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DIVISION S-10—WETLAND SOILS

Soil Nitrogen Dynamics in Organic and Mineral Soil Calcareous Wetlands in Eastern New York

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ABSTRACT

Calcareous wetlands are of great interest in conservation biology. Previous research has suggested that there are significant differences in soil microbial N cycle processes between calcareous wetlands developed on organic vs. mineral soils. In the study presented here, we measured potential net N mineralization and nitrification, denitrification enzyme activity and soil inorganic N levels at 25 calcareous wetland sites with variable substrate types. We also evaluated the response of N cycling to livestock grazing by sampling at two sites with heavy grazing activity. All N cycle variables were significantly higher in organic soils than mineral soils on a weight basis; however, there were very few differences when results were expressed on an areal (volume) basis because of the low bulk density of the organic soils. The areal results suggest that organic and mineral soil calcareous wetland sites have similar N water quality maintenance values, that is, the ability to absorb N from upland land areas. Heavily grazed sites had significantly decreased pH and increased NO_3^- levels relative to undisturbed sites, but the differences were small. The lack of strong differences in N cycle variables between mineral and organic soil sites raises questions about the need to make a classification distinction between calcareous peatlands (fens) and calcareous mineral soil wetlands in nutrient cycling and water quality maintenance contexts.

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Classification of wetlands is often highly problematic due to the need to consider soil, plant, and hydrologic factors as fundamental components of these ecosystems (Bridgham et al., 1996). The term *wetland* refers to ecosystems that are characterized by hydric soils and plant and animal species adapted or partially adapted to life in saturated conditions (National Research Council, 1995). However, there are often multiple names for specific wetland types, reflecting the diversity of approaches that have been taken to wetland evaluation and classification through decades and centuries (Mitsch and Gosselink, 1993). Classification problems have taken on new importance in recent years due to intense interest in functional evaluation and classification of wetlands (i.e., their effects on water quality, atmospheric chemistry and biodiversity) (Ehrenfeld, 1986; Johnston, 1991; Brinson, 1993; Ainslie, 1994; Bedford, 1996).

Calcareous wetlands have proven to be particularly challenging to classify and evaluate in a functional context. These wetlands have developed on limestone or other Ca-rich parent materials, are characterized and classified by the presence of calcicole vegetation (i.e., plants that normally grow on soils high in Ca), and lack a closed tree canopy (Boyer and Wheeler, 1989; Johnson and Leopold, 1994; Motzkin, 1994). Many investigators make a distinction between calcareous peatlands (fens) and calcareous wetlands on mineral soil substrates. However, there have been few evaluations of functional differences between calcareous wetlands with mineral vs. organic soils. Functional evaluation of calcareous wetlands is needed because in many areas, they support a variety of rare plant and animal species and are of great interest in conservation biology (Kiviat et al., 1993; Johnson and Leopold, 1994; Almendinger and Leete, 1998). Conservation of these ecosystems is problematic because they are often intensively used for grazing or are surrounded by heavily fertilized agricultural or residential areas (Koerselman et al., 1990). Nutrients from adjacent land uses can disturb the unique biogeochemistry of calcareous wetlands, resulting in changes in plant and animal populations (Verhoeven and Schmitz, 1991; Boeye et al., 1995; Kooijman and Bakker, 1995).

In a previous study (Groffman et al., 1996), we evaluated microbial biomass and activity in calcareous wetlands and three other wetland types—red maple (*Acer rubrum* L.) swamps, clay meadows, and woodland pools—in eastern New York. The objective of the previous study was to determine if different wetland types have distinctive patterns of microbial activities related to nutrient cycling and water quality maintenance functions (e.g., the ability to absorb pollutants, especially NO_3^-, from upland areas). In that study, the calcareous wetlands were the most problematic of the four wetland types evaluated. Variation between calcareous wetland sites was extreme, making it difficult to determine whether there were characteristic levels of microbial biomass and activity in this wetland type relative to the other wetlands. Two of our calcareous wetland sites had mineral soil substrates, while one had an organic soil substrate. Although vegetation and water table levels were similar among the three sites, microbial biomass and activity were much higher at the site with organic soil.

In the study presented here, we tested the hypothesis that microbial N cycling in calcareous wetlands differs significantly with substrate type (organic vs. mineral soil). We tested this hypothesis by measuring potential net N mineralization and nitrification, denitrification enzyme activity, and soil inorganic N levels at 25 sites with different substrate types. We also hypothesized that N cycling differs significantly in calcareous wetlands that are heavily grazed by livestock. We tested this hypothesis by comparing N cycle variables at two sites with heavy grazing activity with three ungrazed sites with very similar water table and soil organic matter levels. The work was associated with an effort to evaluate plant and animal biodiversity functions of calcareous wetlands and to address fundamental questions about functional differences between calcareous wetlands on mineral and organic soils.

MATERIALS AND METHODS

The 25 calcareous wetlands were located in Dutchess and Columbia Counties in eastern New York State and in Litchfield County, in northwestern Connecticut. Mean annual precipitation averaged across five weather stations in Dutchess County is ≈104 cm, 6.6 to 10.2 cm mo^{-1} (Thomas, 1985). The 30-yr mean annual temperature at Poughkeepsie, ≈10 to 50 km from our study sites, is 9.5°C (Thomas, 1985). Average monthly temperatures in the Hudson Valley region of New York State in June, July, and August 1997 were 19.5, 21.2, and 20.2°C respectively, all within 0.5°C of normal. Precipitation in June through August 1997 was 26.3 cm, which was 3.3 cm below the 30-yr average (Northeast Regional Climate Center, 1997).

Potential calcareous wetland sites were first identified on soil maps (Case, 1989, unpublished soil survey of Dutchess County, New York) as areas that were "somewhat poorly drained" or wetter with a surface or subsoil pH >7.0. Aerial photos and air and roadside surveys were then used to eliminate areas that clearly did not support fen plant communities. Final sites were selected to have <50% coverage of 1-m-tall, woody vegetation and the presence of fen indicator plants (at least four fen species per m^2 or 10% coverage by fen species). The sites had to be large enough to encompass three 5 by 5 m sampling plots separated by at least 2.5 m.

Detailed characterization of plant communities at these sites is presented elsewhere (Kiviat et al., unpublished data). The calcareous wetlands in this study had open, low vegetation characterized by shrubby cinquefoil (*Potentilla fruticosa* auct. non L.) and low, narrow-leaved sedges (*Carex* spp.). These sites belong to the Palustrine Emergent Persistent and Palustrine Scrub-Shrub Broad-leaved Deciduous categories of Cowardin et al. (1979). Soils at the sites were mapped as Sun (coarse-loamy, mixed, active, nonacid, mesic Aeric Epiaquepts), Carlisle (euic, mesic Typic Haplosaprist), Limerick (coarse-silty, mixed, nonacid, mesic Typic Fluvaquents), Linlithgo (fine-loamy over sandy or sandy-skeletal, mixed nonacid, mesic Aeric fluvaquents), Alden (fine-loamy, mixed, active, nonacid, mesic Mollic Endoaquepts), or Wayland (fine-silty, mixed, active, nonacid, mesic Fluvaquentic Endoaquept) series. It is interesting to note that none of these soil families has a designation as calcareous. However, we identified calcareous wetlands in this study by the presence of distinctive vegetation known to be adapted to calcareous conditions. Organic and mineral soil sites were evenly distributed throughout the study area. Two of the sites had evidence (hoof prints and manure) of recent heavy grazing by horses (*Equus caballus*) and cattle (*Bos taurus*).

All sites were sampled in June and July 1997 (except for bulk density). At each site, the extent of calcareous wetland, fen vegetation was delineated as described above and three 5 by 5 m sampling plots were located using a random number table. Sites ranged in size from 0.01 to 1.29 ha. A 5.0 cm wide by 50 cm deep hole was augered in the center of each plot. The top 10 cm of soil from each hole was taken for soil analysis and transported to the laboratory on ice. After water table levels in the holes had stabilized (required several hours at some sites), the depth to water table was measured and a water sample was taken for analysis. Conductivity and pH of the water samples were measured immediately using a portable conductivity meter and pH probe, respectively.

Four sites (two organic, two mineral) were sampled for bulk density in fall 1998. Six intact soil cores (5-cm diam., 10-cm depth) were taken at each site, returned to the laboratory, dried, and weighed. These sites were chosen by convenience (ease of access) and a subjective assessment of mineral vs. organic soil conditions. Soils at the four sites ranged from 12 to 43% organic matter. Rock fragments were not present in these soils.

For microbial analyses, soils were sieved (<4 mm), homogenized by hand mixing, and held at field moisture at 4°C in sealed plastic bags between sampling and analysis (<7 d). Soil moisture content was determined by drying at 60°C for 48 h

Table 1. Soil (0–10 cm) variables on a weight basis in organic and mineral soil calcareous wetland sites sampled in summer 1997. Values are mean (standard error) of 12 organic and 13 mineral soil sites, except for bulk density values, which are mean (standard error) of two organic and two mineral soil sites.

Variable	Organic	Mineral
Organic matter, % (w/w)	57 (6)†	18 (1)
Bulk density, g cm^{-3}	0.26 (0.05)†	0.65 (0.05)
Water table depth, cm	8.2 (2.7)†	21.1 (4.8)
Conductivity, μS	480 (30)†	580 (20)
pH	7.0 (0.04)‡	7.2 (0.06)
Moisture content, % (w/w)	78 (2)†	54 (2)
NO_3^-, mg N kg^{-1}	1.3 (0.4)	0.8 (0.2)
NH_4^+, mg N kg^{-1}	20.4 (2.8)†	5.8 (0.9)
Denitrification enzyme activity, μg N kg^{-1} h^{-1}	1519 (376)‡	711 (130)
Potential net N mineralization, mg N kg^{-1} d^{-1}	−11.2 (2.5)†	−1.4 (1.0)
Potential net nitrification, mg N kg^{-1} d^{-1}	2.3 (1.0)	0.9 (0.4)

† Indicates significant difference between organic and mineral sites in a one-way analysis of variance at $P < 0.01$.
‡ Indicates significant difference between organic and mineral sites in a one-way analysis of variance at $P < 0.05$.

(McInnes et al., 1994). Soil organic matter content was determined by loss on ignition at 450°C for 4 h (Nelson and Sommers, 1996). Mean bulk density values for mineral and organic soils were used to convert data on organic matter, inorganic N, denitrification enzyme activity, and potential net N mineralization and nitrification from a weight to a volume basis.

Denitrification enzyme activity was measured using the short-term anaerobic assay described by Smith and Tiedje (1979). Sieved soils were amended with NO_3^-, dextrose, chloramphenicol, and acetylene, and were incubated under anaerobic conditions for 90 min. Gas samples were taken at 30 and 90 min, stored in evacuated glass tubes, and analyzed for N_2O by electron capture gas chromatography.

Amounts of inorganic N (NO_3^- and NH_4^+) in soil were determined by extraction with 2 *M* KCl followed by colorimetric analysis with a Perstorp Flow Solution Analyzer. Potential net N mineralization and nitrification were measured from the accumulation of NO_3^- plus NH_4^+ and NO_3^- alone during a 7-d aerobic incubation at room temperature.

Differences between mineral and organic (>30% organic matter) and between disturbed (evidence of heavy grazing) and undisturbed site samples were analyzed by one-way analysis of variance of site means using the General Linear Models (for normally distributed data) or NPAR1WAY (for nonnormally distributed data) routines of the Statistical Analysis System (SAS Institute, 1988). Relationships among variables were analyzed by computing Pearson (linear) and Spearman (nonparametric) correlation coefficients (SAS Institute, 1988). We report the higher of the two correlation coefficients because we were interested more in the strength of the relationships between variables than in their linearity.

RESULTS

Using a breakpoint of 30% organic matter, our sampling design produced 13 mineral and 12 organic soil sites. Two of the mineral soil sites were disturbed; that is, they were heavily grazed, with obvious manure input.

The organic soil sites had higher ($P < 0.01$) water tables and water content and lower bulk density ($P < 0.01$) and porewater pH ($P < 0.05$) than the mineral soil sites (Table 1). Conductivity did not differ between sites with mineral or organic soils.

Table 2. Soil (0–10 cm) variables on a volumetric basis in organic and mineral soil calcareous wetland sites sampled in summer 1997. Values are mean (standard error) of 12 organic and 13 mineral soil sites.

Variable	Organic	Mineral
Soil organic matter, kg m^{-2}	16.4 (11.2)†	10.7 (6.8)
NH_4^+–N, kg ha^{-1}	5.9 (0.7)†	3.4 (0.5)
NO_3^-–N, kg ha^{-1}	0.41 (0.15)	0.52 (0.14)
Denitrification enzyme activity, mg N m^{-2} h^{-1}	44 (10)	40 (6)
Potential net N mineralization, kg N ha^{-1} d^{-1}	−3.2 (0.7)†	−0.7 (0.6)
Potential net nitrification, kg N ha^{-1} d^{-1}	0.7 (0.3)	0.6 (0.2)

† Indicates significant difference between organic and mineral sites in a one-way analysis of variance at $P < 0.01$.

Given large differences in bulk density, it is important to compare differences between mineral and organic soil sites on both a weight and area (volume) basis. On a weight basis, most N cycle variables measured (KCl extractable NH_4^+, denitrification enzyme activity, and potential net N mineralization) were higher ($P < 0.01$ or 0.05) at organic soil sites than at mineral soil sites (Table 1). However, on a volume basis, several of these differences were not present (Table 2), and only soil organic matter, NH_4^+, and potential net N mineralization differed among organic and mineral soil sites on a volumetric basis. There were no correlations between N cycle variables and soil organic matter content on a volumetric basis, but there were strong correlations among the N cycle variables themselves (Table 3). Potential net N mineralization was positively correlated with water table depth, and negatively correlated with NH_4^+. Nitrification was negatively correlated with pH.

A comparison of the two disturbed (heavily grazed) sites with the three undisturbed sites with the most closely matched organic matter contents and water table levels found lower pH ($P < 0.05$) and higher NO_3^- ($P < 0.10$) in the disturbed relative to the undisturbed sites (Table 4).

DISCUSSION

Are There Functional Differences between Organic and Mineral Soil Calcareous Wetlands?

Differences in inorganic N availability and denitrification between organic and mineral soil sites were much more marked on a weight than volumetric basis. The weight basis results are consistent with our previous study (Groffman et al., 1996) that found very high levels of microbial biomass and activity in an organic soil calcareous wetland compared with two mineral soil sites and with many other studies that have shown that soil biological activity increases with organic matter content (Paul and Clark, 1996). However, when considered on a volumetric basis, the results suggest that there are very few differences in inorganic N availability and denitrification between organic and mineral soil calcareous wetlands sites in our region. It is important to note that our analysis was restricted to the top 10 cm of the soil profile. However, biological activities are generally highest near the soil surface (Paul and Clark, 1996),

Table 3. Significant correlations between volumetric estimates of potential net N mineralization, net nitrification, denitrification enzyme activity and other variables in 25 organic and mineral soil (0–10 cm) calcareous wetlands sampled in summer 1997. Values are Pearson product moment or Spearman nonparametric correlation coefficients, whichever was higher.

Potential net N mineralization	Potential net nitrification	Denitrification enzyme activity
NH_4^+–N (−0.75)***	DEA (0.48)**	Nitrification (0.48)**
Water table depth (0.55)**	Mineralization (0.48)**	Mineralization (0.37)*
DEA† (0.37)*	pH (−0.43)*	

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
** Significant at the 0.001 probability level.
† DEA is denitrification enzyme activity.

Table 4. Soil (0–10 cm) variables (mean and standard error) on a weight basis in two heavily grazed and three undisturbed mineral soil calcareous wetland sites sampled in summer 1997. The undisturbed sites were closely matched to the grazed sites by water table and soil organic matter data.

Variable	Grazed	Undisturbed
Organic matter, % (w/w)	0.17 (0.02)	0.18 (0.02)
Water table depth, cm	7.4 (3.0)	8.7 (2.0)
Conductivity, μS	610 (10)	600 (20)
pH	6.9 (0.02)†	7.2 (0.07)
NO_3^-, mg N kg^{-1}	1.4 (0.5)‡	0.2 (0.1)
NH_4^+, mg N kg^{-1}	7.5 (0.3)	5.4 (1.7)
Denitrification enzyme activity, μg N kg^{-1} h^{-1}	1020 (95)	679 (226)
Potential net N mineralization, mg N kg^{-1} d^{-1}	−2.0 (1.0)	1.4 (2.6)
Potential net nitrification, mg N kg^{-1} d^{-1}	1.6 (0.8)	0.9 (0.4)

† Indicates significant difference between grazed and undisturbed sites in a one-way analysis of variance at $P < 0.05$.
‡ Indicates significant difference between grazed and undisturbed sites in a one-way analysis of variance at $P < 0.10$.

so our sampling was probably representative of a high percentage of the N cycling activity of the soil profile. Moreover, differences between organic and mineral soil sites should be most marked at the top of the soil profile as soil organic matter levels generally decline sharply with depth in most soil profiles (Paul and Clark, 1996).

The equal denitrification enzyme activity and the fact that both wetland types exhibited net immobilization (i.e., negative net mineralization) suggest that organic and mineral soil wetland sites have similar water quality maintenance values, at least as far as N is concerned. Denitrification is considered to be an important sink for NO_3^-, a drinking water pollutant and agent of marine eutrophication (Howarth et al., 1996). Nitrate is the most commonly detected groundwater pollutant in the USA and often moves from upland land uses into wetlands (USEPA, 1990; Johnston, 1991). Net mineralization is the product of microbial production and consumption of inorganic N. The fact that all of our sites had negative net mineralization suggests that there is potential for microbial absorption of exogenous N in these wetlands.

It is interesting to note that the organic soil sites had higher levels of soil NH_4^+, but lower rates of potential net N mineralization, than the mineral soil sites on both a weight and a volumetric basis. These results suggest that there may be subtle differences in N cycling between organic and mineral soil sites. The relatively high NH_4^+ levels in the organic soil sites suggest that plant available N may be higher in organic soil than mineral soil wetland sites. The high rates of potential net immobilization in the organic soil sites suggest that these sites may be less susceptible to nutrient loss following disturbance. Our potential net mineralization–immobilization assay was done with sieved (i.e., disturbed) samples. This disturbance probably increased C availability and stimulated immobilization more in the organic soil sites than the mineral soil sites.

The lack of strong functional difference with regard to N dynamics between mineral and organic soil sites raises questions about the need to make a distinction between calcareous peatlands (fens) and calcareous mineral soil wetlands in several specific contexts. It is interesting to note that there were no differences in porewater conductivity and few differences in plant community composition between our mineral and organic soil sites (Kiviat et al., 1998, unpublished data). Investigators in other regions have also noted a lack of marked difference in plant community composition between organic and mineral soil calcareous wetland sites (Tyler, 1984; Motzkin, 1994; Nekola, 1994). Previous studies in eastern New York have found no differences in bog turtle (*Clemmys muhlenbergii*) habitat value of mineral and organic soil sites (Kiviat, 1978). Even though they do not have the organic soil that many would consider to be a requirement for classification as a fen (Bridgham et al., 1996), the fact that our mineral soil sites have similar denitrification enzyme activity, net N mineralization, plant community composition, and the ability to support bog turtles as organic soil sites suggests that they should be in the same functional class as the organic soil sites in nutrient cycling, water quality maintenance, and rare plant and wildlife habitat contexts in our region. Some caveats to this conclusion include the fact that our work did not consider all possible wetland functions and that we did not consider soil depth and its effect on hydrologic flow paths and rates. These topics will be addressed in future research.

Regulation of Nitrogen Cycling in Calcareous Wetlands

The strong correlations among the N cycle variables (mineralization, nitrification, and mineralization) and the lack of correlation between these variables and soil organic matter or spatial variation in water table depth suggest, in a preliminary way, that the inherent ability of the soil to supply inorganic N to plants and microbes is a stronger controller of N cycling among sites than is hydrology or wetland soil type (organic vs. mineral). Mineralization was positively correlated with water table depth, which is a logical result as the aerobic conditions associated with low water tables are known to foster mineralization (Williams, 1974; Humphrey and Pluth, 1997). However, none of the other N cycle variables were correlated with water table depth, suggesting that spatial variation in hydrology was not a strong controller of N cycling among these sites. It is important to note that we only measured water table depths at one date; therefore, these results must be evaluated with caution. However, while water tables are highly dynamic within and between sites and seasons, these data suggest that variables other than water table should be considered as strong controllers of N dynamics in calcareous wetlands in our region.

While calcareous wetlands are characterized by an abundance of bases, N and P status can vary widely (van Wirdum, 1993; Motzkin, 1994). Total and available N status has been shown to be influenced by external inputs, grazing (see below) and harvesting (Koerselman et al., 1990, 1993; Verhoeven and Schmitz, 1991; Boeye and Verheyen, 1994). It is important to note that vegetation in these wetlands is more likely to be limited by P and porewater conductivity rather than N (Kooijman and Bakker, 1995; Bootsma and Wassen, 1996; Boeye et al., 1995, 1997; Verhoeven et al., 1996). Therefore, regulation of N cycling may not be under tight biological control in these sites (Vitousek et al., 1982).

Response to Heavy Grazing

A critical issue in wetland ecology is how wetlands respond to nutrient inputs from the surrounding landscape. This issue is of particular interest in calcareous wetlands that have unique vegetation with distinct nutrient requirements and that have been shown to be sensitive to nutrient inputs from surrounding areas (Koerselman et al., 1990; Bridgham and Richardson, 1993; Johnson and Leopold, 1994; Boeye et al., 1995, 1997; Verhoeven et al., 1996). Our comparison of heavily grazed and undisturbed mineral soil sites suggests these wetlands have some capacity for a resilient response to N inputs; specific processes increase to process and remove the inputs. The decreased pH and increased NO_3^- levels in the grazed sites suggests that manure inputs from grazing have been nitrified (Schlesinger, 1991). However, the lack of difference in extractable NH_4^+ and the low levels of NO_3^- suggest that an increase in denitrification in the grazed relative to the undisturbed sites may have acted as a negative feedback response to N inputs, reducing the amount of extra N available to the plant community (Table 4). An increase in denitrification in response to N inputs has been observed in several wetland studies (Bowden, 1987; Broderick et al., 1988; Warwick and Hill, 1988; Schipper et al., 1991; Ambus and Christensen, 1993; Hanson et al., 1994; Lowrance et al., 1995). However, the ultimate importance of this denitrification response to preserving the unique vegetation and wildlife of calcareous wetlands is unclear. As stated above, fen vegetation may be more limited by P and porewater conductivity than N, and N inputs may therefore not induce major changes in the plant community. Manure P inputs may be particularly important. Still, our data suggest that grazing may not cause significant changes in N cycle processes in these wetlands.

Our comparison of disturbed and undisturbed calcareous wetlands is also complicated by effects of grazing other than N input from manure. Grazing has been found to have multiple effects on N dynamics and plant community composition (Holland and Detling, 1990; Shariff et al., 1994; Pastor et al., 1993; Frank and Groffman, 1998). Grazing may be critical to the maintenance of the herbaceous vegetation of calcareous wetlands in humid regions like Eastern New York (Kiviat et al., unpublished data). Denitrification response to grazing may be important to controlling N availability and plant competition in these wetlands, but a full evaluation of its importance will require studies where grazing and N inputs are manipulated in a controlled way.

CONCLUSIONS

Although KCl extractable NH_4^+, denitrification enzyme activity, and potential net N mineralization were higher at organic soil sites than at mineral soil sites on a weight basis, the lower bulk density of organic soils minimized most of these differences on a volumetric basis.

The lack of difference in observed values for N cycle variables between organic and mineral soil sites on a volumetric basis suggests that their N water quality maintenance function (i.e., their ability to absorb exogeneous N) on an areal basis may be similar. This similarity should be considered in functional classification and comparison of these wetlands in water quality contexts.

Heavy grazing did not induce marked differences in inorganic N availability, mineralization, nitrification, or denitrification in these wetlands.

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