THE ROLE OF *SPHAGNUM* IN THE ACID-BASE CHEMISTRY OF BOG WATERS

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12/13/03

ABSTRACT

The role of the unique cation exchange properties of *Sphagnum* in contributing to acidity of bog systems was investigated in two Atlantic White Cedar Swamps in Woods Hole, Massachusetts: one with and one without *Sphagnum*. In the *Sphagnum*-dominated system, Hidden Swamp, the CEC of the *Sphagnum* exceeds the capacity of the soil to buffer against a decrease in pH. The total acidity contribution from *Sphagnum* to the water there is measured as 0.68 mEq m^{-2} y^{-1}, which is about 66 times lower than the estimated contribution from acid rain, but may still be important in assessing overall acidity inputs to the system. The bog without *Sphagnum*, Swamp Y, has a lower pH and an increased alkalinity. Because Hidden Swamp has a higher concentration of base cations in the water than Swamp Y, the pH difference between the swamps cannot be attributed to different nutrient concentrations, and Hidden Swamp must have a source of acidity. However, there is such a wide variety of potential sources and sinks for acidity, and the measured potential contribution of *Sphagnum* is so low, that *Sphagnum* cannot be identified as the major source of acidity until the relative importances of other sources are also assessed. More thorough studies with complete input-output budgets for mass and charge should be done to determine the primary mechanisms for control of acid-base chemistry in these systems.

Keywords and phrases: Sphagnum, bog, cation exchange, acidity, acid-base chemistry

INTRODUCTION

Peat-accumulating wetlands occupy 2-3% of the earth's land surface (Clymo, 1987). Most are located within 250 km of a coast, and are not elevated more than 50 m above sea level. Because of their proximity to coastal areas, bogs are susceptible to impacts of coastal development. Many bogs are now threatened, due to altered hydrology, nutrient loading, and impact of adjacent roads. When undisturbed, they are ombrotrophic, obtaining most of their nutrient inputs from atmospheric deposition and precipitation. Water and sediments of bogs are acidic, with a typical pH less than 4.5 (Clymo 1967). However, effects of disturbance include a change in species composition, altered water and sediment chemistry, and usually an increase in pH.

Sphagnum moss is an important constituent of peatland vegetation, and as a bryophyte is a member of the largest group of land plants (Gorham et al, 1985). Their rate of growth depends on water supply, and different species occupy characteristic habitats with varying water levels and specific ranges in chemical conditions (Clymo and Hayward, 1982). *Sphagnum* is also sensitive to atmospheric pollutants because of its one-cell thick, uncuticularized leaves (Clymo, 1987). For these reasons, *Sphagnum* is highly susceptible to the effects of disturbance, and *Sphagnum* species typically disappear from disturbed sites.

Because of unique cation exchange properties generated by *Spahgnum* plants, they have been studied as important sources of acidity in *Sphagnum*-dominated bogs. *Sphagnum* growth results in the continuous formation of cation exchange sites at the plant apex (Clymo, 1967). Most (if not all) uronic acids at these sites are manufactured in a free acid form: -COOH. When precipitation or groundwater flows over the plants, the hydrogens (H^+) on the carboxyl groups are then exchanged for cations in the water. This displaces the H^+ into solution, lowering the pH of surrounding waters (Gorham and Cragg, 1960). Clymo found that growth rates of *Sphagnum* are adequate to maintain a typical bog at pH 4, entirely by ion exchange mechanisms (Clymo, 1964).

Ion exchange by *Sphagnum* is just one of the various factors that may control bog acidity. Other studies have attributed possible sources of acidity to CO_2 build-up, oxidation of reduced N and S, assimilatory cation uptake, production of organic acids during decomposition, and acid deposition (Urban, 1987). Potential sinks include decompositional release of cations, alkalinity inputs, assimilatory anion uptake, dissimilitory anion reduction, and weathering reactions (Urban, 1987). The contribution to total bog acidity by each of these mechanisms varies among specific environments, and the relative importance of each has been argued over past decades.

To study the role of *Sphagnum* in a bog system, I examined whether bog disturbance changes the way acid-base chemistry is controlled, and whether this may be dependent on the presence of *Sphagnum*. In an undisturbed, *Sphagnum*-dominated bog, I assessed the importance of *Sphagnum* in maintaining low pH by comparing the contributions of exchangeable bases and exchangeable acids due to *Sphagnum* with what comes from soil pools. If *Sphagnum* is an important factor for generating acidity in bog systems, a disturbed site where *Sphagnum* has disappeared should have a higher pH than the undisturbed site, and a higher acid neutralizing capacity (alkalinity). The *Sphagnum*-dominated system should also have a larger amount of alkalinity caused by organic acids than by carbonate alkalinity, and lower amounts of sulfate uptake and denitrification (detectable by increased sulfate (SO_4^{2-}) and nitrate (NO^{3-}) concentrations).

METHODS

I examined two Atlantic White cedar swamps: Hidden Swamp, and Swamp Y. Hidden Swamp is located behind the Devil's Lane parking lot, and is adjacent to stands of forest on all sides. Because of inputs from run-off, this swamp is no longer ombrotrophic, but is still characterized as 'healthy'. The cedar trees are still reproducing, and the ground level is dominated by *Sphagnum*. Swamp Y is located across the street from the Devil's Lane parking lot, and is adjacent to a road and a gravel parking lot. The swamp's hydrology has been altered so that it is always flooded, and there is a possible inflow of nutrients from nearby cabins (including a daycare center) and uphill septic tanks. The cedars there are no longer reproducing, *Sphagnum* species are absent, and the site is considered to be disturbed.

The percent cover of *Sphagnum* in Hidden Swamp was estimated by creating perpendicular transects across the bog; one line was approximately North-South and extended 60 m, and the other was approximately East-West and extended 63 m. Every third meter on each line, I placed a 1 x 1 m quadrat and estimated the percent area of the quadrat that was comprised of a *Sphagnum*-moss complex. I also collected five 10 x 10 cm *Sphagnum* 'brownies' with 100% *Sphagnum* cover from random locations for moisture analysis. I then used this data to estimate total *Sphagnum* surface mass in Hidden Swamp. Swamp Y also contains trace amounts of *Sphagnum*, but could not be quantified and is negligible for the purpose of this study.

P v. I curves were calculated in an LI-6400 leaf chamber from live *Sphagnum* samples taken from Hidden Swamp. I used an LAI-2000 with a quantum sensor attachment to obtain a value of light attenuation to *Sphagnum* on the bog floor, taking readings for this at 11 locations on the North-South transect. By applying this light attenuation measurement to the Falmouth daily surface radiation data that WHOI has collected over the past year, I calculated the average amount of irradiance received by *Sphagnum* each day for a year. I then used a sine wave to develop a model that distributed light throughout the day on a minute scale. By averaging the photosynthetic rates that each P v. I curve predicted to correspond with the received light levels, this sine model supplied values that could be summed up to estimate daily GPP. I then generated 60 random days of data to create a daily GPP model, based on a Julian day and its coinciding total daily radiation. I plotted daily GPP against daily radiation and fit a new curve to derive a daily GPP model from the minute-minute information. By applying this model to the daily radiation for one year, I was able to scale up to total GPP of *Sphagnum* over one year. This modeling was based on a procedure from Rastetter et al (2003).

I analyzed filtered water samples from both swamps for pH, alkalinity, strong anion concentrations (NO^{3-} and SO_4^{2-}), and Ca^{++}, Mg^{++}, K^+ and Na^+ concentrations. I collected surface water samples from 6 locations in each swamp, determining these precise sites as representative of the entire swamp systems after examining a GIS map of both areas. From Hidden Swamp I extracted 3 pore water samples using a vacuum pump attached to a pipette, but could not do the same in Swamp Y because it is flooded. I used a pH meter for pH analysis, and determined alkalinity by performing a Gran potentiometric titration with 0.16N H_2SO_4 (Kling et al, 1991). The first titration endpoint in this method indicates the amount of acid required to convert all HCO_3^- to H_2CO_3, which is when the water loses its buffering capacity. At this point, total alkalinity of the water can be calculated, and all carbonate alkalinity is lost. A 0.1 M NaOH solution is added to raise pH again, and a second titration with H_2SO_4 is performed. Alkalinity can again be calculated, and the difference between the two alkalinity values obtained is the contribution of organic alkalinity. To determine nitrate and sulfate concentrations, I followed a nutrient analysis procedure adapted from Murphy and Riley (1962). Cation concentrations were detected with an atomic absorption spectrophotometer.

Two peat cores taken from Hidden Swamp were sectioned into depth intervals of 0-6 cm, 12-18 cm and 24-30 cm. I determined cation exchange capacity (CEC) as the sum of exchangeable bases and exchangeable acids through a method adapted from Robarge and Fernandez (1986). Where the method calls for dry soil samples for cation extractions from mineral soil, I used wet peat. For the measurement of exchangeable bases (Ca^{++}, Mg^{++}, K^+, Na^+) I used 1N NH_4Cl extracting solution (an unbuffered salt is preferred in order to minimize changes in soil pH) and the dry weight equivalent of 4 g of peat from each depth. Every depth interval was replicated in each core. The resultant filtrates from this extraction and all standards contained 0.1% lanthanum chloride to suppress ionization of the calcium, and the exchangeable base concentrations were detected with an atomic absorption spectrophotometer. These concentrations were converted from ppm to mEq/g as detailed in the protocol.

For the measurement of exchangeable acidity (also called potential acidity), defined as the sum of exchangeable Al and exchangeable H in a soil, I used 1N KCl extracting solution (an unbuffered salt is again preferred) and the dry weight equivalent of 2 g of peat from each depth. Every depth interval was again replicated in each core. The KCl extract was filtered, and titrated with 0.00082N NaOH to the phenolphthalein endpoint. Total acidity calculations were given in the protocol, and I did not measure exchangeable Al, as it is not pertinent to this study.

I also adapted the Robarge and Fernandez (1986) methods to measure CEC of *Sphagnum*. To determine the amount of *Sphagnum* to combine with each extract, I used a pH meter to estimate the amount of moss it would take to begin to lower the pH of 50 mL of 1N KCl. This was the dry weight equivalent of about 0.2 g *Sphagnum*, but I used the dry weight equivalent of about 0.4 g *Sphagnum* for the KCl exchangeable acidity extract, and about 0.75 g for the NH_4Cl exchangeable base extract. The rest of the procedure is the same as for the peat measurements.

RESULTS

There are approximately 7.6 g (dry) *Sphagnum* per m^2 in Hidden Swamp, and 28871 g (dry) *Sphagnum* in the entire bog (Table 1). The GPP for *Sphagnum* in Hidden Swamp is 1.6 g C m^{-2} y^{-1}, or 3.2 g (dry) *Sphagnum* m^{-2} y^{-1}. Assuming that respiration is 50% of GPP, NPP is 0.8 g C m^{-2} y^{-1}, or 1.6 g (dry) *Sphagnum* m^{-2} y^{-1}.

Sphagnum from Hidden Swamp has a larger total CEC (mEq/g) than peat (Fig. 1 & Table 2). CEC of peat soil is largest in the 24-30 cm depth interval, and smallest in the 12-18 cm interval. The amount of the total CEC comprised of exchangeable bases (base saturation) is 72% (Fig. 1). *Sphagnum* has a higher concentration of exchangeable base cations (Ca^{++}, Mg^{++}, K^+, Na^+: mEq/g) than peat at all depths (Fig. 2 & Table 2). Na^+ is the most abundant exchangeable base in the *Sphagnum*, and K^+ concentration is low for all samples.

Multiplying NPP *Sphagnum* (g m^{-2} y^{-1}) by the CEC of *Sphagnum* (mEq/g) indicates that *Sphagnum* in Hidden Swamp has a total CEC of 0.93 ± 0.03 mEq m^{-2} y^{-1} (Table 1). If an average of 72% of this total CEC is held by exchangeable bases (this agrees with a variety of published data), this indicates that 0.68 ± 0.03 mEq m^{-2} y^{-1} protons are released by CEC of *Sphagnum*, and gives a prediction of potential acidity released to the bog via this mechanism.

The pore water in Hidden Swamp has a higher pH than surface water, but pH of both surface and pore water in Hidden Swamp is lower than in Swamp Y (Table 3). Total alkalinity (mEq/L) is largest in water from Swamp Y, lower in pore water from Hidden Swamp, and lowest in surface water from Hidden Swamp (Fig. 3). Organic alkalinity (mEq/L) is also largest in water from Swamp Y, slightly lower in pore water from Hidden Swamp, and lowest in surface water from Hidden Swamp (Fig. 4).

Total base cation concentrations (Ca^{++}, Mg^{++}, K^+, Na^+: mEq/L) are higher in Hidden Swamp than in Swamp Y and pore water in Hidden Swamp has a higher total cation concentration than surface water (Fig. 5 & Table 4). Both the surface and pore water in Hidden Swamp have higher nitrate and sulphate concentrations (µM) than Swamp Y (Figs. 6 & 7).

DISCUSSION

In interactions between CEC of *Sphagnum* with CEC of the soil, *Sphagnum* is a source of acidity, and soil is a neutralizer. Each *Sphagnum* exchange site is created with an exchangeable proton, while soil exchange sites have some exchangeable acids, but are mostly occupied by exchangeable bases. Over time, protons from the *Sphagnum* are exchanged for base cations from the soil, until a dynamic equilibrium is reached. This is when both the *Sphagnum* and the soil have the same amount of exchangeable bases occupying their exchange sites (base saturation, Fig. 1). In this way, cation exchange in the soil buffers it from becoming more acidic due to the *Sphagnum* cation exchange.

Sphagnum in the Hidden Swamp system has a lower CEC than average reported values (0.7-1.7 mEq/g Hemond, 1977), but it is still greater than soil CEC (Fig. 1), so the number of protons released from *Sphagnum* exchange sites may exceed the number that the soil is able to take up. This reduces the soil's buffering capacity and increases acidity of the soil and pore water (analyzing pore water provides an indication of how the sediments affect overlying water). The pore water and soil in Hidden Swamp have slightly higher pH values than surface water, but are still relatively low (Table 2). Pore water in Hidden Swamp has a higher concentration of total base cations than the surface water, which could also contribute to increased pH (Fig. 5).

The difference in CEC among the three depth intervals of the peat core may be explained by the pattern of the rooting zone. The top layer from the core (0-6 cm) consists of the newest layer of decomposing organic matter. The middle section (12-18 cm) is mostly occupied by roots, and the bottom layer (24-30 cm) is below the rooting zone, where the largest amount of peat (decomposing organic matter) is found. Because the middle layer has the most roots, it has less soil matter per g material, and a correspondingly lower CEC (Fig. 1). The trend for total exchangeable base cations at varying soil depths is also explained by the different total exchange capacities (Fig. 2).

Sphagnum has a higher concentration of total exchangeable base cations than soil, also reflecting its larger total exchange capacity (Figs. 1 & 2).

A divergent trend in exchangeable base cation concentrations is seen in *Sphagnum* from Hidden Swamp. The CEC of *Sphagnum* is expected to increase with increasing atomic number and valence: $Na^+ < K^+ < Ca^{++} < Mg^{++}$ (Kilham, 1982), so Mg should be the most highly concentrated exchangeable base found on *Sphagnum*. In Hidden Swamp, Na^+ is found in highest concentration on *Sphagnum* (Fig. 2). A study by Hemond, 1977 showed that *Sphagnum* increasingly exchanges H^+ for Na^+ as pH increases. However, the pH of Hidden Swamp is not high enough that this mechanism is expected to control CEC.

Swamp Y has a higher pH and a larger ability to buffer against acidity (alkalinity) than Hidden Swamp, which corresponds with the absence of *Sphagnum* from Swamp Y (Table 2 and Fig. 3). The increased pH of water in Swamp Y could be explained by a higher base cation concentration, but this is not the case. Surface water in Swamp Y has a lower base cation concentration than in Hidden Swamp, indicating that Hidden Swamp must have a source of acidity that Swamp Y does not have. Both sites receive the same amounts of acid rain, which inputs about 45 mEq m^{-2} y^{-1} into each system (typical acid rain input to New England, Giblin et al, 1990). While the potential acidity released to the bog via cation exchange from *Sphagnum* is only about 0.68 mEq m^{-2} y^{-1}, this may have a small contribution to the difference in acidity. Bryophyte growth also contributes to acidity by assimilatory cation uptake. To maintain electroneutrality, if a plant takes up a positively charged ion, another positively charged ion is then released. The converse is true for negative ions (Kilham, 1982). However, up to 90% or more of the original plant material may be decomposed, leading to the release of these basic cations and consuming acidity (Urban 1987). In a completely balanced system, nutrient uptake by plants would equal nutrient regeneration during decomposition, so that acid-base chemistry is not affected by differential uptake of anions and cations (Kilham, 1982). However, this is not usually the case, and further research on the effects of cation and anion uptake by plants in Hidden Swamp and Swamp Y should be done to fully understand these mechanisms.

Soil has the ability to neutralize acid by CEC, or through anaerobic metabolism. Mechanisms of anaerobic metabolism include denitrification and sulphate reduction, which generate alkalinity and may contribute to the increased alkalinity of Swamp Y. For every mEq of NO^{3-} or SO_4^{2-} that is lost (reduced), 1 mEq of alkalinity is produced. However, any alkalinity generated through sulphate reduction may be balanced by re-oxidation of reduced S compounds, which generates acidity. This indicates that S reduction and oxidation do not have long-term effects on acidity in bog systems (Urban, 1987). N is typically limiting to plant growth in bog systems, and uptake of NO^{3-} by *Sphagnum* is rapid, so N retention by peatlands is generally high, and NO^{3-} concentrations in bog waters should be low (Urban, 1987). This rate of NO^{3-} uptake by bryophytes is large enough to prevent much NO^{3-} from reaching reducing anaerobic zones where denitrification can occur. Although bog systems are expected to have low denitrification rates to begin with, because NO^{3-} and SO_4^{2-} concentrations were lower in Swamp Y than in Hidden Swamp (Figs. 6 & 7), water in Hidden Swamp is probably more oxic and has even less N and S reduction. Since pore water is in contact with the soil, where N and S reduction occurs, I expected NO^{3-} and SO_4^{2-} concentrations in pore water to be lower than in surface water. Because anaerobic metabolism of the soil does not appear to be the source of the increased alkalinity seen in the pore water (Fig. 3), the alkalinity there must be generated by CEC of the soil.

One component of total alkalinity in peatlands is organic alkalinity, and there is a wide variety of organic acids (including humic and fulvic acids) in bog waters. One organic acid input is the release of polygalacturonic acid from cell walls of *Sphagnum* upon decomposition (up to 30% d.w. of *Sphagnum* is galacturonic acid, Clymo, 1963). Different concentrations of organic alkalinity reflect either the amounts of organic acids present, or different pk values (the average pH at which protons are added or removed). The positive organic alkalinity in water from Swamp Y may be buffering the bog towards an increase in pH, while the organic alkalinity in water from Hidden Swamp appears to buffer it towards a decrease in pH (Fig. 4). The measured organic alkalinity of pore water in Hidden Swamp is inconclusive from the data available. More research is needed to determine how much the organic alkalinity contributes to the pH and buffering capacity of these systems.

CO_2 build-up is another potential source of total acidity, but it probably does not affect the levels of acidity seen in the systems studied here. While dissolved CO_2 can contribute to total acidity, it is not likely to be the determinant of pH in systems with pH below 4.5. This is because maintaining pH below 4.5 via CO_2 requires a partial pressure of CO_2 that is 100 times that of atmospheric concentrations (Urban 1987), an unlikely condition.

The inputs and outputs of acidity in any bog system are so numerous and variable that it is difficult to identify what plays the largest role in a bog's acid-base chemistry. The H^+ input from acid rain is about 66 times larger than the H^+ input from *Sphagnum* via cation exchange. A study of Thoreau's Bog is Massachusetts (Hemond, 1980) showed that acid deposition was neutralized by alkalinity generated by N and S reduction, while another study suggests that acid rain predominates over internal sources of hydrogen-ion production (Kilham, 1982). In either case, *Sphagnum* does seem to play a role in generating acidity in environments where it is dominant. The potential acidity contribution from *Sphagnum* in Hidden Swamp is much lower than the *Sphagnum*-dominated Marcell Bog in northcentral Minnesota (0.68 mEq m^{-2} y^{-1} vs. 129 mEq m^{-2} y^{-1}; Urban, 1987).

The difference between this previously published value and what I found in Hidden Swamp may exist for a number of reasons. The method used here to estimate productivity from a direct photosynthesis (carbon fixation rate) has not been attempted before, and may be a poor measure of actual *Sphagnum* productivity (other published *Sphagnum* NPP values range from 45-150 g C m^{-2} y^{-1}; Brisbee et al, 2001). Although Hidden Swamp is not yet considered to be a 'disturbed' site, it borders a road and a parking lot. There are few *Sphagnum* mats throughout the system, and the density of the cedar forest around the bog reduces light availability. Either *Sphagnum* was never more abundant here, or it is in a state of decline and the controllers of acid-base relationships are changing. This could include the loss of *Sphagnum* to the system, but as there is no earlier data on *Sphagnum* in Hidden Swamp, this cannot be proven. What is evident is that while the CEC of *Sphagnum* may contribute slightly to the acidity seen in Hidden Swamp, it does not stand on its own as a primary mechanism for acid-base control. Truly assessing acid-base chemistry of a bog system requires a complete input-output budget for mass and charge. Future studies that focus on this task may provide a more thorough report of what controls acidity in these systems.

ACKNOWLEDGEMENTS

I would like to thank Chuck Hopkinson, Anne Giblin, Pat Micks, Ed Rastetter, Joe Vallino, Aimlee Laderman, Gus Shaver, Jerry Melillo, Becky Karasack, Marcus Gay, Leslie Graham, Ian Washbourne, Caitlin Hicks, Katie Kleese, and Beth Bernhardt for their help in completing this study.

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Table 1. *Sphagnum* standing stock and productivity in Hidden Swamp.

Sphagnum in Hidden Swamp	
Frequency (%)	39
AVG mass (g/m^2)	7.6
Total surface mass in bog (g d.w.)	28871
GPP (g C m^{-2} y^{-1})	1.6
GPP (g d.w. *Sph.* m^{-2} y^{-1})	3.2
NPP (g C m^{-2} y^{-1})	0.8
NPP (g d.w. *Sph.* m^{-2} y^{-1})	1.6
Total CEC in bog (mEq m^{-2} y^{-1})	0.93 ± 0.03 (n=3)
Potential acidity contributron (mEq m^{-2} y^{-1})	0.68 ± 0.03 (n=3)

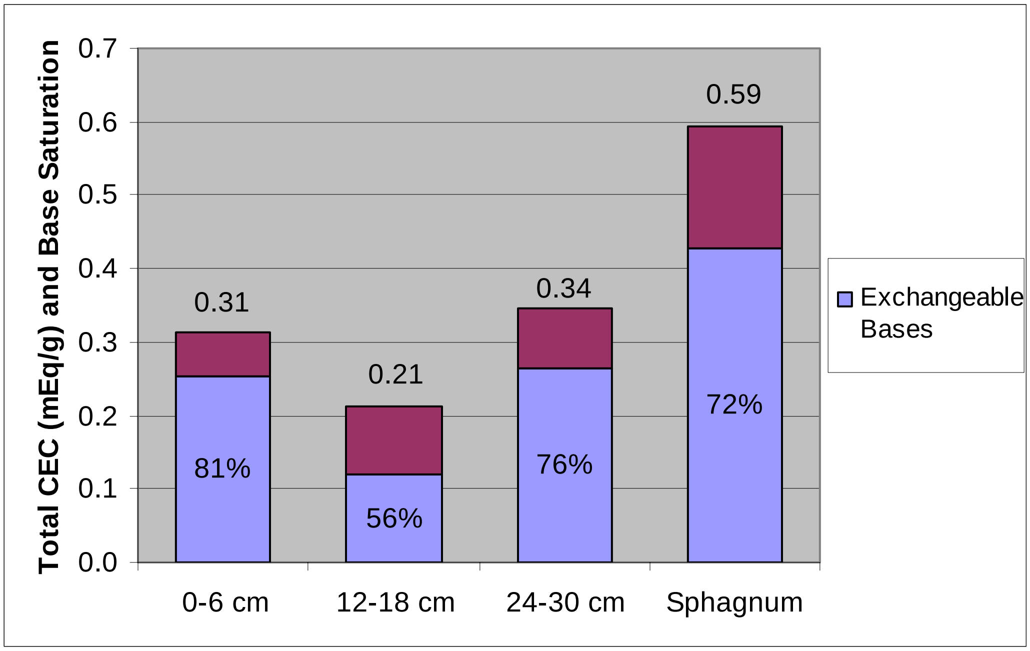

Figure 1. Total cation exchange capacity (CEC, mEq/g) for *Sphagnum* and a peat core (replicated and averaged) sectioned into three depth intervals. The percent of CEC comprised of exchangeable bases is the base saturation (%) and is reported on the graph. All samples are from Hidden Swamp.

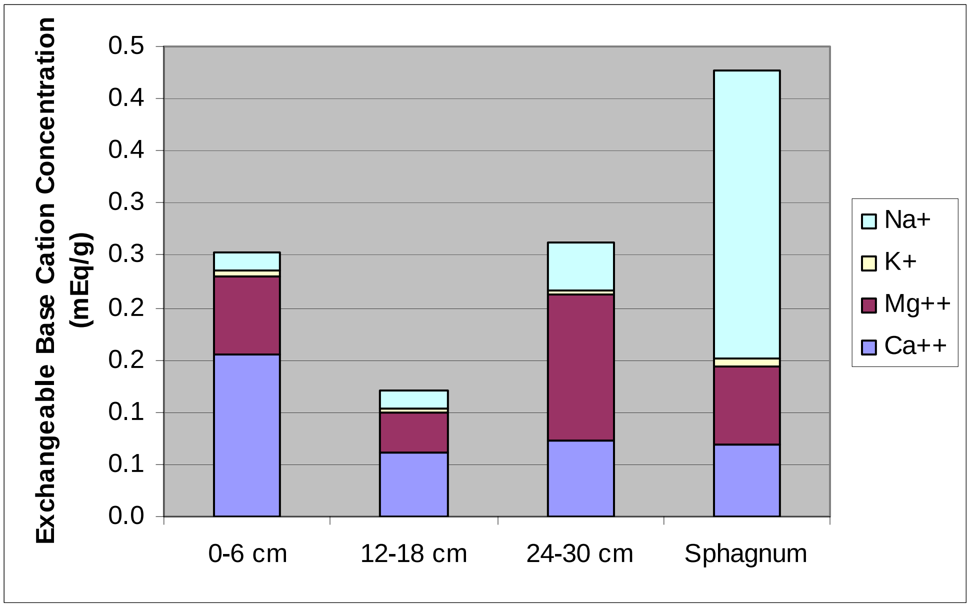

Figure 2. Exchangeable base cation concentrations (Ca^{++}, Mg^{++}, K^{+}, Na^{+}) for *Sphagnum* and a peat core (replicated and averaged) sectioned into three depth intervals. All samples are from Hidden Swamp.

Table 2. Mean ± standard error of CEC and exchangeable base cation concentrations (mEq/g) of *Sphagnum* and a peat core sectioned into three depth intervals from Hidden Swamp (values also illustrated in Figs. 1 & 2, n = 3 for *Sphagnum*).

	Sphagnum	*Peat*		
mEq/g	**Mean ± SE**	**0-6 cm**	**12-18 cm**	**24-30 cm**
CEC	0.59 ± 0.033	0.327	0.301	0.210
Ca^{++}	0.067 ± 0.003	0.154	0.062	0.074
Mg^{++}	0.074 ± 0.005	0.075	0.039	0.138
K^{+}	0.006 ± 0.002	0.006	0.003	0.004
Na^{+}	0.276 ± 0.032	0.018	0.018	0.047

Table 3. pH of surface water ± standard error in Hidden Swamp and Swamp Y, and pore water in Hidden Swamp (n=6 for surface water, n=3 for pore water).

Site	**Average pH ± SE**
HS Surface Water	3.75 ± 0.03
HS Pore Water	4.02 ± 0.22
HS Soil	4.24 ± 0.08 *
Swamp Y	4.32 ± 0.1

** Obtained from Hicks, 2003, unpublished data*

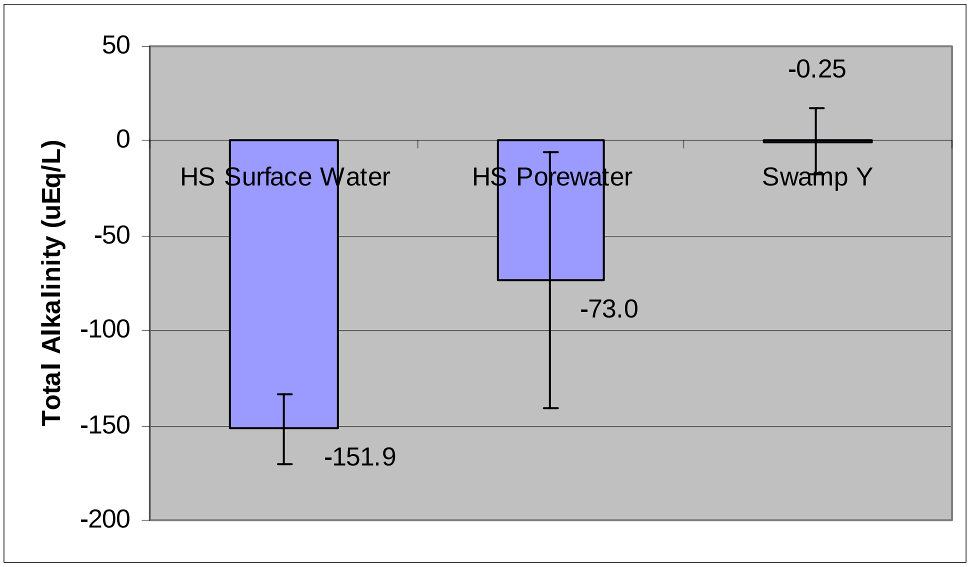

Figure 3. Total alkalinity ± standard error (uEq/L) of surface water in Hidden Swamp and Swamp Y, and pore water in Hidden Swamp (n=6 for surface water, n=3 for pore water).

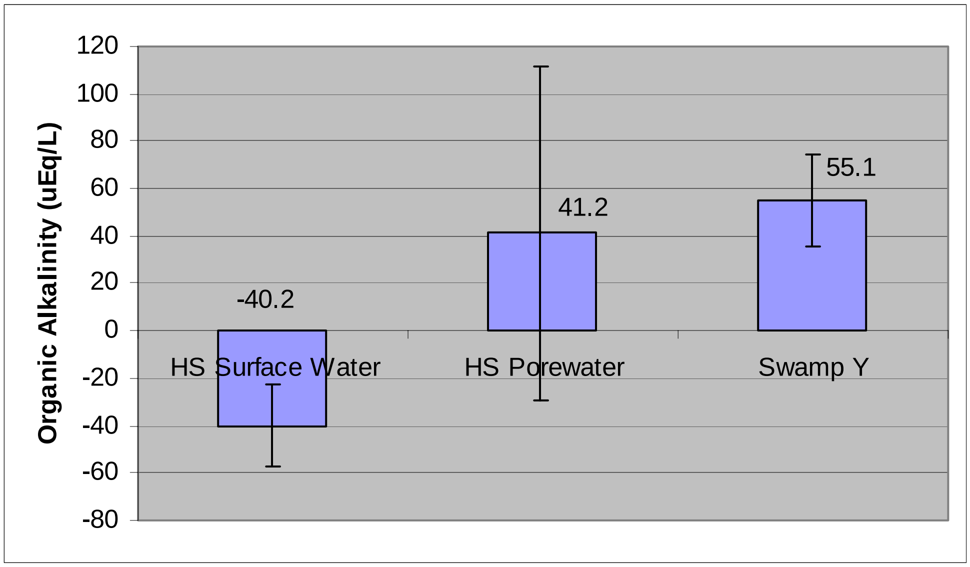

Figure 4. Organic alkalinity ± standard error (uEq/L) of surface water in Hidden Swamp and Swamp Y, and pore water in Hidden Swamp (n=6 for surface water, n=3 for pore water).

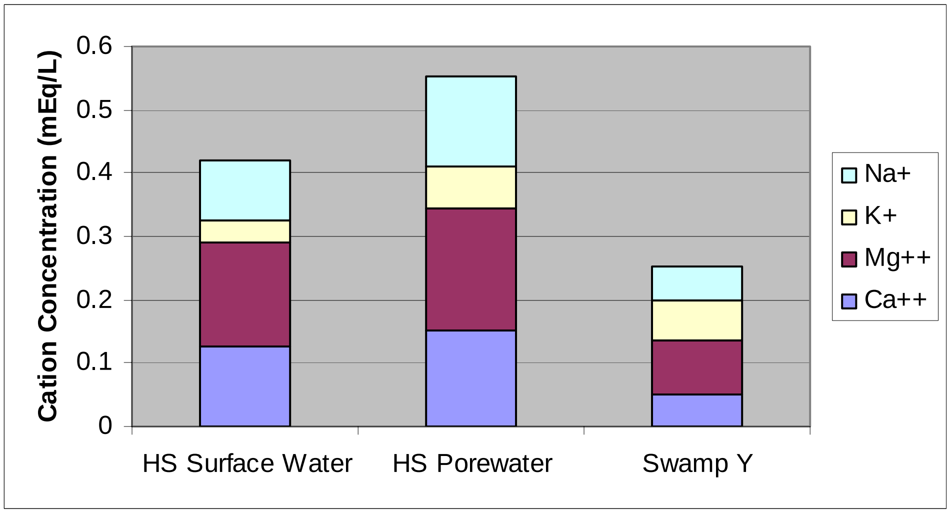

Figure 5. Total base cation concentrations (Ca^{++}, Mg^{++}, K^{+}, Na^{+}) of surface water in Hidden Swamp and Swamp Y, and pore water in Hidden Swamp.

Table 4. Mean ± standard error of base cation concentrations (mEq/g) of surface water from Hidden Swamp and Swamp Y, and pore water from Hidden Swamp (values also illustrated in Fig. 5, n = 6 for surface water, n=3 for pore water).

	Mean ± SE (mEq/g)			
Site	*Ca^{++}*	*Mg^{++}*	*K^{+}*	*Na^{+}*
Hidden Swamp Surface Water	0.13 ± 0.01	0.16 ± 0.01	0.03 ± 0.01	0.1 ± 0.01
Hidden Swamp Pore Water	0.15 ± 0.03	0.19 ± 0.03	0.07 ± 0.02	0.14 ± 0.02
Swamp Y	0.05 ± 0.00	0.09 ± 0.00	0.07 ± 0.00	0.05 ± 0.01

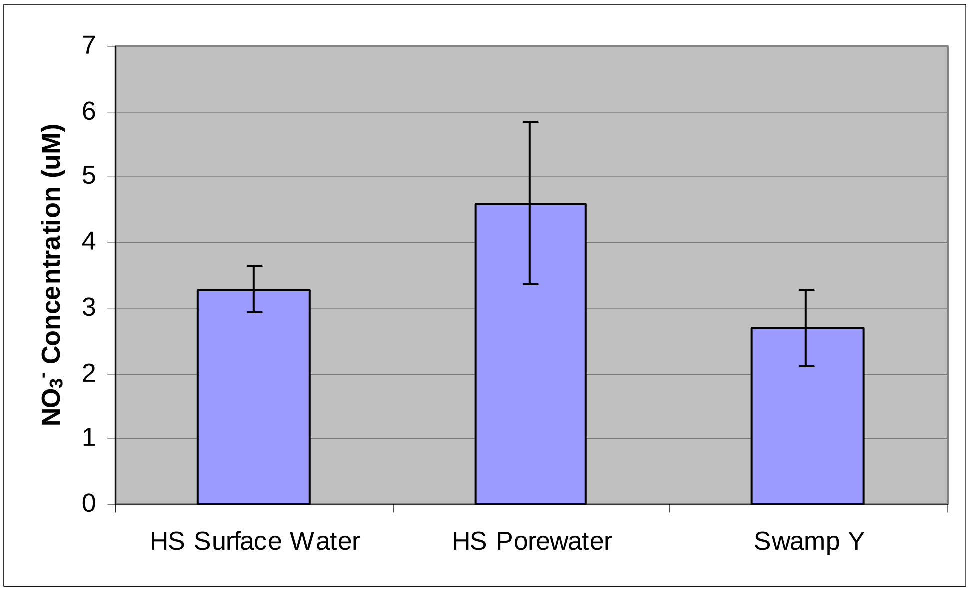

Figure 6. Nitrate concentration ± standard error (µM) of surface water in Hidden Swamp and Swamp Y, and pore water in Hidden Swamp (n=6 for surface water, n=3 for pore water).

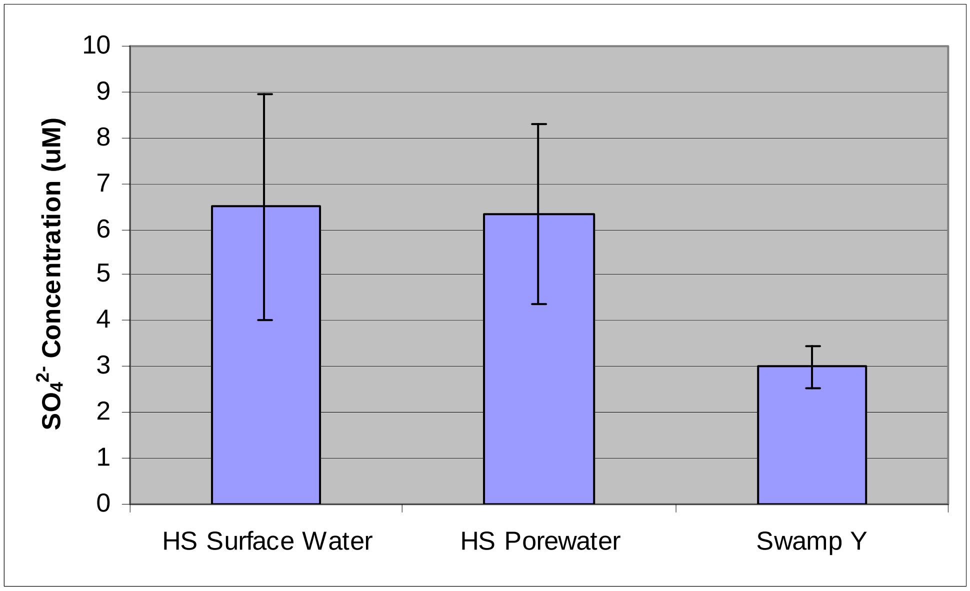

Figure 7. Sulphate concentration ± standard error (µM) of surface water in Hidden Swamp and Swamp Y, and pore water in Hidden Swamp (n=6 for surface water, n=3 for pore water).