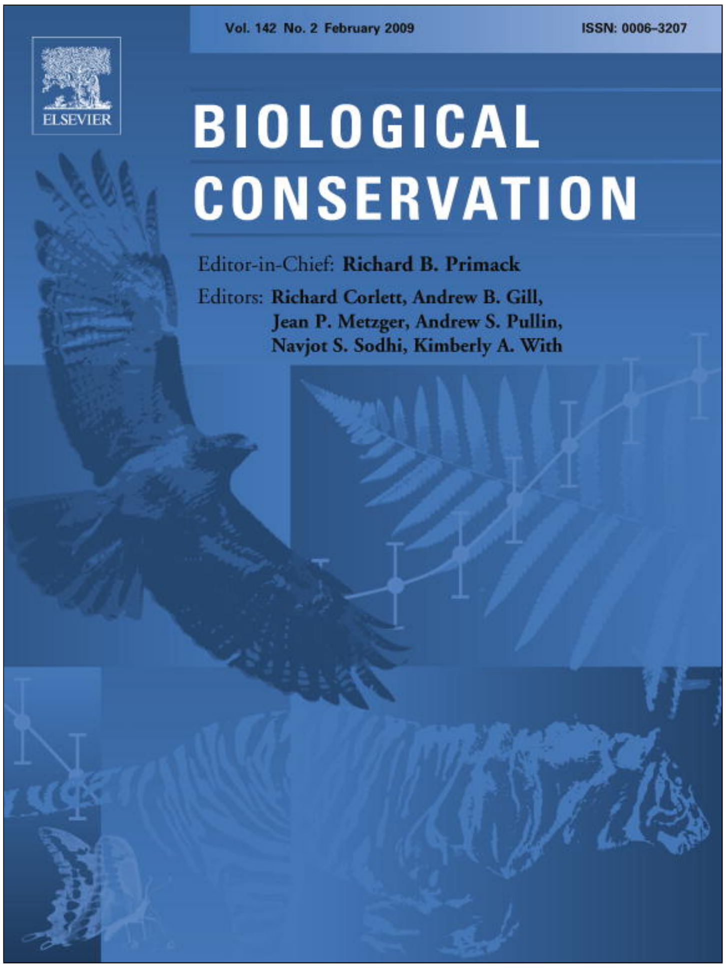

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Effects of woody debris, microtopography, and organic matter amendments on the biotic community of constructed depressional wetlands

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ABSTRACT

To increase wetland acreage and biodiversity, Delaware agencies constructed >220 depressional wetlands. During construction, agencies included amendments thought to increase biodiversity. Because the efficacy of amendments is unknown, we investigated their effects on macroinvertebrate and vegetative communities. We selected 20 standardized wetlands (five contained coarse woody debris (CWD) and microtopography amendments (land surface ridges and furrows), five had neither, five had CWD only, and five had microtopography only). Additionally, 12 wetlands had received organic matter amendments (i.e., straw). Insect richness ($P = 0.010$; $r^2 = 0.16$), insect biomass ($P = 0.023$; $r^2 = 0.13$), intolerant insect biomass ($P = 0.033$, $r^2 = 0.03$), Ephemeroptera biomass ($P = 0.027$; $r^2 = 0.12$), and Odonata biomass ($P = 0.046$; $r^2 = 0.10$) increased with CWD volume. Obligate plant percent cover increased with microtopographic variation ($P = 0.029$; $r^2 = 0.120$). Although organic matter amendments did not increase percent soil organic matter ($t_{13.7} = -1.16$, $P = 0.264$), total ($P = 0.027$; $r^2 = 0.12$), native ($P = 0.036$; $r^2 = 0.11$), and facultative ($P = 0.001$; $r^2 = 0.24$) plant richness increased with percent soil organic matter. To enhance biodiversity, constructed wetlands should contain CWD, but additional research is needed to understand the benefits of microtopography and organic matter amendments.

1. Introduction

Wetland construction is a common practice for compensatory mitigation and wildlife management. Unfortunately, constructed wetlands often fail to support biotic communities comparable to those in similar, naturally occurring wetlands (Galatowitsch and Van Der Valk, 1996; Zelder and Callaway, 1999; Brown and Veneman, 2001; Campbell et al., 2002; Balcombe et al., 2005; Spieles, 2005; Petranka et al., 2007). The vegetative communities of constructed wetlands frequently have lower species richness, less vegetative cover, higher occurrence of exotic species, and fewer obligate wetland species than natural wetlands (Galatowitsch and Van Der Valk, 1996; Zelder and Callaway, 1999; Brown and Veneman, 2001; Campbell et al., 2002; Balcombe et al., 2005; Spieles, 2005). Similarly, aquatic macroinvertebrates are often less abundant and diverse in constructed wetlands (Brown et al., 1997; Brown and Batzer, 2001). Therefore, efforts are needed to

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identify wetland construction techniques that improve the ability of constructed wetlands to support diverse biotic communities.

Constructed wetlands are often deficient in structural diversity (e.g., downed wood, organic matter, litter accumulation, and microtopographic variation) compared to naturally occurring wetlands (Mitsch and Gosselink, 1993; Whittecar and Daniels, 1999; Bruland and Richardson, 2005; Stolt et al., 2000; Moser et al., 2007). Habitat heterogeneity enhances soil moisture, nutrient, and elevation gradients, which supports a variety of physical niches (Titus, 1990; Carroll, 1993). Thus, the deficiency in structural diversity may partially explain the deficiency in constructed wetland biodiversity. These differences between constructed and natural wetlands are problematic for many agencies and organizations that are constructing wetlands with two main objectives: to emulate natural wetlands and to enhance local biodiversity.

Reflecting national trends, Delaware has experienced significant reductions of natural wetlands and has constructed wetlands to augment losses. To realize their objectives of emulating natural wetlands and increasing biodiversity, resource management agencies began adding coarse woody debris (CWD), substrate microtopography, and organic matter amendments when constructing depressional wetlands. Although these amendments have the potential to influence biodiversity (Street, 1983; Carroll, 1993; Bruland and Richardson, 2004), their effects have not been quantified in constructed depressional wetlands. Therefore, our study objectives were to determine the effects of amendments (CWD, microtopography, and organic matter) on biotic communities (i.e., aquatic macroinvertebrate and vegetative communities) of constructed depressional wetlands.

2. Methods

2.1. Study sites

Approximately 224 shallow, depressional, palustrine wetlands were constructed in Delaware between 1989 and 2002 by government and conservation agencies. Most of these wetlands were constructed on hydric soils, and therefore were considered “restored”. However, since wetlands were not necessarily restored to their historical wetland type, we hereafter refer to these wetlands as “constructed”. During wetland construction, Delaware agencies added coarse woody debris (CWD) to some sites in the form of logs and stumps, created microtopographic variation in some wetlands by forming land surface ridges and furrows using heavy machinery, and included particulate organic matter in some wetlands in the form of straw.

Using baseline information on 224 Delaware constructed wetlands; we selected 20 constructed wetlands as study sites. All 20 study sites were located in Kent County, Delaware located on the Delmarva Peninsula within the Atlantic Coastal Plain physiographical province. We only considered wetlands of similar size (0.2–0.8 ha), age (2–6 years old at the time of site selection and start of data collection), percent open water (15–50%), percent of cattail (*Typha* spp.) and common reed cover (*Phragmites australis*; <30% collectively), and adjacent land use (agricultural fields) as potential study sites. Additionally, we only considered depressional wetlands if they had been constructed in marginal agricultural fields where the source of hydrology was precipitation and surface runoff.

Wetlands were also scored based on the amount of microtopography created at each wetland using a scale of 0–10 and were classified as having CWD and organic matter amendments present or absent. We classified wetlands with microtopography scores of 6–10 as having microtopography present and sites with scores of 0–4 as having microtopography absent. We selected five wetlands for each of four treatments: wetlands with CWD and microtopography present, wetlands with CWD and microtopography absent, wetlands with CWD present but microtopography absent, and wetlands with CWD absent but microtopography present. Within each treatment category, 2–4 wetlands had received organic matter amendments (total = 12 wetlands).

Data collection was conducted in 2004 and 2005. During that period, the study sites were dominated by herbaceous emergent vegetation. Common emergent species included American bur-reed (*Sparganium americanum*), bugleweeds (*Lycopus* spp.), bulrushes (*Scirpus* spp.), cattail, marsh seedbox (*Ludwigia palustris*), rice cutgrass (*Leersia oryzoides*), rushes (*Juncus* spp.), sedges (*Carex* spp.), and smartweeds (*Polygonum* spp.). Common shrub species included common buttonbush (*Cephalanthus occidentalis*), multi-floral rose (*Rosa multiflora*), northern arrow-wood (*Viburnum dentatum*), and silky dogwood (*Cornus amomum*). Although none of the wetlands contained trees with a diameter at breast height (dbh) >7.5 cm, saplings were present at many sites including black willow (*Salix nigra*), green ash (*Fraxinus pennsylvanica*), red maple (*Acer rubrum*), river birch (*Betula nigra*), sweet gum (*Liquidambar styraciflua*), and willow oak (*Quercus phellos*).

2.2. Amendment quantification

To verify database information for each selected wetland and to evaluate the effects of the amendments as continuous variables, we quantified the amount of CWD, microtopographic variation, and percent soil organic matter present at each site in September–October 2005. We measured end diameters and length of all downed logs >10 cm in diameter and the midpoint diameter and total height for all stumps present at each site to the nearest 1.0 cm. We used the equation for a conic frustrum to determine volume of downed logs [$V = \pi l/12 (d^2 + db + b^2)$; where l = length, d = end diameter 1 and b = end diameter 2] and the equation for a cylinder volume to determine volume of stumps ($h\pi r^2$; where h = stump height and r = stump mid radius). We summed downed wood and stump volumes to estimate total volume (m^3) of CWD for each wetland.

To quantify the degree of microtopographic variation present at each wetland, we recorded substrate elevations along transects using a Laserplane 800 laser level and Laser Legs tripod Model 1151 (Spectra Precision, Dayton, Ohio, USA). We spaced transects 10 m apart and recorded elevations at every 1 m for $\geqslant$100 readings at each site. For each wetland, we calculated mean microtopographic variation of absolute differences between consecutive elevation readings (m/m).

To quantify the amount of soil organic matter present, we collected nine soil samples from each site along a random azimuth (three samples within each of three 0.25 m^2 plots; one plot placed at each wetland edge and one from the center). We used AMS chrome plated soil probe (AMS, American Falls, Idaho, USA) with a 2.2-cm diameter to attain soil samples 10–15 cm deep. The Delaware Department of Natural Resources and Environmental Control Environmental Lab (Dover, Delaware, USA) determined percent soil organic matter present in the samples using the loss on ignition method (Storer, 1984; Campbell et al., 2002). We used mean percent soil organic matter of the nine samples to represent soil organic matter for each wetland.

2.3. *Biotic community surveys*

2.3.1. *Aquatic macroinvertebrate sampling*

We sampled the macroinvertebrate communities at each wetland within a 1-week period in early April 2004 and 2005 using a standard D-frame aquatic net and an aluminum 0.20-m^2 quadrat frame (Fairchild et al., 1999). At each site, three samples were obtained (two samples from opposite edges of the wetland and one sample from deeper water at the approximate midpoint) along a random azimuth. Prior to collecting the sample, we pressed the frame into the substrate to prevent individuals from escaping the sample unit. Each sample consisted of one sweep of the net within the quadrat frame. Because this method may underestimate benthic invertebrates (Fairchild et al., 1999), we modified the technique by attaching a bar to the handle of the net at 1 m, parallel to the ground, allowing it to rest along the edge of the quadrat frame (Wall, 2007). This modification ensured that we sampled a 2 cm depth of the benthic substrate as well as the water column. Each sample was rinsed through a 500-μ sieve and fixed in 10% formalin. After three weeks of storage, we replaced the formalin with 95% ethanol (Gaston et al., 1996). Because family-level richness was valuable in evaluating wetland restoration success (Fairchild et al., 1999), we identified all insects to family (via Merritt and Cummins, 1996). Additionally, we identified all non-insect macroinvertebrates to lowest possible taxonomic level (via Pennak, 1989).

For each wetland and year, we calculated insect family richness, non-insect order richness, and macroinvertebrate order richness. However, “order” richness was a simplification since two taxa were identified only to the lowest practicable level. We identified “worms and leeches” as class Annelida and copepods as subclass Copepoda. Thus, Annelida and Copepoda were treated as orders for statistical analysis.

We obtained dry biomass of each insect family and lowest non-insect taxonomic unit for each site. We dried samples (excluding caddisfly cases) in an 800 W L-C oven (Model 3511; Lab-Line Instruments, Melrose Park, IL, USA) for 24 h at 105 °C (Fairchild et al., 1999) and determined mass to the nearest 0.0001 g using a Mettler AE 100 microbalance with a glass draft-shield (Mettler Toledo Lab Products, Northbrook, IL, USA). For each wetland and year, we pooled insect family biomass to determine insect order biomass. We also pooled biomass to determine total insect, non-insect, and macroinvertebrate biomass.

We considered several macroinvertebrate taxa to be “intolerant” of poor wetland quality based on Gernes and Helgen (1999) and Rader et al. (2001) who demonstrated that certain macroinvertebrate orders were useful in assessing wetland health because their richness decreased with environmental degradation. For each wetland and year, we determined intolerant insect family richness, intolerant non-insect family richness, intolerant insect biomass, intolerant non-insect biomass, and snail biomass.

2.3.2. *Fish sampling*

When sampling for macroinvertebrates, we recorded if fish were captured. Additionally, we sampled the fish communities present at each wetland in November 2005 using a 6-mm mesh polyester seine net. At each wetland, we executed three sweeps of the net, varying the length of the net and sweep depending on the width of the wetland or particular area being sampled. Based on both sampling methods, we determined fish presence/absence at each wetland.

2.3.3. *Vegetation sampling*

We sampled the herbaceous vegetation communities in August and September 2004 and 2005. To randomly select sampling units, we created a 5 × 5 m grid covering the wetland prior to vegetation sampling and identified each grid intersection point that occurred in emergent vegetation. From these, we randomly selected 17 emergent vegetation points to be sampled at each wetland. For each selected point, we placed a 1-m^2 (0.5 m × 2 m) rectangular plot over the grid intersection. We estimated the percent cover of each species and recorded the midpoint of its respective cover classes (<1%, 1–5%, 6–25%, 26–50%, 51–75%, 76–99%, and 100%; Galatowitsch et al., 2000; Naugle et al., 2000; Balcombe et al., 2005). We calculated native, exotic, obligate (OBL), facultative wetland (FACW), and total plant species richness for each wetland and year. Using the midpoints of the cover classes (Galatowitsch et al., 2000) we determined mean percent cover of native, exotic, OBL, FACW, and total plants.

2.3.4. *Statistical analysis*

We conducted all analyses using SAS (version 9.1, Cary, NC). To verify that wetlands with CWD, microtopography, and organic matter amendments contained greater CWD volume, microtopographic variation, and percent organic matter than those wetlands without amendments, we used a t-test. To determine if CWD volume affected percent soil organic matter, we used simple linear regression. We used a t-test to determine if the presence/absence of fish affected insect biomass. We determined macroinvertebrate community diversity at each wetland using the Simpson’s diversity index (Simpson, 1949). We used simple linear regression to determine if amount of CWD, microtopography, or percent soil organic matter was related to biotic variables.

3. Results

Constructed wetlands with CWD and microtopography amendments present had greater volumes of CWD and greater variation in microtopography than wetlands without

Table 1 – A comparison of mean coarse woody debris volume, microtopographic variation, and percent soil organic matter between constructed wetlands with and without CWD, microtopography, and organic matter amendments in 20 Kent County, Delaware constructed wetlands, 2004–2005.

Amendment	n	$\bar{x}$	SE	df	t-value	P
Coarse woody debris[a]						
Present	10	2.36	0.563			
Absent	10	0.06	0.047	9.1	−4.06	0.003
Microtopography[b]						
Present	10	0.23	0.021			
Absent	10	0.15	0.023	18.0	−2.84	0.011
Organic matter[c]						
Present	12	3.41	0.593			
Absent	8	2.68	0.217	13.7	−1.16	0.264

a Volume of coarse woody debris was measured in m^3.
b Microtopographic variation was measured in m/m.
c Organic matter was measured as % soil organic matter.

(Table 1). However, constructed wetlands with organic matter amendments did not differ in percent soil organic matter from wetlands without those amendments (Table 1). The amount of CWD present in a wetland was not related to percent soil organic matter ($F_{1,18} = 0.09$, $r^2 = 0.005$, $P = 0.768$). Although we detected five species of fish (two carnivorous and three omnivorous) at 13 wetland sites, wetlands with fish and without fish did not differ in insect biomass ($t_{38} = 1.66$, $P = 0.105$).

We captured 9918 individual insects (seven orders, 28 families) and 103,485 individual non-insect macroinvertebrates (11 orders) in 2004 and 2005. We observed 118 plant species in the constructed wetland sites in 2004 and 2005.

In the macroinvertebrate community, CWD volume was positively related to insect family richness, total insect biomass, intolerant insect biomass, odonate biomass, and ephemeropteran biomass (Tables 2 and 3). In the vegetation community, CWD volume was not related to any richness or percent coverage variable (Table 2).

Microtopographic variation was not related to any aspect of the macroinvertebrate community (Tables 2 and 3). Microtopographic variation was positively related to OBL percent cover (Table 2).

In the macroinvertebrate community, percent soil organic matter was not related to any aspect of the macroinvertebrate community (Tables 2 and 3). Percent soil organic matter was positively related to FACW richness, total richness, and native plant richness (Table 2).

4. Discussion

4.1. *Influences of coarse woody debris on communities*

CWD amendments were effective in increasing richness and biomass values of the macroinvertebrate community, specifically that of insects. The volume of CWD was related to increased insect richness and biomass. The importance of CWD in enhancing macroinvertebrate communities in streams is well documented (Anderson et al., 1978; Benke et al., 1985; Wallace et al., 1993; Braccia and Batzer, 2001). Our results suggest that CWD is also an important habitat component for insect communities in constructed depressional wetlands. Aquatic insects are vital components of the wetland food web (Guntenspergen et al., 2002; Nicolet et al., 2004), and constructed wetlands with enhanced insect communities may be more attractive to vertebrates as foraging habitat.

CWD volume was positively related to the richness and biomass of taxa known to be sensitive to wetland integrity (e.g., obligate wetland plant richness and ephemeropteran, odonate, and intolerant insect biomass), suggesting that CWD may be improving overall wetland health. For example, CWD may be enriching wetlands with nutrients through decomposition. Although we found that percent soil organic matter did not increase with CWD volume, the wetlands in this study were only 2–6 years old during soil sampling. Research indicates that the soil of constructed wetlands may take decades (>30 years) to form properties, including percent soil organic matter, similar to those found in natural wetlands (Craft and Seneca, 1988; Kentula, 2000). Thus, CWD may be contributing organic matter and nutrients in forms useful to insects and plants even though no relationships were detected between CWD volume and percent soil organic matter.

4.2. *Influences of microtopography on communities*

Wetlands that were constructed with microtopography amendments did not have increased total plant richness. These results are inconsistent with Vivian-Smith (1997) and Moser et al. (2007), who found that experimental wetlands with microtopography had greater plant richness and abundance than those without microtopography. Substrate structural heterogeneity may contribute to plant community richness in constructed wetlands by creating soil nutrient and moisture niches, enhancing overall plant richness. Since wetlands with microtopography amendments in this study contained little substrate variation ($\bar{x} = 0.23$ m/m), future research should investigate the efficacy of more pronounced microtopographic variation in enhancing the biotic community of constructed wetlands.

Table 2 – Relationships between mean coarse woody debris volume, substrate microtopographic variation, and soil organic matter and the macroinvertebrate and vegetative communities of 20 Kent County, Delaware constructed wetlands, 2004–2005. Bold text indicates significant results ($P \leqslant 0.050$).

	Estimate	SE	Intercept	SE	R^2	$F_{1,38}$	P
Coarse woody debris[a]							
Macroinvertebrate community							
Insect families	**0.60**	**0.23**	**7.80**	**0.47**	**0.16**	**7.33**	**0.010**
Insect orders	0.20	0.12	4.50	0.24	0.04	1.70	0.110
Non-insect orders	0.00	0.18	4.60	0.37	0.00	0.02	0.897
Total macro. orders	0.20	0.19	9.10	0.40	0.02	0.81	0.374
Intolerant insect richness	0.20	0.14	2.10	0.29	0.05	2.07	0.158
Intolerant non-insect richness	0.30	0.13	2.10	0.26	0.09	3.84	0.057
Insect diversity	0.00	0.02	0.47	0.04	0.00	0.00	0.981
Non-insect diversity	−0.00	0.01	0.98	0.01	0.01	0.18	0.675
Macro. diversity	−0.00	0.01	0.96	0.01	0.00	0.14	0.707
Vegetative community							
Species richness	0.30	0.09	27.80	1.86	0.00	0.11	0.740
Native richness	0.10	0.77	23.70	1.58	0.00	0.03	0.875
Exotic richness	0.20	0.31	4.20	0.63	0.01	0.34	0.561
OBL[d] richness	0.40	0.34	12.60	0.69	0.03	1.26	0.268
FACW[e] richness	−0.20	0.31	6.10	0.63	0.01	0.24	0.626
Total plant% cover	−1.39	1.38	95.78	2.84	0.03	1.00	0.323
Native% cover	−0.51	2.14	77.28	4.40	0.01	0.06	0.814
Exotic% cover	0.03	0.66	7.58	1.35	0.00	0.00	0.960
OBL% cover	−0.83	2.12	64.98	4.36	0.01	0.15	0.696
FACW% cover	−0.18	0.52	6.39	1.08	0.01	0.12	0.733
Microtopography[b]							
Macroinvertebrate community							
Insect families	3.50	5.20	7.90	1.70	0.01	0.46	0.501
Insect orders	1.40	2.48	4.40	0.51	0.01	0.31	0.583
Non-insect orders	1.60	3.82	4.40	0.79	0.00	0.17	0.684
Total macro. orders	2.90	4.11	8.70	0.85	0.01	0.51	0.478
Intolerant insect richness	2.60	3.06	1.80	0.63	0.02	0.73	0.398
Intolerant non-insect richness	−0.80	2.81	2.50	0.58	0.00	0.08	0.783
Insect diversity	0.37	0.42	0.40	0.09	0.02	0.78	0.384
Non-insect diversity	−0.11	0.11	0.99	0.02	0.03	1.14	0.293
Macro. diversity	−0.03	0.11	0.97	0.02	0.00	0.07	0.794
Vegetative community							
Species richness	18.60	18.77	24.70	3.87	0.03	0.98	0.328
Native richness	13.70	16.03	21.20	3.31	0.02	0.73	0.397
Exotic richness	4.90	6.41	3.50	1.32	0.02	0.58	0.450
OBL richness	8.40	7.07	11.40	1.46	0.04	1.41	0.243
FACW richness	7.90	6.35	4.40	1.31	0.04	1.55	0.220
Total plant% cover	10.92	29.40	92.02	6.07	0.01	0.14	0.712
Native% cover	69.09	43.57	63.50	8.99	0.62	2.51	0.121
Exotic% cover	−11.73	13.69	9.86	2.82	0.02	0.73	0.397
OBL% Cover	**95.15**	**41.87**	**45.83**	**8.64**	**0.12**	**5.17**	**0.029**
FACW% cover	−9.62	10.92	8.00	2.25	0.02	0.78	0.384
Organic matter[c]							
Macroinvertebrate community							
Insect families	−0.30	0.25	9.30	0.89	0.03	1.04	0.315
Insect orders	−0.10	0.12	4.80	0.43	0.01	0.23	0.632
Non-insect orders	0.20	0.18	3.90	0.65	0.04	1.68	0.203
Total macro. orders	0.20	0.20	8.70	0.71	0.02	0.80	0.378
Intolerant insect richness	−0.10	0.15	2.70	0.53	0.01	0.52	0.474
Intolerant non-insect richness	0.20	0.13	1.70	0.47	0.06	2.24	0.142
Insect diversity	0.02	0.02	0.41	0.072	0.03	1.03	0.316
Non-insect diversity	**−0.01**	**0.01**	**1.01**	**0.017**	**0.13**	**5.74**	**0.022**
Macro. diversity	−0.01	0.01	0.99	0.017	0.09	3.93	0.055
Vegetative community							
Species richness	**2.00**	**0.88**	**21.90**	**3.07**	**0.12**	**5.32**	**0.027**
Native richness	**1.60**	**0.75**	**18.70**	**2.63**	**0.11**	**4.75**	**0.036**
Exotic richness	0.40	0.31	3.20	1.09	0.04	1.53	0.224

(continued on next page)

Table 2 – *continued*

	Estimate	SE	Intercept	SE	R^2	$F_{1,38}$	P
OBL richness	8.40	7.07	12.30	1.24	0.04	1.41	0.243
FACW richness	**1.00**	**0.28**	**2.90**	**0.98**	**0.24**	**11.88**	**0.001**
Total plant% cover	−0.48	1.45	95.59	5.07	0.01	0.11	0.743
Native% cover	1.25	2.20	72.77	7.73	0.01	0.32	0.574
Exotic% cover	−0.98	0.66	10.67	2.32	0.05	2.18	0.148
OBL% cover	1.17	2.19	60.33	7.67	0.01	0.29	0.596
FACW% cover	0.23	0.54	5.44	1.90	0.01	0.18	0.670

a Volume of coarse woody debris was measured in m^3.
b Microtopographic variation was measured in m/m.
c Organic matter was measured as % soil organic matter.
d Obligate wetland plant.
e Facultative wetland plant.

Microtopography was related to obligate wetland plant percent cover. Since obligate wetland plants occur in wetlands 67–99% of the time, they are dependent upon wetland habitat and are sensitive to hydrologic conditions. Previous research suggests that microtopographic variation not only enhances wetland plant richness but it may also improve hydrologic conditions (Barry et al., 1996; Bledsoe and Shear, 2000). Tweedy and Evans (2001) found that restored wetlands given microtopography amendments retained more water than wetlands without amendments. Future research should investigate the effects of microtopography amendments on wetland hydrology in constructed depressional wetlands.

4.3. *Influences of organic matter on communities*

Organic matter amendments did not increase percent soil organic matter, but the soil of constructed wetlands may take decades to form properties similar to those found in natural wetlands (Craft and Seneca, 1988; Kentula, 2000); therefore, other processes must be affecting the macroinvertebrate community. Previous research demonstrated that when organic matter amendments were included in a wetland, they were rapidly colonized by fungi, bacteria, and algae, providing macroinvertebrates with food and shelter (Street, 1983; Gabor et al., 1994). Thus, the application of organic matter amendments to newly constructed wetlands may provide an influx of resources that renders the wetland quickly habitable, accelerating macroinvertebrate colonization. Warren and Spencer (1996) included organic matter amendments into experimental ponds and did not detect differences in macroinvertebrate abundances and biomass between ponds with and without the treatments. However, Warren and Spencer (1996) inoculated their experimental ponds with macroinvertebrates and covered them with mesh, thus preventing natural colonization from taking place. Future research should compare rates of macroinvertebrate colonization between newly constructed wetlands with and without organic matter amendments.

Percent soil organic matter positively influenced aspects of the vegetative communities, suggesting its importance to constructed wetland biota (Bailey et al., 2007). Bruland and Richardson (2004) demonstrated the value of percent soil organic matter for overall wetland integrity by documenting that soil organic matter was correlated with all aspects of soil function measured, including water-holding capacity and microbial biomass. Our results indicate that percent soil organic matter is a valuable tool in enhancing the biotic communities of constructed wetlands. However, our constructed wetland sites averaged only 3% soil organic matter, whereas 5% is indicative of wetland hydrologic conditions (Mitsch and Gosselink, 2000), and natural wetlands usually contain 20–30% (Mitsch and Gosselink, 1993). Future long term research is needed to identify construction practices that will ultimately increase the percent soil organic matter content of constructed wetlands.

5. Management implications

Our results suggested that the amendments may benefit biotic community richness and diversity within constructed wetlands. Because CWD increased insect richness and biomass, we recommend including amendments in the form of stumps and downed wood to constructed depressional wetlands. Aquatic insects are vital components of the wetland food web and increased biomass may improve the value of a constructed wetland as wildlife foraging habitat. In this study, wetlands with CWD amendments contained a mean volume of 2.4 m^3 of stumps and downed logs, suggesting that $\geqslant 2.0$ m^3 may be sufficient in successfully enhancing the insect community in wetlands of similar size (0.2–0.8 ha).

Microtopography and organic matter amendments also enhanced the biotic community of constructed wetlands. Wetland construction and restoration success is usually evaluated by plant community measurements and success is often threatened by insufficient cover of aquatic plants (Kentula, 2000; Brown and Veneman, 2001). Microtopography amendments may be a useful tool when constructing wetlands, but its positive effects must first be verified in future studies using greater microtopographic variation. Although not affected by organic matter amendments, percent soil organic matter was a vital habitat component in the constructed wetlands. Stauffer and Brooks (1997) found that applying salvaged marsh surface from a natural marsh to a constructed wetland resulted in greater soil organic matter. Additionally, Atkinson and Cairns (2001) determined that decomposition rates for wetland plant species peaked at intermediate water depth and resulted in increased litter accumulation. Future research must assess these and other

Table 3 – Relationships of mean coarse woody debris volume, substrate microtopographic variation, and soil organic matter with macroinvertebrate biomass (g) for 20 Kent County, Delaware constructed wetlands, 2004–2005. Bold text indicates significant results ($P \leqslant 0.050$).

	Estimate	SE	Intercept	SE	R^2	$F_{1,38}$	P
Coarse woody debris[a]							
Coleoptera	0.0034	0.0038	0.0204	0.0077	0.02	0.79	0.378
Diptera	0.0032	0.0044	0.0303	0.0090	0.01	0.52	0.477
Ephemeroptera	**0.0027**	**0.0012**	**0.0010**	**0.0024**	**0.12**	**5.28**	**0.027**
Hemiptera	0.0035	0.0019	0.0044	0.0039	0.08	3.26	0.079
Lepidoptera	0.0002	0.0002	0.0002	0.0004	0.03	1.25	0.271
Odonata	**0.0259**	**0.0126**	**0.0528**	**0.0258**	**0.10**	**4.24**	**0.046**
Snail	0.0605	0.0313	0.1170	0.0643	0.09	3.74	0.061
Trichoptera	0.0011	0.0012	0.0037	0.0024	0.02	0.89	0.350
Insect	**0.0398**	**0.0168**	**0.1129**	**0.0345**	**0.13**	**5.61**	**0.023**
Non-insect	0.0407	0.0475	0.3181	0.0975	0.02	0.73	0.397
Total	0.0805	0.0533	0.4310	0.1095	0.06	2.28	0.139
Intolerant insect	**0.0296**	**0.0134**	**0.1147**	**0.0575**	**0.03**	**4.92**	**0.033**
Intolerant non-insect	0.0450	0.0396	0.0329	0.1875	0.08	1.29	0.263
Microtopography[b]							
Coleoptera	0.0266	0.0798	0.0194	0.0165	0.01	0.11	0.740
Diptera	−0.1428	0.0892	0.0613	0.0184	0.06	2.56	0.118
Ephemeroptera	0.0039	0.0259	0.0035	0.0053	0.01	0.02	0.882
Hemiptera	−0.0181	0.0418	0.0121	0.0086	0.01	0.19	0.667
Lepidoptera	0.0014	0.0039	0.0002	0.0008	0.01	0.13	0.717
Odonata	0.0896	0.2780	0.0670	0.0574	0.01	0.10	0.749
Snail	0.0146	0.6886	0.1874	0.1421	0.00	0.00	0.983
Trichoptera	0.0145	0.0244	0.0023	0.0050	0.01	0.35	0.556
Insect	−0.0249	0.3778	0.1658	0.0780	0.01	0.00	0.948
Non-insect	0.1844	1.0065	0.3322	0.2077	0.01	0.03	0.856
Total	0.1595	1.1519	0.4979	0.2377	0.01	0.02	0.891
Intolerant insect	0.1080	0.2977	0.0728	0.0614	0.01	0.13	0.719
Intolerant non-insect	0.3501	0.8447	0.1753	0.1743	0.01	0.17	0.681
Organic matter[c]							
Coleoptera	−0.0005	0.0039	0.0262	0.0138	0.01	0.02	0.890
Diptera	−0.0073	0.0044	0.0568	0.0154	0.06	2.77	0.104
Ephemeroptera	0.0000	0.0013	0.0042	0.0045	0.00	0.00	0.989
Hemiptera	−0.0004	0.0021	0.0099	0.0072	0.01	0.04	0.845
Lepidoptera	0.0001	0.0002	0.0002	0.0007	0.01	0.26	0.615
Odonata	−0.0103	0.0136	0.1161	0.0477	0.02	0.57	0.455
Snail	0.0081	0.0339	0.1648	0.1187	0.01	0.06	0.812
Trichoptera	−0.0022	0.0012	0.0119	0.0040	0.09	3.67	0.063
Insect	−0.0206	0.0183	0.2252	0.0641	0.03	1.27	0.267
Non-insect	0.0451	0.0490	0.2268	0.1718	0.02	0.85	0.363
Total	0.0245	0.0566	0.0245	0.0566	0.01	0.19	0.668
Intolerant insect	−0.1093	0.1511	0.1322	0.0510	0.01	0.52	0.474
Intolerant non-insect	0.2017	0.1347	0.1257	0.1445	0.56	2.24	0.143

a Volume of coarse woody debris was measured in m^3.
b Microtopographic variation was measured in m/m.
c Organic matter was measured as % soil organic matter.

techniques to identify construction practices that will increase percent soil organic matter in constructed wetlands.

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