacuoles and senesced material allow wetland plants to adjust their metabolisms (Deng et al., 2009; Mitsch and Gosselink, 2007; Snowden and Wheeler, 1995). Rhizospheric oxygenation (radial oxygen loss – ROL) causes the formation of ferric oxide or ferric phosphate root precipitates, with monocots (i.e., rushes and sedges) being more tolerant to high iron concentrations than dicots (Snowden and Wheeler, 1995). Wetland monocots are often used in treatment wetlands for uptake of excess nutrients and phytoremediation of heavy metals including micronutrients, aluminum, lead, and cadmium (Aslam et al., 2007; Debing et al., 2009; Deng et al., 2009; Lai et al., 2011). Toxic levels of heavy metals has been shown to reduce overall levels of tissue macronutrients depending on tolerance as a function of the spatial pattern of ROL along the root, thus can negatively affect growth and development (Deng et al., 2009; Snowden and Wheeler, 1995).

This study investigated above ground plant tissue nutrient levels and soil conditions in four created mitigation wetlands in the northern Virginia piedmont. The wetlands ranged in age from 3 to 10 years. Vegetation tissue macro- and micro-nutrient levels were examined by both wetland site and soil condition (SC). Soil conditions developed in our previous work on vegetation community development were leveraged for this assessment (Dee and Ahn, 2012). The study focused on the following research questions:

(1) Do vegetation tissue macro- and micronutrient concentrations differ significantly by wetland site and soil condition?
(2) Do macronutrient ratios vary significantly by wetland site and soil condition?
(3) Can plant tissue nutrient levels be used as indicators of plant biomass in created wetlands?

2. Methods

2.1. Site descriptions

The study sites consisted of four created mitigation wetlands located in the northern Virginia Piedmont physiographic province that is part of the Potomac River watershed in either in Prince William or Loudoun counties. 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 (3 years old during study year) in Loudoun County, Virginia (39°1′ N, 77°36′ W). Bull Run Wetland Bank (BR, 38°51′13″ N, 77°32.6′59″ W) is a 20.2 ha wetland and upland buffer complex, constructed by WSSI in 2002 (7 years old during study year) in Prince William County, Virginia (38°51′ N, 77°32′ W). North Fork Wetlands Bank (NF) is a 50.6 ha wetland, constructed by WSSI in 1999 (10 years old during study year) in Prince William County, Virginia (38°49′ N, 77°40′ W). Manassas Wetland Compensation Site is a 16.2 ha wetland, located where Broad Run and Cannon Branch converge east of the Manassas Regional Airport (MW, 38°43.3′ N, 77°30.2′ E), that was created by Parsons Transportation Group (PTG) in 2000 under a Virginia Department of Transportation (VDOT) permit (HDR, 2009). More site details can be found in Dee and Ahn (2012).

2.2. Field work

A total of 22 study plots (10 m × 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 $n = 5$) (Ahn and Peralta, 2009; Ahn and Dee, 2011; Wolf et al., 2011). Sampling occurred in August and September 2009 including vegetative species identification, species percent cover, peak above-ground biomass (AGB), and soil. 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) using a square meter quadrat for vegetation identification and percent cover, a 0.25 m^2 quadrat for AGB and a beveled soil auger with a removable aluminum liner (diameter = 4.7 cm, length = 10 cm) for soil samples. Percent cover of AGB samples was 100% or greater and all live plants had normal healthy turgidity. Collection method details can be found in Dee and Ahn (2012).

2.3. Lab work

AGB samples were dried at 48 °C (drying cabinet maximum temperature) until a constant mass was reached (i.e., <5 g difference). Dried live (i.e., not standing litter) plant matter including leaves, blades, and stems was proportionally selected from each AGB sample (i.e., based on a visual estimate of species percent in dry biomass) and ground using a Wiley Mill. Ground tissue and soil samples were sieved through a 2 mm mesh then placed in 5 mm vials for shipment to the Plant and Soil analysis lab at University of Delaware (UD). Plant tissue total elemental composition was accomplished using microwave digestion and Inductively Coupled Plasma (ICP) spectroscopy procedures for percent macronutrients (i.e., P, K, S, Ca, Mg, and S) and micronutrient (mg kg^{-1}) levels