

Nutrient limitations on peat decomposition and nutrient loading in Atlantic White Cedar swamps

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Abstract

Like many wetlands, Atlantic White Cedar (*Chamaecyparis thyoides*) swamps are experiencing anthropogenic disturbances causing changes in hydrology and increased nutrient loading. In this study, I examined the effects of nutrient increases on peat decomposition. I analyzed peat and porewater nutrients in two initial cores. I incubated eight cores in the laboratory—two fertilized with phosphate, two fertilized with nitrate, two fertilized with ammonium, and two controls. I measured the cores' CO₂ and CH₄ production rates with a gas chromatograph and a Li-COR (CO₂ only). After incubation, I analyzed porewater nutrients in all incubated cores. Nutrient loading was examined with a land use model and a comparison of surface water nutrients. The initial C:N and C:P ratios of the peat were higher than the molar ratios needed by bacteria, suggesting both N and P are limiting. The porewater N:P ratios varied with depth suggesting porewater N and P are each limiting at different depths in the cores. The CO₂ and CH₄ fluxes of all incubated cores increased. The CO₂ fluxes of the phosphate-treated cores and ammonium-treated increased the most, further supporting that both N and P are limiting. The CH₄ data was inconclusive. Porewater ammonium increased during the incubation indicating increased mineralization of N. Porewater phosphate decreased during the incubation in all but the phosphate-treated cores indicating that phosphate was limiting, and therefore immobilized by the bacteria, in the other cores. Porewater nitrate decreased in all fertilized cores suggesting an increased use of nitrate as an electron acceptor. For the loading question, Swamp Y, which is closer to development than Hidden Swamp, had higher surface water phosphate and ammonium concentrations. The amount of N loading depended on watershed delineation, but in general Hidden Swamp had higher N loading than Swamp Y. Because added nutrients increase peat respiration rates, increased nutrient loading into cedar swamps may alter their capacity as a carbon sink.

Keywords and phrases: *decomposition, respiration, peat cores, limiting nutrients, Atlantic White Cedar swamp, water chemistry, nutrient loading*

Introduction

The range of Atlantic White Cedar (*Chamaecyparis thyoides*) swamps is naturally restricted. White cedar swamps are confined to the coast of the Eastern United States below 44° N latitude. Most white cedar swamps are within 250 km of the shore and no more than 50 m above sea level (Laderman 1987). White cedar swamps are characterized by low nutrients, low pH (3.1 to 4.5), deep formations of peat, and periods of standing water. Humans are increasingly intruding upon their narrow range. Humans log or drain many cedar swamps for development and agriculture. Cape Cod is no exception, where white cedar swamps dot the landscape in kettle depressions. Many white cedar swamps are lost, having been converted into cranberry bogs (Laderman 1987). Many of the remaining white cedar swamps on the Cape are adjacent to roads and housing developments with septic tanks.

The anthropogenic impacts that do not erase the swamps from the landscape change the swamps' hydrology and nutrient loading. Roads can block the outflow of water creating a dam that leaves standing water in the swamp year round (Atkinson et al. 2003). Cedars though partial to wet places, cannot withstand long periods of total inundation and often die within a few years of flooding. Drainage ditches can lower water tables within the swamps (Ehrenfeld and Schneider 1991). Septic tank effluent in the groundwater and storm runoff can bring excess nutrients into the swamps. Alterations in hydrology can change rates of CO₂ respiration in the peat of cedar swamps (Duttry et al. 2003). Lower water tables and drier peat increase rates of decomposition. Increased nutrient loadings into the swamps may also change rates of peat decomposition.

The decomposition of organic matter is often limited by its relative amounts of nutrients (Aber and Mellilo 2001). The more easily digestible nutrients organic matter has, the faster the microbes can decompose it. External nutrients in the surrounding water may also affect rates of decomposition. In freshwater wetlands, phosphorus limits primary productivity because it is held just below the sediment-water interface by iron oxides (Valiela 1995). This geochemical sequestering of phosphorus also prevents it from diffusing up into layers of decaying organic matter. Studies in the Everglades (Qualls and Richardson 2000, DeBusk and Reddy 1998, and Amador and Jones 1993) and in coastal marshes (Sundareshwar et al. 2003) have shown that phosphorus in the water limits decomposition rates. Amador and Jones (1993) have also shown that ammonium inhibits decomposition if high amounts of phosphate are present. A study on decomposition in streams did not see much of an effect of phosphorus on carbon mineralization but did see a positive effect of nitrate (Howarth and Fisher 1976). Nutrients that are not part of the decomposing substrate can affect decomposition, but which nutrients do and the magnitude of their effect may be site specific.

The purpose of my investigation was to examine whether phosphate, nitrate, or ammonium affect peat decomposition rates in cedar swamps and whether anthropogenic nutrient loading is occurring in Woods Hole's cedar swamps. I answered the first question through laboratory incubation of peat cores from one cedar swamp fertilized with phosphate, nitrate, or ammonium. I answered the second question by sampling surface water in two of Woods Hole's cedar swamps and by modeling the nitrogen loading into those two cedar swamps.

Methods

Study Sites

The two Atlantic White Cedar swamps studied were both in Wood's Hole, Massachusetts. The first study site, "Hidden Swamp," is located behind the Devil's Lane parking lot of the Marine Biological Laboratory. Forest stands surround the swamp on all sides. It has the hummock and hollow topography typical of many cedar swamps with standing water in many of the hollows. Hidden Swamp has a healthy and actively reproducing white cedar population (Laderman, personal communication). Past SES projects have considered Hidden Swamp a non-impacted site. The second study site, "Swamp Y," is located across the road from the Devil's Lane parking lot. This swamp is bordered by a road on one side, a gravel parking lot on the other side, and houses with septic tanks on the remaining sides. Swamp Y has an altered hydrology, most likely due to the surrounding development. It has standing water year round that is causing the cedars to die. Past SES projects have considered Swamp Y an impacted site.

Nutrient Limitation

The nutrient limitation question of my study was investigated through a laboratory incubation of peat cores from Hidden Swamp fertilized with phosphate, nitrate, or ammonium. In November, 2003 I took eight 45 cm long peat cores for my fertilization experiment from two hollows within Hidden Swamp using a 16 cm diameter stainless steel corer. The corer had a sharp end that cut through most of the roots in the peat. Roots that the corer could not slice through were cut with a pair of clippers. After obtaining each core, I transferred them into a PVC core tube of equal size where they remained for the duration of the experiment. Each core tube had about 4 cm of headspace. I took two other cores for initial nutrient analysis from the same two hollows using the stainless steel corer. In the field, I cut those cores into five, 6 cm sections (0-6 cm, 6-12 cm, 12-18cm, 18-24 cm, and 24-30 cm). The sections were then stored in the refrigerator for later analysis.

I used the two sectioned cores to measure initial porewater concentrations of nitrate, ammonium, and phosphate, initial KCl extractable ammonium, as well as the carbon, nitrogen, and phosphorus content of the peat. On each section, I performed a deionized water (DI) extraction using 80 mL of DI and 10 g of peat and a KCl extraction using 50 mL of 1M KCl and 5 g of peat. For both extractions, the peat solution was then mixed on a shaker table for one hour. I then centrifuged the DI extraction samples before gravity filtering all samples through Whatman 42 filters. The KCl extraction samples were then frozen for later ammonium analysis. I further filtered the DI extraction samples through a Whatman GF/F filter and sub sampled them for ammonium, nitrate, and phosphate analysis. Nitrate samples were frozen, and the ammonium and phosphate samples were acidified for later analysis. Nitrate concentrations were analyzed using a Lachat QuikChem 8000 Autoanalyzer. Ammonium (Solarzano 1969) and phosphate (Murphy and Riley 1962) concentrations were obtained through colorimetric analysis using a Shimadzu UV-VIS Spectrophotometer. While I was weighing out the peat for the extractions, I also measured a wet weight of peat from each section for moisture content analysis. I measured the dry weights after two days in the drying oven and then ground up the dry peat using a Wiglbud for C, N, and P analysis. I used a Perkin Elmer Series II CHN Analyzer 2400 to obtain the C and N content of the peat. For the P analysis, peat

samples were ashed with 50% weight by volume $\text{Mg}(\text{NO}_3)_2$, then shaken for 16 hours with 1N HCl. I used the colorimetric analysis to find the phosphate concentration in the resulting solution.

For my fertilization experiment, I set up the eight cores in the lab and let them adjust to room temperature for six days before taking initial CO_2 and CH_4 flux measurements using a Shimadzu 14A gas chromatograph (GC) with Porapak Q column, a flame ionization detector, and a thermal conductivity detector. I sealed the cores and, using a syringe, took three sets of gas samples from the headspace of the cores over the course of several hours. Each set of gas samples was injected into GC within 45 minutes to prevent gas loss from the syringes. Rates were calculated as the linear change in concentration over time (Duttry et al. 2003) adjusted for head space volume and peat surface area.

After initial CO_2 respiration and methane production rates were taken, the fertilization treatments began with two control cores, two cores fertilized with phosphate, two cores fertilized with nitrate, and two cores fertilized with ammonium. Before fertilizing the cores, I pumped out an amount of water equivalent to what I would be putting in the cores. I fertilized the cores by injecting seven equal amounts of a 10 mM solution of the desired nutrient using a long syringe bringing the porewater concentrations of the desired nutrient to about 300 μM . I measured CO_2 respiration using a Li-COR 6200 10 times throughout the 19 day incubations. I also measured CO_2 respiration and CH_4 flux three times throughout the incubation using a GC as with the initial flux measurements. During incubation, water lost from the cores due to evaporation was replaced with DI in order to keep the surface of the peat constantly wet as it was in the bog. At the end of the incubation I took apart the eight cores to measure final porewater concentrations of nitrate, ammonium, and phosphate, and final KCl extractable ammonium. I performed the same extractions as on the initial cores on peat from three sections within each core (0-6 cm, 12-18 cm, and 24-30 cm).

Nutrient Loading

As part of my investigation of nutrient loading in the swamps, I took water samples from both Hidden Swamp and Swamp Y and modeled the nitrogen loading. The water samples were collected by dipping acid-washed bottles into the surface water. Using an aerial photograph as a guide, I sampled the surface water at various locations in each swamp in order to get water samples that together would represent the entire swamp. In Hidden Swamp these samples came from the standing water in the hollows. All samples were filtered through a Whatman GF/F before being preserved for later nitrate, ammonium, and phosphate analysis. To model the nitrogen loading into the two swamps, I used ArcMap (ESRI) to delineate watersheds in two ways: one based on surface topography and the other based on the groundwater divide. I used an orthographic projection to count the number of houses in each watershed. I then used a land use model developed by Valiela et al (1997) to calculate the magnitude of nitrogen loading into the two swamps (Table 1). I also calculated the nitrogen loading on the basis of precipitation alone by using the current year's precipitation data from the Falmouth wastewater treatment forest.

Results

Initial peat nutrients

The depth profiles of the initial cores showed that porewater concentrations of KCl extractable ammonium and phosphate changed with depth, whereas the nitrate and ammonium concentrations were more consistent with depth (Fig. 1). The concentration KCl extractable ammonium increased with depth, with the highest concentration occurring at 24-30 cm. Phosphate was absent from the first depth layer but had its highest concentrations in the second depth layer before decreasing with depth. Ammonium was very low in the first depth layer and absent from the third depth layer. The mean initial porewater N:P molar ratios also changed with depth (Fig 2). The highest N:P ratios were in the first and fifth depths, while the lowest were in the second through fourth depth layers. The mean initial C:N ratios of the peat decreased with depth (Fig. 3) and ranged from 45.6 in the first depth layer to 32.5 in the fifth depth layer. The mean initial C:P ratios of the peat did not have any trend with but remained high, ranging from 2296 to 3508 (Fig. 4). The mean initial N:P ratios of the peat increased with depth (Fig 5).

Incubations

The mean respiration rates increased over time in all of the cores including the controls (Fig. 6 and 7). The rates, as measured with the Licor, had a lag time of a few days after fertilization before they began to increase (Fig. 6). The rates of the phosphate-treated cores had the greatest magnitude of increase over the length of the incubation, with the ammonium-treated cores having the second greatest magnitude of increase. However, the respiration rates of the ammonium cores started to decrease after their initial increase, while the rates of the phosphate cores continued to increase for several more days. The nitrate-treated cores had the least amount of increase throughout the incubation, less than even the control. All rates began to decrease slightly throughout the last nine days of incubation.

The respiration rates as measured with the GC showed some different trends than the rates measured with the Li-COR. As in the Li-COR measurements, during the first 10 days of incubation, the phosphate-treated cores had the greatest rate increase, almost doubling their respiration rate, and the ammonium-treated cores had the next greatest rate increase (Fig 7). The respiration rates of the ammonium-treated cores also began to decrease after 10 days while the rates of the phosphate cores plateaued. Unlike the Li-COR measurement, the GC measurement had the nitrate cores increasing greatly throughout the incubation, so that by day 17, their respiration rate equaled the rate of the phosphate cores. The rates of the control cores increased faster than the treated cores at first but over the course of the incubation had only a small net increase.

The methane flux rates increased for all cores except one control core during the incubation (Fig 8). The increase of the treated cores' methane fluxes lagged behind the increase the control cores' methane fluxes. All of the treated cores' methane fluxes had roughly the same magnitude of increase from the second to third time point. Overall, the nitrate cores had the greatest increase because their methane fluxes continued to increase from the third to fourth time point, unlike the rest of the cores whose fluxes decreased over those time points.

Post incubation nutrients

The porewater concentrations of all nutrients changed in the incubated cores relative to the initial cores. The mean concentrations of KCl extractable ammonium increased at all depths in all incubated cores relative to the initial cores (Fig. 9). The mean concentrations of porewater ammonium also increased at all depths relative to the initial cores (Fig. 10). The increase in KCl extractable and porewater ammonium concentrations was not different in the ammonium treated cores relative to the other incubated cores. The porewater phosphate concentration only increased in the phosphate-treated cores relative to the initial cores (Fig. 11). The phosphate cores had increases in concentration greater than their fertilization concentration of 300 μ molar in the 12-18cm and the 24-30cm depth layers. The rest of the incubated cores did not have any porewater phosphate. The porewater nitrate concentrations decreased in all of the incubated cores relative to the initial cores (Fig. 12). The porewater nitrate decreased the most in the 12-18cm and 24-30cm depth layers of the nutrient-treated cores. The nitrate-fertilized cores did not have higher porewater concentrations of nitrate than the other cores.

Nutrient loading

Swamp Y and Hidden Swamp differed significantly in their ammonium and phosphate surface water concentrations but did not differ in their nitrate surface water concentrations. Swamp Y had a higher concentration of ammonium than Hidden Swamp (Fig. 13). Swamp Y also had a higher concentration of phosphate than Hidden Swamp (Fig. 13). Both Swamp Y and Hidden Swamp had low nitrate concentrations of about 3 μ molar (Fig. 13). The nutrient concentrations in the surface water were generally lower than the concentrations in the porewater of the deeper peat layers (Fig. 1).

The amount of nitrogen loading into Swamp Y and Hidden Swamp depended on how the watersheds were delineated (Fig 14 and 15). The topographic-derived watersheds were larger than the groundwater divide-derived watersheds and had more nutrient loading (Table 2). Topographic watersheds that assumed the swamps had no groundwater interaction and only included surface runoff, had less nitrogen loading into the two swamps than either of the groundwater watersheds. Hidden Swamp's loading was higher than Swamp Y's loading because both of its possible watersheds included the watershed of Swamp Y. Using a topographic watershed and assuming all of the nitrogen loaded into Swamp Y stays in Swamp Y, the nitrogen loaded into Hidden Swamp was much lower than the nitrogen loaded into Swamp Y. All watershed scenarios had nitrogen loading into the swamps much higher than what the swamps would receive under proposed pristine conditions. The pristine conditions assumed the swamps were ombrotrophic and therefore only received nitrogen inputs from precipitation.

Discussion

Nutrient limitation and Incubations

The first purpose of this study was to examine whether nutrients limit peat decomposition in cedar swamps and, if so, which nutrient—phosphate, nitrate, or ammonium—is limiting. Bacterial decomposers have an ideal C:N molar ratio of 15:1, an ideal C:P molar ratio of 30:1, and an ideal N:P molar ratio 5:1 (Amador and Jones 1993). If the nutrient needs of the bacteria are not met by the decomposing organic

matter, then bacteria can fulfill their nutrient needs by taking up external nutrients (Aber and Mellilo 2001). If the nutrient needs are not met by organic matter or by external nutrients, then nutrients can limit the rate at which bacteria can decompose organic matter. Peat molar ratios can be good indicators of the relative nutrient amounts available to bacteria but can be misleading because not all of the nutrients in the peat are easily digested by bacteria. At all depths the C:N and C:P molar ratios of the organic matter in the cedar swamp were above the molar ratios needed by bacteria (Fig. 3 and 4). To maintain their molar ratios, the bacteria must therefore take up external nutrients from the peat's porewater or burn off CO₂ by not incorporating carbon into their biomass. At all depths, the N:P molar ratios were also higher than what the bacteria need suggesting the bacteria are more P limited than N limited and may preferentially take up P from the porewater. The porewater N:P molar ratios varied with depth (Fig 2). The data suggests P was limiting in the first and fifth depth layers because of the high molar ratio in those layers, indicating a lot of available N relative to P. The data suggests N was limiting in the second, third, and fourth depth layers because of the low molar ratios in those layers, indicating less available N relative to P. Because both porewater P and N are limiting at different depths and because both are limiting in the peat, the addition of either could increase decomposition.

During the incubation, the decomposition rates as measured by CO₂ respiration had the greatest increase in the cores fertilized with either phosphate or ammonium (Fig. 6 and 7). This increase further indicates both phosphorus and nitrogen are limiting to peat decomposition. After their initial increase, the respiration rates of the ammonium-treated cores began to decrease suggesting a possible P limitation. Similarly, a secondary nitrogen limitation may have caused the plateau in the respiration rates of the phosphate cores. The results tracking the nitrate addition were conflicting. The slight increase in respiration as measured by the Li-COR despite nitrogen limitation may be explained by the need for nitrate to be reduced before being utilized as a nutrient, a transformation the ammonium does not go through. The large but delayed increase in respiration as measured by the GC may be explained by a bacterial community shift in favor of higher energy nitrate-reducing bacteria within the peat core (D'Angelo and Reddy 1994). At this time there is no explanation for the difference in trends measured by the two instruments. The controls also experienced an increase in respiration rates, though not of the magnitude of the phosphate and ammonium cores. The increase in the cores' respiration rates can not therefore be fully explained by the addition of nutrients. Greater temperatures during incubation compared to natural conditions may have contributed to this increase. New substrate for decomposition due to the freshly cut roots left in the cores may have also contributed to this increase, as could the lack of competition with plant roots for nutrients. The overall respiration values, which ranged from 40 to 70 mmol CO₂ m⁻² d⁻¹, were lower than respiration values from another laboratory incubation of saturated cedar swamp cores, which ranged from 86 to 173 mmol CO₂ m⁻² d⁻¹ (Duttry et al 2003). Those cores may have had higher respiration rates because they were from the warmer climes of Virginia and North Carolina.

The increase in the methane fluxes of the fertilized cores lagged behind the initial increase in the methane fluxes of the control cores (Fig. 8). New substrate to decompose and an absence of active roots may have contributed to the general increase in methane production. The fertilization procedure, which introduced aerobic water, may have

caused the time lag of the fertilized cores. The aerobic water could have provided a substrate for methane oxidizing bacteria that would consume the methane being produced before it reached the head space. The two control cores had different trends demonstrating an inherent variability in respiration rates. Core a's increase relative to the fertilized cores supports the hypothesis that the fertilization procedure inhibited methane production. Core b's lack of increase supports the hypothesis that nutrients increase methane production. I hypothesized nitrate fertilization would shut down methanogenesis by causing the methanogens to become outcompeted by the denitrifying bacteria, but the nitrate fertilization had the opposite effect, increasing methane production. Another study, which added nitrate to cedar swamp cores, found nitrate inhibited CH₄ production in the cores from a site with flooded peat, but did not inhibit CH₄ production in the cores from a site with partially dry peat (Hartman 2001). My peat cores fell somewhere in between as they were only flooded to the surface of the peat and had no overlying water.

Porewater concentrations of KCl extractable ammonium and DI extractable ammonium greatly increased in all incubated cores compared to initial values just as the respiration rates increased in all incubated cores (Fig 9 and 10). This increase can be explained in two ways. Either the cores experienced an increase in the mineralization of the organic matter during the incubation, or the ammonium was being mineralized at the same rate as in the swamp but the lack of root uptake was causing it to build up. Most likely, the increase in porewater ammonium was due to a mixture of these two processes—more organic N being mineralized and less being taken up. The ammonium fertilized core had porewater concentrations only slightly higher than those of the other incubated cores indicating it used most of the ammonium it was given. This lack of difference implies that mineralization did not increase greatly due to the added ammonium. However, mineralization rates may have been higher, but the bacteria were incorporating the mineralized ammonium into their biomass, which I did not measure.

The phosphate cores were the only incubated cores to show a great increase in phosphate porewater concentrations (Fig 11). All the other incubated cores had less phosphate than the initial cores. The phosphate cores showed an increase in concentration greater than their fertilization concentration in the deeper layers indicating a net mineralization of phosphate in those layers. The decrease in concentration relative to their fertilization concentration shows a net immobilization of phosphate by the microbes in the first depth layer. The lack of phosphate in the other incubated cores indicates a net immobilization of phosphate in all depth layers. Since the other cores have lost their phosphate, had the incubation proceeded longer, I would have expected a decrease in the respiration rates of the other cores relative to the rate of the phosphate cores. Such a trend would suggest phosphorus is more limiting than nitrogen.

The decrease in nitrate concentrations in all incubated cores relative to the initial cores indicates an increase in the use of nitrate as an electron acceptor (Fig. 12). It does not indicate an increase in nitrate uptake because ammonium is preferentially taken up, and it was available in high concentrations in the porewater. All fertilized cores had lower nitrate values in 12-18 cm and 24-30 cm depth layers than the control cores suggesting the added nutrients stimulated a greater use of electron acceptors.

This study suggests that both P and N are limiting to decomposition, but that P is more limiting than N because the peat N:P molar ratios are initially high, the respiration

rates had a greater response to P, and only the phosphate-treated cores had an increase in porewater phosphate. These conclusions match those of Amador and Jones (1993) who found respiration rates of Everglades peat with low C:P values responded positively to phosphate fertilization. Where there was enough P, as there was in the initial porewater of my cores, they also saw a response to ammonium addition. A study in the Great Dismal swamp found that both N and P were limiting because both were immobilized during litter decay (Day 1982). My porewater data suggested a net immobilization of P in the non phosphate-treated cores. A salt marsh study found P, not N, limited microbial growth (Sundareshwar et al 2003) while another saw an affect of simultaneous phosphate and ammonium addition (Morris and Bradley, 1999).

Nutrient Loading

As the first part of my study has shown, external nutrients influence decomposition rates in Atlantic white cedar swamps. Thus nutrient loading into the cedar swamps may decrease the swamps' capacities as carbon sinks. Greater surface water nutrient concentrations may be indicative of nutrient loading. Ehrenfeld and Schneider (1991) found the water chemistry of cedar swamps reflected the input of stormwater runoff and septic tank effluent. The greater ammonium and phosphate concentrations in Swamp Y suggest Swamp Y experiences more nutrient loading than Hidden Swamp (Fig. 13). Such differences in concentrations may also suggest the internal nutrient cycling of the two swamps vary. Swamp Y may have greater nutrient concentrations than Hidden Swamp because it has more nutrient mineralization than uptake. However, the greater nutrient concentrations in Swamp Y match observations of the swamps' surrounding environments. Swamp Y is adjacent to a road and houses with lawns and septic tanks while Hidden Swamp is surrounded by forest. Another study on cedar swamps found that sites near more development had increased phosphate and ammonium groundwater concentrations (Ehrenfeld and Schneider 1991).

These values for surface water concentrations can be compared to a previous SES study (Kelsey 1997). Since 1997, the nutrient concentrations in the surface waters of Swamp Y have changed. The phosphate concentration is now 8.5 μ Molar and was less than 1 μ Molar. The ammonium concentration is now 19 μ Molar and was 150 μ Molar. The nitrate concentration remains consistent with the values found in the previous study at around 2 μ Molar. These changes may reflect a difference in the nutrient loading to Swamp Y over the past seven years or to the increasingly altered hydrology of Swamp Y. Seven years ago Swamp Y was not entirely flooded year round as it is today (Kelsey 1997). The phosphate concentrations of Hidden Swamp are similar to the concentrations found in the non-impacted site of Kelsey's study (1997), but the ammonium concentrations are much less. As in my study, Kelsey found higher surface water phosphate concentrations in the presumed impacted swamps compared to the presumed non-impacted swamp. Kelsey also found significantly higher phosphate groundwater levels in the presumed impacted swamps and cited increased nutrient loading as a possible cause.

Contrary to what has been assumed, the modeled nitrogen loading into Hidden Swamp is actually greater than the modeled nitrogen loading into Swamp Y. The reason for the greater N loading into the presumed non-impacted swamp is its larger watershed. With both types of possible watersheds I delineated, the Hidden Swamp's watershed

encompassed Swamp Y's watershed and then some. If I assume Swamp Y stores all of the N that is loaded into it, then the N loading into Hidden Swamp is much less than the loading into Swamp Y. The current N loading from all the possible watersheds is much greater than the pristine ombrotrophic loading in which the swamps only receive N from precipitation. It is hard to determine to what extent N loading into the two swamps occurs because the water table and groundwater divide data for this part of the cape are scarce making delineating watersheds a best guess situation. Also no one is sure to what extent these swamps interact with the groundwater and even if they interact at all. If these cedar swamps are indeed ombrotrophic, then they are raised above the water table and do not receive groundwater (Gorham 1987). Future studies should examine the interactions between these swamps and groundwater in order to better quantify nutrient loading. Also the model was only for N loading, so future studies should examine P loading as well. Although the P loading should be low due to its tendency to get adsorbed onto soil particles and caught in iron oxides (Valiela 1995).

Conclusion

Development is changing the water chemistry and hydrology of Atlantic White Cedar wetlands along the Atlantic coast (Tangley 1984). The cedar swamps in Cape Cod are not impervious to these development effects. Swamp Y now has standing water year round and, as I have shown, has higher surface water ammonium and phosphate concentrations than a swamp in a less-developed area. Swamp Y's increased nutrients may be due to nutrient loading from its watershed or to its altered hydrology. Previous studies in the cedar swamps have suggested that altered hydrology can affect decomposition rates, especially if the development leads to lower water tables and less anoxic peat (Atkinson et al 2003 and Duttry et al 2003). While Swamp Y is not at risk for drier peat, it is at risk for increased nutrients, which as my study suggests, can increase decomposition rates as well. Hidden Swamp is also at risk because my loading model has shown it is experiencing substantial nitrogen inputs from its watershed—possibly more loading than Swamp Y and definitely more loading than in its own pristine state. In the future loaded nutrients may increase decomposition rates causing the cedar swamps to switch from a carbon sink to a carbon source. However, this study suggests that P may be more limiting than N due to molar ratios and a greater respiration response to P addition. Since P loading is substantially less than N loading, there may not be much of an effect on the carbon cycle in these swamps. But if these same nutrient/decomposition interactions I have demonstrated are occurring in other wetlands throughout the world where P loading is significant, there may be an effect on the global carbon cycle.

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Constants

People per household	1.8 people
Per capita nitrogen release	4.8 kg N
Minimum lot size	0.4047 ha
Lawn size	0.0465 ha
Fertilizer application rate	115 kg N/ha
Precipitation	0.48 g N m ⁻² y ⁻¹

Attenuation in transit through seepage face

Septic N	26.2%
Fertilizer N	15.5%
N in precipitation through soils	9.6%
N in precipitation on impervious surfaces	25.4%

Table 1. All of the above except the precipitation constant are assumptions of the Valiela et al (1997) land use model used to model nitrogen into the cedar swamps. The precipitation constant is from unpublished rainfall data measured at the Falmouth Wastewater Treatment Forest.

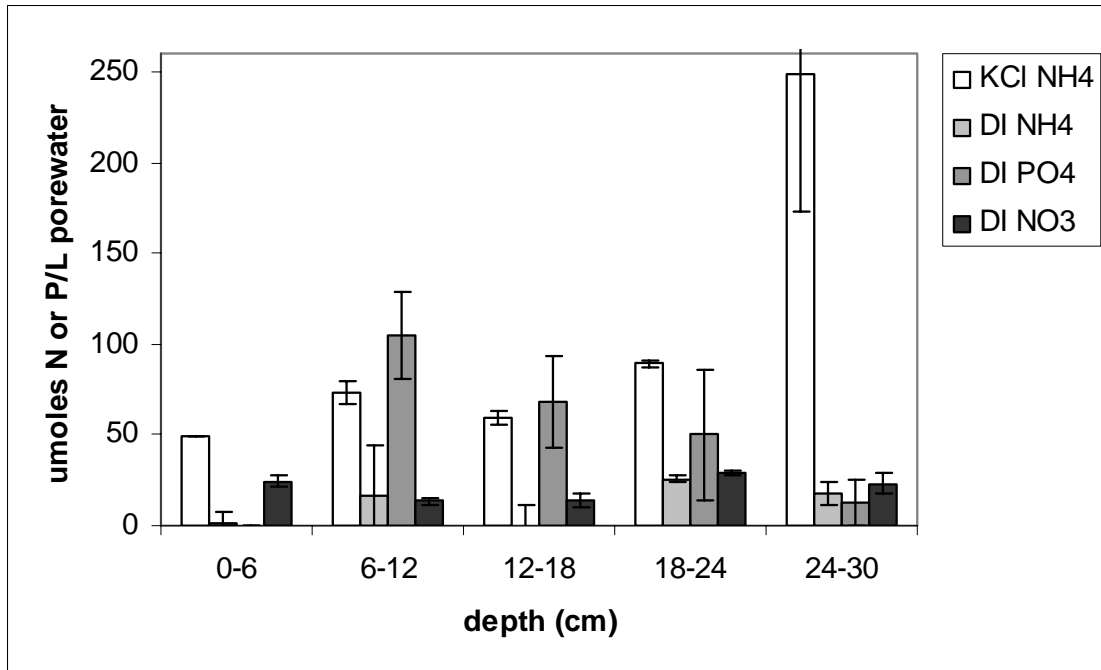


Figure 1. Mean initial peat porewater nutrient concentrations with depth (n=2). The error bars represent the range. The nutrients shown are ammonium extracted with potassium chloride, and ammonium, phosphate, and nitrate extracted with deionized water.

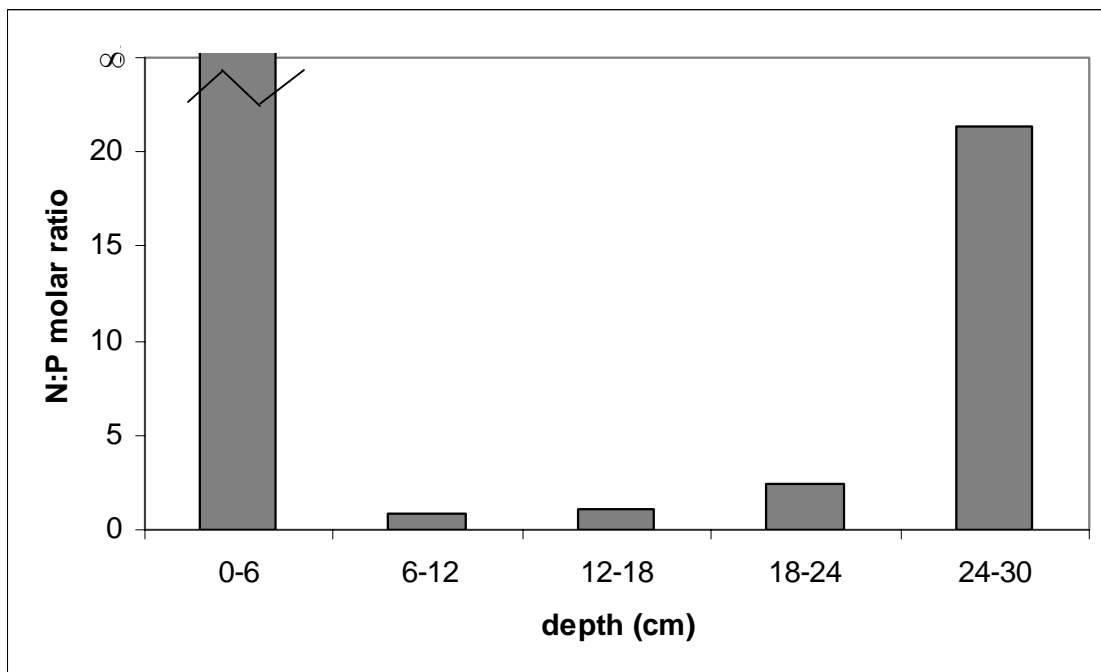


Figure 2. Mean initial peat porewater N:P molar ratios with depth (n=2). The moles of N used to calculate the ratio are the sum of the KCl extracted ammonium and the DI extracted nitrate. The molar ratio of the first depth section is technically infinity because there was no phosphate.

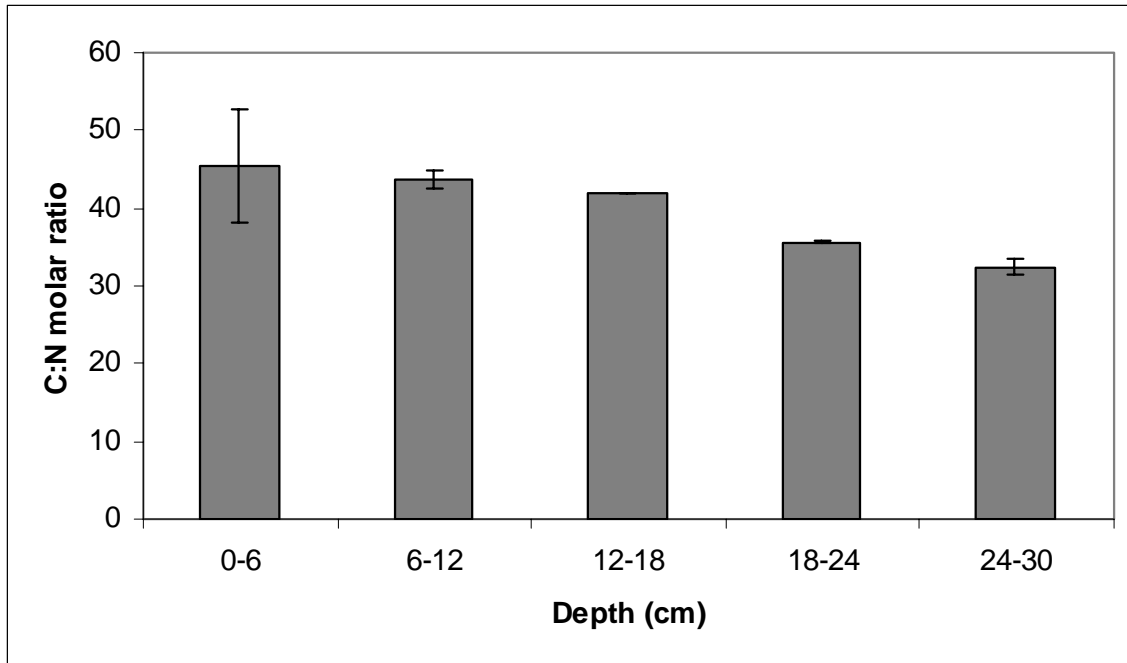


Figure 3. Mean initial peat C:N molar ratios with depth (n=2). The error bars represent the range.

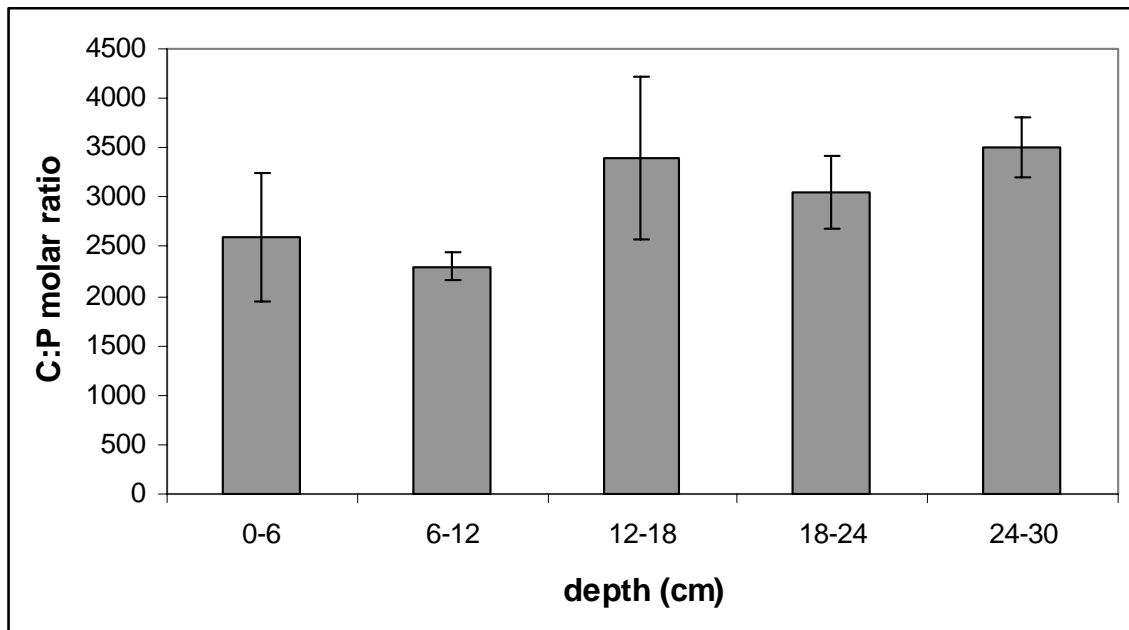


Figure 4. Mean initial peat C:P molar ratios with depth (n=2). The error bars represent the range.

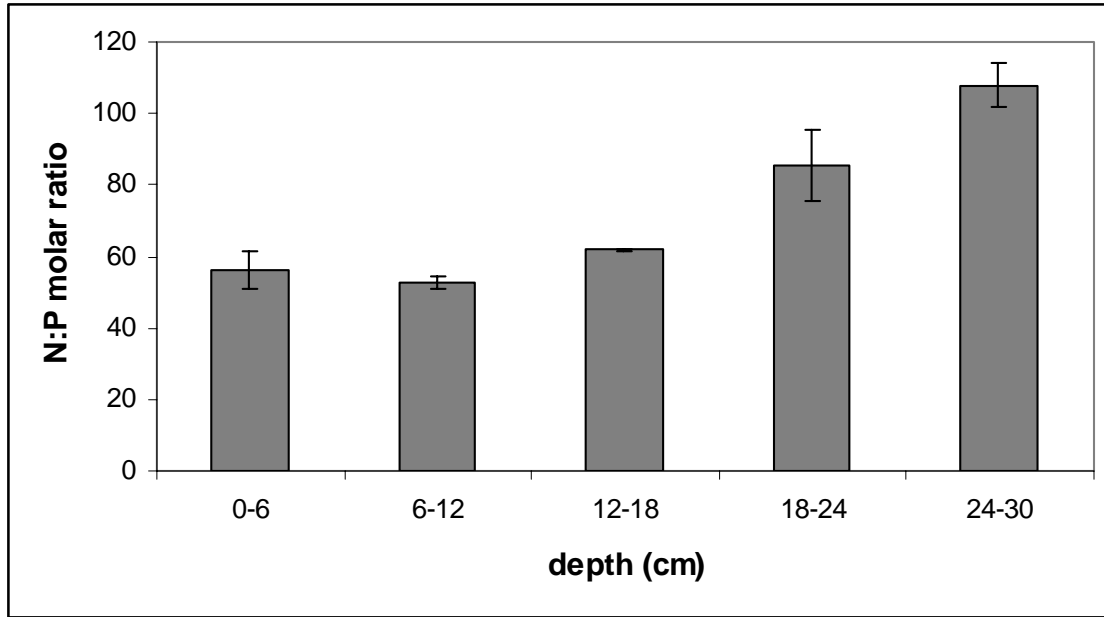


Figure 5. Mean initial peat N:P molar ratios with depth (n=2). The error bars represent the range.

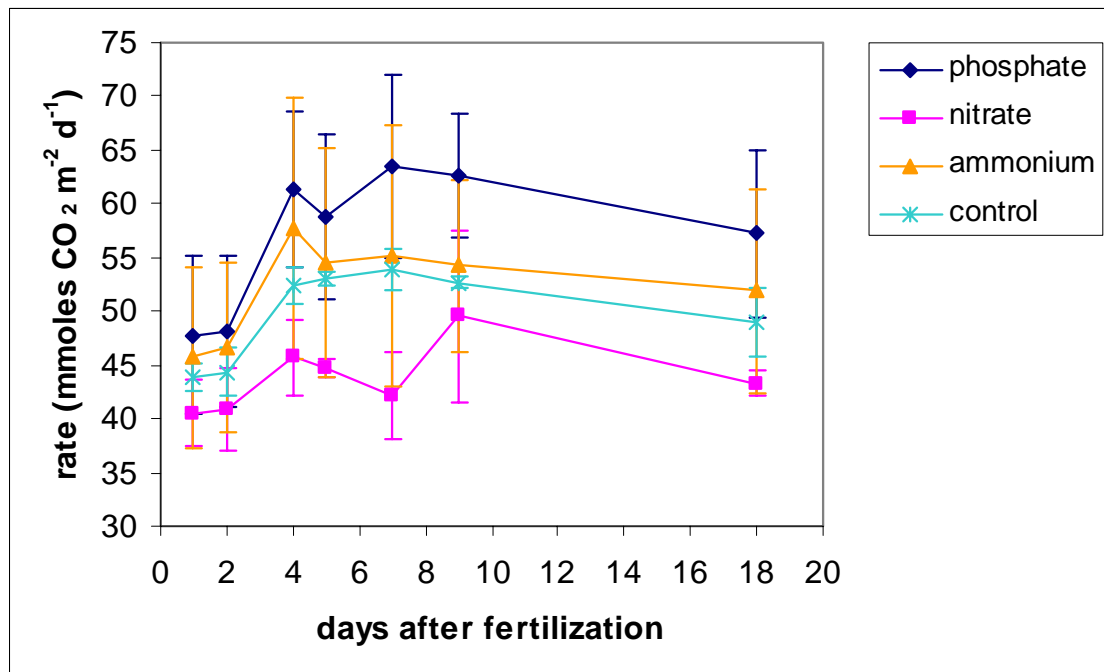


Figure 6. Mean CO₂ respiration of the incubated cores using the Licor (n=2). The error bars represent the range.

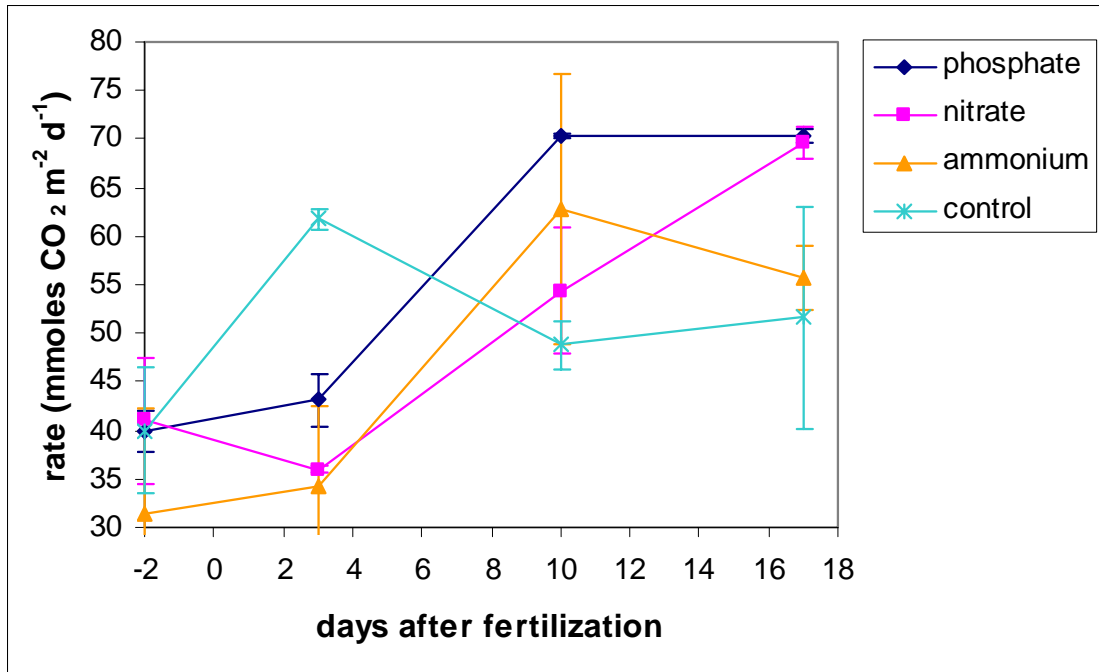


Figure 7. Mean CO₂ respiration of the incubated cores using a gas chromatograph (n=2). The first time point at -2 days is the initial rate before fertilization. The error bars represent the range.

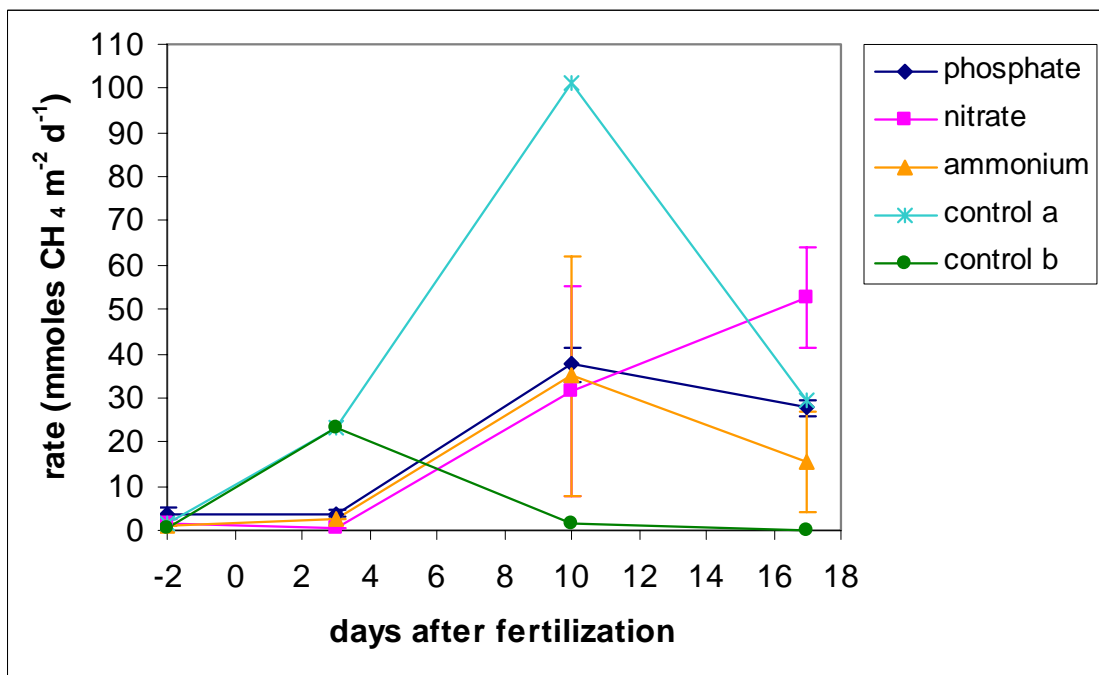


Figure 8. Mean CH₄ flux of the incubated cores using the gas chromatograph (n=2, except for controls). The first time point at -2 days is the initial rate before fertilization. The error bars represent the range.

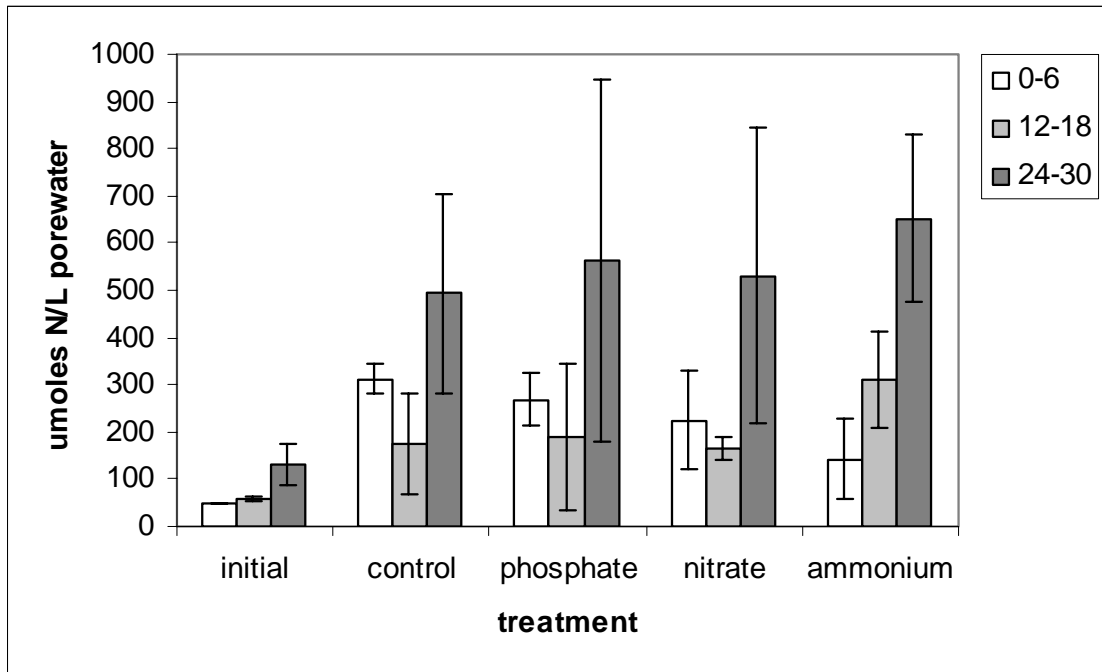


Figure 9. Mean initial and post-incubation KCl extractable ammonium concentrations (n=2). The error bars represent the range.

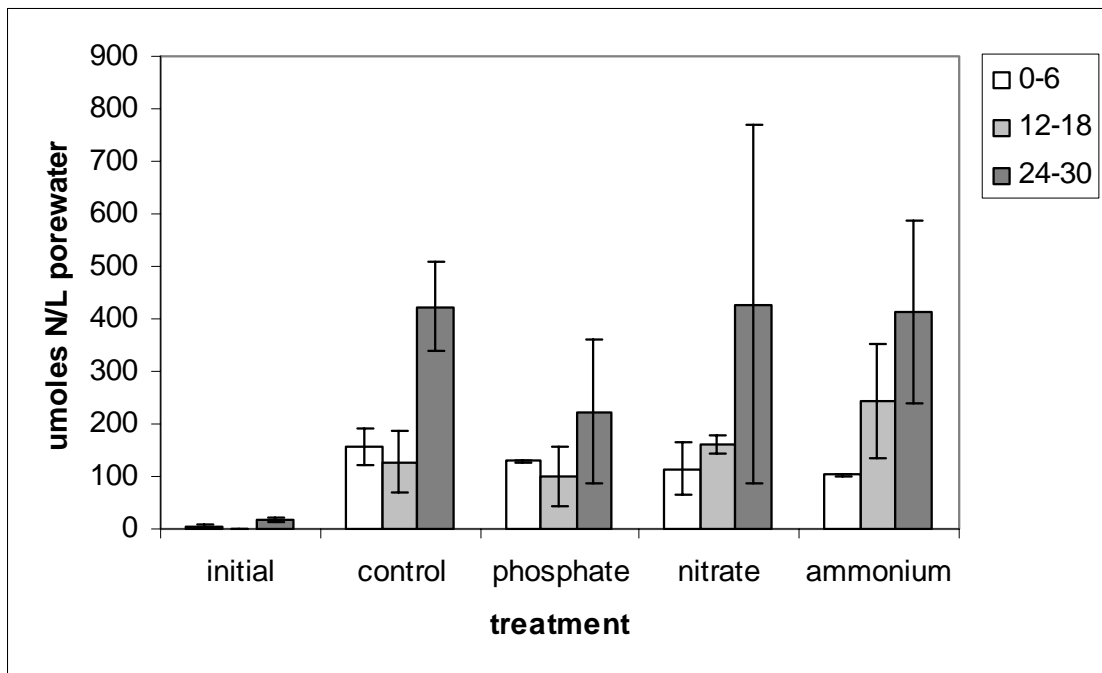


Figure 10. Mean initial and post-incubation porewater ammonium concentrations (n=2). The error bars represent the range.

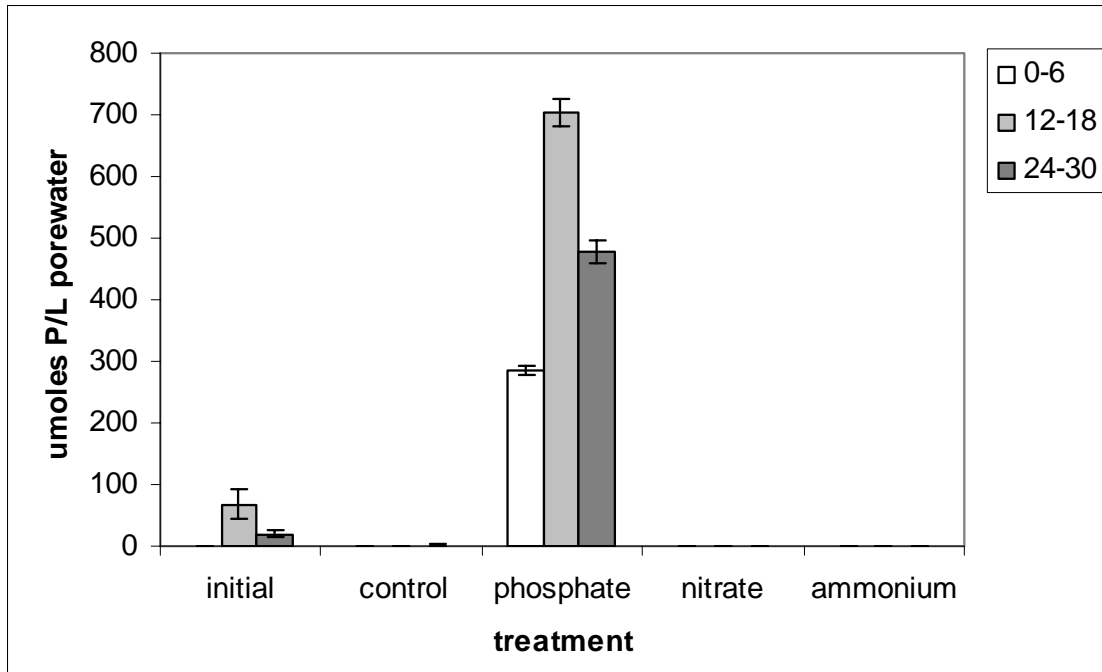


Figure 11. Mean initial and post-incubation porewater phosphate concentrations (n=2). The error bars represent the range.

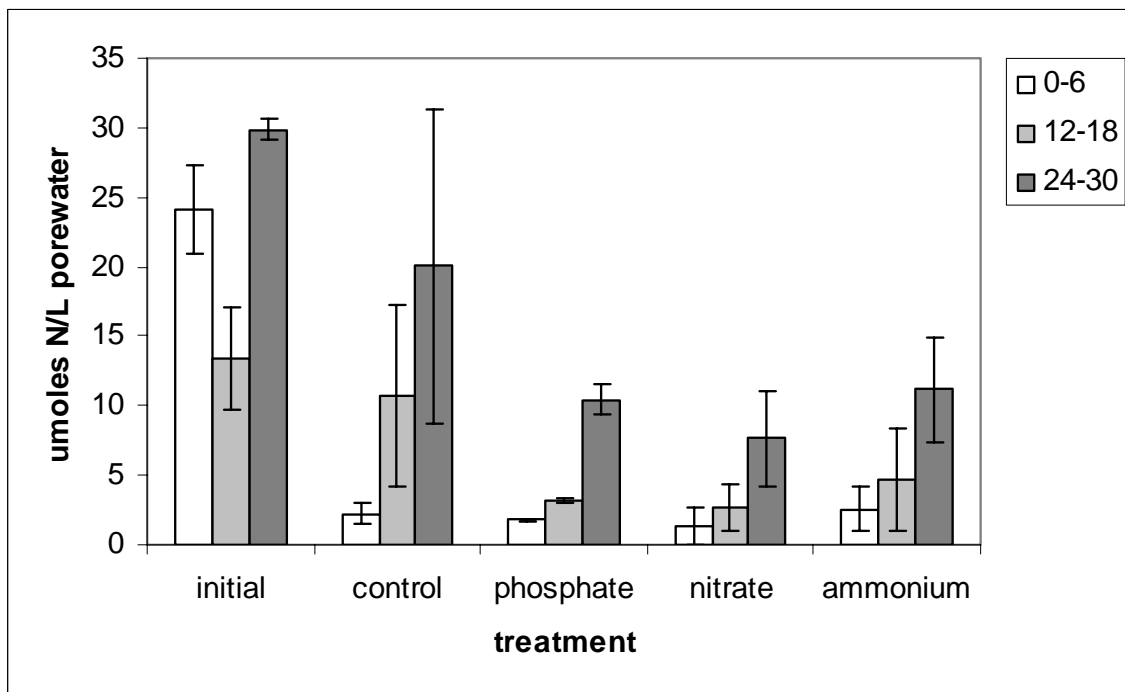


Figure 12. Mean initial and post-incubation porewater nitrate concentrations (n=2). The error bars represent the range.

		Topographic groundwater watershed	Separate Topographic groundwater watershed	Topographic surface watershed	Groundwater divide watershed	Pristine
Hidden Swamp (0.98 ha)	<i>Watershed area (ha)</i>	19.63	5.20	5.20	10.48	na
	<i>Houses</i>	50	5	5	29	0
	<i>Loading (kg N/y)</i>	155	16	41.3	89.6	5.0
Swamp Y (1.13 ha)	<i>Watershed area (ha)</i>	13.30	13.30	13.30	5.35	na
	<i>Houses</i>	45	45	45	16	0
	<i>Loading (kg N/y)</i>	139	139	37.2	49.5	5.5

Table 2. Nitrogen loading into two cedar swamps (kg N/y) using various watershed types. The topographic groundwater watersheds are based on surface elevations as are the separate topographic watersheds but with Hidden Swamp's watershed not including Swamp Y's watershed. The topographic surface watershed is the same as the separate topographic watersheds but assumes no swamp/groundwater interactions so the only loading is from runoff. The groundwater divide watersheds are based on the shortest path the groundwater can move from the groundwater divide to the coastline. The pristine loading assumes the swamps are ombrotrophic with the only nitrogen inputs coming from rain.

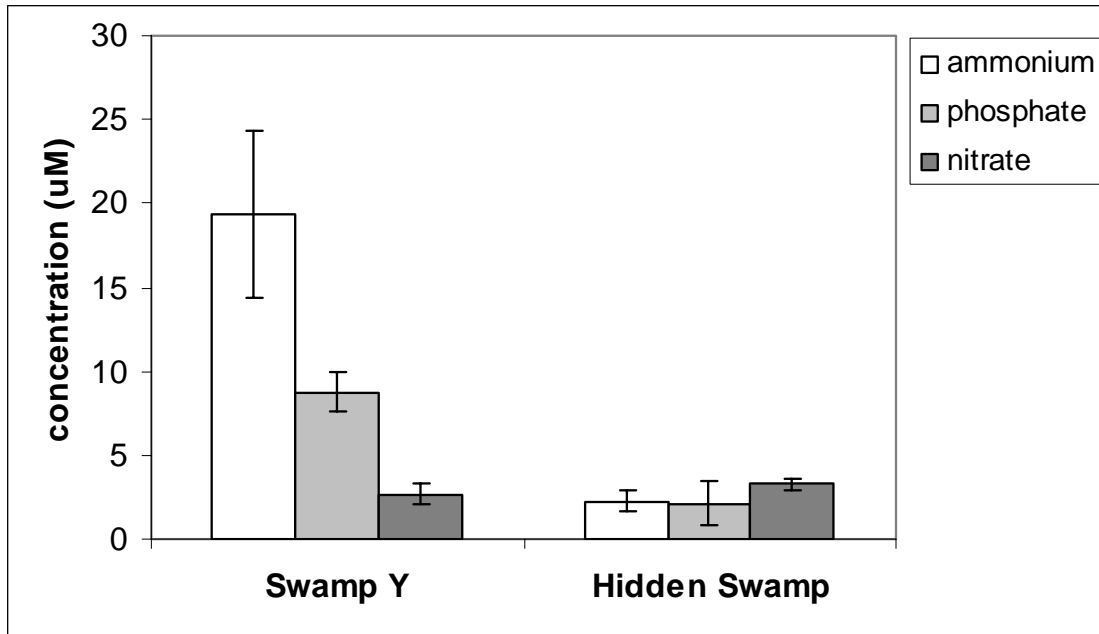


Figure 13. Mean ammonium, phosphate, and nitrate concentrations in the surface water of the two cedar swamps (n=6). The error bars represent the standard error.