The Effects of Beaver Dams on Nutrient Cycling in Cart Creek, a Tributary of the Plum Island Estuary

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Abstract

North American beavers are ecosystem engineers that create wetland ecosystems. In doing so, they increase the capacity of the natural ecosystem to remove excess nitrogen from the water. Possible mechanisms for this process include nitrification and denitrification performed by microbes that inhabit sediment in beaver ponds and denitrification catalyzed by electron donation to nitrate by carbon in the wood of the dam, similar to the mechanism used in a permeable reactive barrier. The presence of these mechanisms was examined in beaver dams in Cart Creek, a tributary in the Plum Island Estuary watershed in Essex, MA. The ability of the dams to catalyze denitrification was measured by analyzing nutrient concentration upstream and downstream of each of the dams. The ability of the sediments to nitrify and denitrify was analyzed by performing nutrient flux experiments on sediment cores. The denitrification catalyzed by the beaver dam itself was found to be insignificant, but the capacity for sediments of the beaver pond to perform nitrification and denitrification was found to be quite large. While the sediments from the beaver pond did not perform better than those from other areas of the creek, the formation of the beaver pond itself increases the surface area of the sediment in the creek, which increases the capacity of the creek to remove excess nutrients from the water. Thus, the presence of beaver dams in a stream enhances the capacity of that stream to remove excess nutrients from the water.

Keywords and phrases: beaver dams, *Castor canadensis*, nutrient fluxes, nitrification, denitrification, Cart Creek, Plum Island Estuary watershed
Introduction

Keystone species are species that have a disproportionately large impact on an ecosystem. One category of keystone species is ecosystem engineers, which have a large impact on an ecosystem because they create or maintain that ecosystem. A prime example of an ecosystem engineer is the North American beaver (*Castor Canadensis*). Beavers cut down trees for food and building materials, and they then build dams across streams to form ponds for protection and transportation. These ponds transform the original habitat into wetland habitat, which fundamentally alters the ecosystem’s properties. In the case of beavers transforming a forest into a wetland, one important property that changes is the ability of the ecosystem to remove excess nitrogen from the stream water.

The addition of beaver dams may facilitate this change in several ways. When beavers build dams in a stream, they cause the water to slow down, which allows sediments to accumulate. The sediments then provide habitat for microbes that may perform nitrification and denitrification to remove nitrogen from the water. The beavers also facilitate this process by alternating the aerobic water of the stream – which enables nitrification to occur – with the anaerobic water of the ponds – which enables denitrification. Moreover, the dam itself may have a role in filtering excess nitrogen out of the creek. Wood tends to filter nitrate out of the water by allowing it to come into contact with electron donors – carbon – in the wood that aid denitrification (Huno et al. 2018). We use wood in Permeable Reactive Barriers (PRBs) that are installed in streams or groundwater to decrease the nutrient load of a body of water for this exact reason. Previous research has suggested that beaver dams have a similar effect on the nitrate concentration of the stream (Klotz 2010).
This increased capacity of the ecosystem to remove excess nitrogen from the stream can mitigate the effects of increasing urbanization. One area that exhibits this exact phenomenon is the Plum Island Estuary (PIE) watershed (Figure 1). In this area, even though the population density in the region has tripled in recent years, the nitrogen export into the PIE has not increased (Wollheim et al. 2014). This trend results from the extraordinary ability of the Parker and Ipswich watersheds to retain nitrogen – 65% to 85% retention in urban areas and 93% to 97% retention in forested areas (Wollheim et al. 2005). This lack of change may be, in part, a result of the growing beaver population in the area. Since the arrival of Europeans to North America, the fur trade had caused beaver populations to decline. However, a 1996 law in Massachusetts banned the use of many types of traps used to kill and capture beavers. This change, in addition to an absence of predators and conservation efforts, has allowed the beaver population in the PIE watershed to increase. Over time, the tributaries, such as Cart Creek, the study site of this project, have become increasingly dammed, which may account for the high nitrogen retention of the watersheds.

In this study, I tried to test several hypotheses. First, I examined whether the beaver dams affect the nutrient concentrations in Cart Creek by evaluating the nutrient concentrations at various points along the creek. Second, I assessed the chemical composition of the sediments along the river to see which areas are more organic. Finally, I examined the potential of the microbes in the soil to remove nitrogen from the water, and how the microbes from different locations along the creek differ in that ability.

Methods

Site: Cart Creek
Cart Creek is a freshwater stream that is a part of the Parker Watershed in the overall Plum Island Estuary watershed in Essex County, MA (Figure 1). The creek itself flows through the Martin Burns Wildlife Management Area for much of its length and almost all of the length within the study area. Thus, most of the sites sampled along the creek are removed from sources of nutrient influx. However, there are urban sources of nutrients upstream of the study area, and the stream also flows under I-95, which could also be a source of nutrients in the form of car exhaust.

There are many beaver dams along the creek, four of which were examined in this study (Figure 2) (Table 1). The farthest upstream dam is referred to as the “culvert dam” because it was built within a culvert that went under one of the wildlife area’s dirt roads. The next dam is referred to as the “maintained dam” because, at the time of sampling, the dam had recently been shored up with mud and had no leaks. I labeled the next dam the “small dam,” as it was rather small and did not create much of a beaver pond. It was not very extensively studied. The last dam, the “large dam,” was rather large and had a large impoundment, but it had not been recently maintained, as it contained many leaks.

In addition to the sampling sites at the dams, we also sampled two additional sites. The first site is referred to as the “downstream site” because it was downstream of the dams in the study. It was in an area that did not have much beaver influence or urban influence. The last site is the “road site,” which is located where the creek exits the wildlife area and enters a more urban area, with a paved road and a house adjacent to the site.
Sample Collection

We were at the study site on November 11th and November 12th, 2019. Many of the trees had already lost their leaves at this time, and leaf litter covered the ground and floated in the streams. There were also many pheasant hunters in the area. These dates are within the open season period to trap beavers in Massachusetts (MassWildlife 2019), but we did not see any traps.

We surveyed the site on the first day and collected water and sediment samples. We collected the water samples using a 60mL syringe, then filtered the water immediately using a Swinnex® syringe filter holder loaded with a pre-ashed 25mm GF/F filter. At the dam sampling sites, we collected 60mL water samples from inside the pond and from the stream just below the dam. We also collected 60mL water samples from the inflow into each of the beaver ponds when we could access the area. For the stream sites, we collected one 60mL sample. At the downstream site, we also collected another 60mL sample 100m downstream of the initial sampling point. For the sediment samples, we collected sediment from within the pond or downstream site using an Ekman grab. We also collected one sediment sample from the stream directly downstream from the maintained dam. Lastly, we took larger 1L water samples from above and below the large and maintained dams, below the culvert dam, at the downstream site, and the road site.

On November 12th, we collected sediment cores and carboys of water from Cart Creek. We collected seven cores in total: two from the pond of the maintained dam, two from the pond of the large dam, and three from the downstream site. We then collected four 20L carboys of water from the downstream site. We also took oxygen concentration measurements above and
below the maintained and large dams and at the downstream site using a HQ30D Optical Oxygen
Probe.

**Laboratory Analysis of Samples**

I filtered the water from the carboys through GFF filters to ensure that the water did not
contain any plankton that could affect our measurements of the sediment nutrient fluxes. I then
replaced the water overlying the sediment cores with the filtered water. I placed spinners in the
water to stir the water above the cores and ensure that nutrients were exchanged between the
sediments and the water. I measured initial oxygen concentrations and took initial water samples
for nutrient analysis. The cores were then placed in a warm room and allowed to metabolize.

Every three hours, I took oxygen concentration measurements and collected samples of
the water overlying each of the cores. The water samples were filtered using Swinnex® filter
apparatus loaded with GFF filters. I then froze 20mL of each sample and acidified another
20mL. I repeated this process until I had sampled from the cores five times. I will refer to this
process as the aerobic nutrient flux run.

I then waited until the water above the cores turned anoxic and then repeated this process,
except that I did not replace the water overlying the cores. I instead waited eight to twelve hours
between sampling points because of the lower rates of metabolism. I will refer to this process as
the anaerobic nutrient flux run.

I repeated this process a third time, but this time, the water that I used to replace the water
overlying the cores was spiked with nitrate so that the nitrate concentration was around 200µM,
which is consistent with nitrate concentrations found in urban areas. I once again waited about
three hours between sampling, enough time for the oxygen concentration to drop .25mg/L to
1mg/L. However, one core’s oxygen concentration was dropping rapidly, so I instead waited only an hour and a half between sampling times when sampling from that core. I will refer to this process as the enriched nutrient flux run.

To determine the nutrient and oxygen fluxes of the sediment cores, I first found the rate at which each nutrient changed in each core over time. I then converted that rate to the nutrient flux rate of the sediments using the physical properties of the core.

I then analyzed the water samples – both the water samples taken from the field and the samples taken from the core nutrient flux runs – and analyzed them to measure their nitrate, ammonium, and phosphate concentrations. I also did the same for the sediment samples, as I had extracted their nutrients through KCl extraction. I used a modification of the method of Murphy and Riley (1962) to analyze phosphate concentrations. To analyze ammonium concentrations, I used a modification of the phenol-hypochlorite method published by Solarzano (1969). For nitrate concentrations, I used a modification of the method proposed by Wood et al. (1967) that was performed by a Lachat® QuickChem 8500 Series 2 flow injection analyzer linked with a computer running Omnium 3.0.

I processed the 1L samples to analyze the dissolved inorganic nitrogen (DIN) content of cart creek and δ\textsuperscript{15}N of the DIN, and I also examined the chemical and isotopic composition of the sediments. First, I filtered as much of the sample as possible through a 25mm ashed GF/F filter. The filter was analyzed for the δ\textsuperscript{15}N of the particulate nitrogen in the water. I then filtered the rest of the water through a 47mm GF/F filter. I then processed the remaining water using a modification of the method outlined in Sigman et al. (1997). The diffusion filter was then analyzed for DIN and δ\textsuperscript{15}N of the DIN. Finally, I analyzed the δ\textsuperscript{15}N of the sediment samples
taken from Cart Creek and the C:N content of sediment samples from the cores after concluding the nutrient flux runs.

Results

Nutrient Concentrations along Creek

When we compare the nutrient concentrations over the length of the stream, excluding the road site, there is no overall trend (Figure 3). There is also no consistent trend regarding how nutrient concentrations change before and after each dam. Nitrate and Ammonium concentrations are both very low until we reach the road site. For most of the upriver sites, ammonium is higher in concentration than nitrate. However, once the oxygen concentration increases, that trend begins to switch. Particulate nitrogen and DIN are both higher and seem to increase in the areas where the dams are but decrease as we move downstream. DIN is also much higher at the road site due to urban influence. Phosphate has a very low concentration at all locations, but it is slightly higher at the downstream site and the road site.

The extractable nitrate concentrations in the sediment are very low, but the extractable ammonium concentrations can be very high (Figure 4). The ammonium concentrations within the beaver ponds are higher than those in the stream, with the exception of the road site. The nitrate concentration is highest in the sediment just below the maintained dam, and higher than at the other locations in the pond of the maintained dam. The nitrate concentration is higher at the road sites than at the previous sites.

Chemical and Isotopic Compositions

There is no overall trend of δ¹⁵N of particulate nitrogen in the water along the length of the creek. However, we can see that the δ¹⁵N generally decreases as the water moves through a
dam. The δ^{15}N of the dissolved inorganic nitrogen increases over the length of the creek. It also decreases as the water moves across the maintained dam. The difference in δ^{15}N between the particulate nitrogen and the dissolved inorganic nitrogen is greatest in the area of the dams and least at the road site. The particulate nitrogen in the sediment does not appear to have an overall trend, but it is greatest below the maintained dam and at the road site. All of the δ^{15}N measurements are greatest at the road site.

When we examine the chemical composition of the sediments of Cart Creek, we see that the sediments within the dams contain a higher proportion of carbon than do the sediments at the downstream site (Figure 6). The nitrogen content of the sediments is highest for the sediments from within the ponds and lowest in the sediment just below a dam (Figure 7).

Nutrient Flux Rates

Under aerobic conditions, the nitrate flux rate is most negative in the sediments from the large dam, but it is not that large (Figure 8). The nitrate flux rate for the maintained dam is positive, indicating that nitrate is being released by the sediments rather than taken up. The maintained dam has the largest ammonium flux, which is positive, indicating that ammonium is being released. The ammonium fluxes are also positive for the large dam and downstream site. The oxygen flux rate is highest in the sediment from the large dam, but all of the oxygen flux rates are higher in the sediment from within the beaver ponds than from the downstream site (Figure 9).

Under anaerobic conditions, the ammonium fluxes are much larger on in all of the sediments, indicating that much more ammonium is being released into the water under anaerobic conditions that in aerobic conditions (Figure 10). However, in the maintained dam, the
ammonium flux is smaller under anaerobic conditions that it was under aerobic conditions. The nitrate fluxes under aerobic conditions were small.

Under the conditions of the enriched nutrient run, the nitrate fluxes are negative with large magnitudes, indicating that lots of nitrate is taken up under these conditions. The ammonium fluxes are also very large but positive, indicating that lots of ammonium – even more than in the anaerobic run – is being released into the water above the sediments. The oxygen fluxes under these conditions are also very high, indicating that levels of aerobic respiration are higher under these conditions.

**Discussion**

The fact that we did not observe a decreasing trend in nutrients over the length of the creek does not necessarily indicate that the beaver dams are not good at removing excess nitrate from the stream (Figure 3). The nutrient levels are very low throughout the length of the stream, except at the road site, which indicates that urban influences do indeed add nutrients to the stream. The low levels and lack of a trend that we observe throughout the rest of the stream must then be a result of beaver dams above our sampling site that have already removed the excess nutrients in the stream from the upstream urban influence before we could observe it. This phenomenon attests to the effectiveness of beaver dams at removing excess nutrients from the stream.

The nutrient levels did not change very much from above a dam to below a dam, or at least, the change was not in a consistent direction. This lack of a trend may be due to the water not spending enough time inside of a beaver dam for the wood to act as an electron donor and
catalyze denitrification. We also did not observe high levels of nitrate in the creek, so perhaps under higher nitrate conditions, we would observe such a trend.

The trends of oxygen, ammonium, and nitrate along the length of the stream also attest to the presence of nitrogen-removing processes. When the oxygen concentration is low (in the areas near the dams), the ammonium concentration is higher than the nitrate concentration, indicating that denitrification is occurring and removing nitrate but not ammonium. In the areas where oxygen is higher, like near the downstream site, the two concentrations are closer together, indicating that nitrification is likely occurring.

The concentration of extractable ammonium in the sediments (Figure 4) may correlate with the biological activity in the sediments, as the ammonium in sediments in the ponds than in other locations along Cart Creek. The high nitrate in the sample from below the maintained dam might be the result of contamination because there is very little reason to find that much nitrate in such an inorganic sediment.

The difference in $\delta^{15}$N between the DIN and the suspended particulate nitrogen (Figure 5) indicates that there are a lot of nitrogen-metabolizing processes occurring in the region of the dams because the different $\delta^{15}$N values indicate that there are most likely biological processes occurring that would cause the heavier isotope to have different abundances than in other areas of the stream. The difference in $\delta^{15}$N between the DIN and particulate N is small at the road site, indicating that there is likely not all that much biological nitrogen processing occurring at that location.

The chemical compositions of the sediments (Figures 6 and 7) also support the idea that there is more biological activity in the sediments within the dams. The sediments that were
sampled from within the beaver ponds contain the highest proportions of nitrogen and carbon out of all of the sediments. In contrast, the pebbly sediment from just below the maintained dam contains the least amount of nitrogen, indicating that it is the least organic. This low concentration of nitrogen from the isotopic analysis also supports the notion that the high level of nitrate found in this sample is simply contamination.

The chemical composition of the sediments from the large dam is more organic than those from the maintained dam, which is consistent with the differences in the fluxes between the two dams, in which the sediments from the large dam generally had a greater capacity than those from the maintained dam to remove nitrogen from the water. The high ammonium flux from the sediments of the maintained dam in the aerobic condition is most likely simply the result of the microbes in the sediments being more stressed for some reason, which might be why they also had a less negative nitrate flux (Figure 8). This idea is also supported by the oxygen fluxes (Figure 9), in which the large dam had a greater flux than the greater oxygen flux and thus had a greater aerobic metabolism despite undergoing less decomposition.

The high ammonium fluxes in the aerobic run indicate that there is a lot of decomposition occurring in the cores, with the flux rates roughly proportional to the organic content of the sediments (Figure 10). If decomposition was the only process occurring, you would expect to see higher positive nitrate fluxes. However, we instead observe nitrate fluxes that are close to zero, which indicates that denitrification is occurring in addition to decomposition.

The nitrate fluxes under the enriched conditions also attest to the abilities of the sediments to perform denitrification, even under oxic conditions (Figure 11). The nitrate fluxes are very high in all three types of sediment but are greatest in the large dam and downstream site. The low nitrate flux in the sediment from the maintained dam may be a result of it being stressed
in the aerobic run. Regardless, the high nitrate fluxes even under unfavorable conditions indicate that the sediments of the stream have a large capacity to remove excess nitrogen from the water.

Conclusions

We did not observe a decrease in nutrients over the course of Cart Creek, most likely because the beaver dams upstream that were not sampled in this study had already removed the excess nitrogen from the urban sources upstream. We also did not see a consistent effect of the beaver dams on the concentrations of the nutrients within Cart Creek. This inconsistency may indicate that the dams do not affect the nutrient concentrations in the streams, as the water might not have a long enough resonance time within the wood for any denitrification to occur. Conversely, there might be an effect but it is difficult to tell with the low nutrient levels observed in the stream.

The sediments within the beaver ponds tend to be more organic than those in other places along the stream, even in other places where sediment has accumulated. This trend suggests that the beaver dams may be better at removing excess nitrogen from the water than at other points along the stream. However, I did not observe this behavior in our sediment core nutrient fluxes – the sediment cores from the downstream site had nitrate fluxes that were about equal to that of the sediment from the large dam and was larger than that of the maintained dam. However, the dams do provide other benefits, like they increase the surface area of sediment that contacts water by creating ponds. This benefit means that even though the sediments of a beaver pond might not be superior to those elsewhere in the same creek, the formation of the pond itself increases the capacity of the creek to remove excess nitrogen by increasing the amount of sediment available. Thus, beaver dams most likely do increase the capacity of natural ecosystems to remove nitrogen from the water, although further evidence is needed to support this notion.
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Literature Cited


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Figure 12. Oxygen fluxes in enriched sediment core run
Table 1. Description of sampling sites and distance downstream

<table>
<thead>
<tr>
<th>Site name</th>
<th>Site Description</th>
<th>Distance Downstream (m)</th>
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<tr>
<td>Culvert dam</td>
<td>Small dam built in culvert going under dirt road. Very small pond</td>
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</tr>
<tr>
<td>Maintained dam</td>
<td>Dam freshly maintained on day of sampling, pond is medium-sized, square-shaped and filled with dead trees</td>
<td>290</td>
</tr>
<tr>
<td>Small dam</td>
<td>Small dam with very little pond. Not thoroughly sampled.</td>
<td>350</td>
</tr>
<tr>
<td>Large dam</td>
<td>Large dam with large, linear pond. Not very well maintained – had lots of leaks, but retained water.</td>
<td>715</td>
</tr>
<tr>
<td>Downstream site</td>
<td>Site devoid of beavers but with slow water and lots of silt on the bottom. Long-term sampling site for a Ph.D. student.</td>
<td>1270</td>
</tr>
<tr>
<td>Road site</td>
<td>Site outside Martin Burns Wildlife Management Area near a paved road and house.</td>
<td>2640</td>
</tr>
</tbody>
</table>
Figure 1. Parker River and Ipswich River watersheds. These watersheds are part of the Plum Island Estuary watershed. Cart Creek is the pink waterway in the Parker River watershed. Image from Wollheim et al. 2014. Nitrate uptake dynamics of surface transient storage in stream channels and fluvial wetlands. Biogeochemistry **120**: 239-257. DOI: 10.1007/s10533-014-9993-y
Figure 2. Sampling locations along Cart Creek. Sampling sites included four dams, referred to as “culvert dam,” “maintained dam,” “small dam,” and “large dam.” Two additional sites were not in areas influenced by beavers, referred to as “downstream site” and “road site.”
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