Manipulating residence time in agricultural headwater streams: impacts on nitrogen removal and aquatic communities

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Effects of Residence Time on Nitrogen Removal in Agricultural Headwater Streams

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Problem and Research Objectives

The main objective of our study was to examine the effects of residence time on nitrogen removal via denitrification in headwater streams. We focused our attention in an agricultural watershed in Northeastern Ohio, severely impacted by nitrogen loading. Our study system, the Upper Sugar Creek Watershed, is indeed heavily impaired due to agricultural activity; land use in the watershed is roughly 90% agriculture (OEPA, 2002). Unfortunately, the majority of land within this watershed is privately owned. This made locating land owners that would allow us to artificially manipulate agricultural drainage – as originally planned – on their property difficult. Instead of manipulating the residence time within headwater streams, we located headwater streams that naturally have varying residence times. Within the Upper Sugar Creek Watershed we identified five headwater streams. Along each stream, we located one reach in agricultural/urban land use and one reach in forested land use. By selecting these specific reach types we expected to observe a wide range of residence times. At all our reaches, hydrology, water quality, sediment, and denitrification data were measured over 3 seasons (Summer and Fall, 2005 and Spring 2006) to determine if residence time significantly affects nitrogen removal.

Methodology

Each stream reach consisted of 50 meters of stream length and along each study reach there were no stream or tile inputs. Discharge was calculated using the 6/10 depth method and velocity was measured with a SonTek FlowTracker Handheld Acoustic Doppler Velocimeter. In order to measure residence time, we used slug injections of Rhodamine WT. Injections were made at the top of the each reach and the concentration of Rhodamine WT was measured at the bottom on each reach *in situ* with a YSI 6600 equipped with a Rhodamine probe. Using the time-concentration profiles collected in the field and equations from Fischer (1968), we measured the average time required for an aqueous contaminant to travel 50 meters (i.e., residence time).

Water samples were collected in the field and stored at 4°C. Once in the laboratory, water samples were analyzed for nitrate (NO_3^-) with a Lachat QuikChem 8500 after being filtered through a 0.45 µm membrane filter. The top 3 cm of sediments were collected at 4 random locations along each 50-meter reach. At each location, one sample was collected to determine the standing stock of ash free dry mass (AFDM) and one sample was collected to use for denitrification assays. All sediments were stored at 4°C until processed in the laboratory. Standing stock was calculated on an aerial basis by first measuring the surface area of sediment collected and then determining the AFDM. The AFDM of each sediment sample was assessed by taking the difference in mass of each sediment sample before and after combustion at 550°C. Denitrification rates were measured with the acetylene inhibition method on aggregate sediment slurries from each reach. Slurries yielded rates in units of mg N g AFDM^{-1} hr^{-1} and by multiplying these rates by the standing stock from each reach, denitrification rates were measured in units of mg N m^{-2} hr^{-1}.

To relate denitrification rates to an in-stream nitrogen removal metric we used the following equation from Alexander et al. (2000)

$$-k = \frac{U \cdot h}{C}$$

where –k is the loss rate of NO_3^- due to denitrification per unit time, U is the aerial denitrification rate, h is the water column height, and C is the concentration of NO_3^-. Sediment was also analyzed for total carbon on a CE Instruments NC 2100 Analyzer.

Principal Findings

Total carbon and standing stock were not significantly different ($p = 0.231$ and $p = 0.278$, respectively; Table 1) for agricultural/urban and forested reaches. In addition, NO_3^- concentrations from both reach types were not significantly different ($p = 0.823$; Table 1) and discharge from our reaches were not significantly different as well ($p = 0.782$; Table 1). Also, denitrification rates measured from the agricultural/urban reaches and the forested reaches were not significantly different ($p = 0.958$; Table 1). Because discharge can drastically affect residence time, we compared residence times by running an ANCOVA with discharge as the covariate. We found that the forested sites have a significantly higher residence time than the agricultural/urban sites ($p = 0.034$; Figure 1). Thus, the study sites included in our project did have significantly different residence times.

Table 1. Data obtained from the study sites over 3 field seasons (Summer and Fall, 2005 and Spring 2006). All values are the mean ± 1 standard deviation.

Reach Type	Discharge (m^3 sec^{-1})	NO_3^- (mg N L^{-1})	Total Carbon (%)	Standing Stock (g AFDM m^{-2})	Denitrification Rate (mg N m^{-2} hr^{-1})
	mean ± standard deviation				
Ag/Urban	0.02 ± 0.04	10.9 ± 10.8	3.3 ± 0.6	560 ± 234	4.4 ± 3.8
Forest	0.02 ± 0.03	11.6 ± 10.8	3.7 ± 1.0	638 ± 135	4.3 ± 4.1

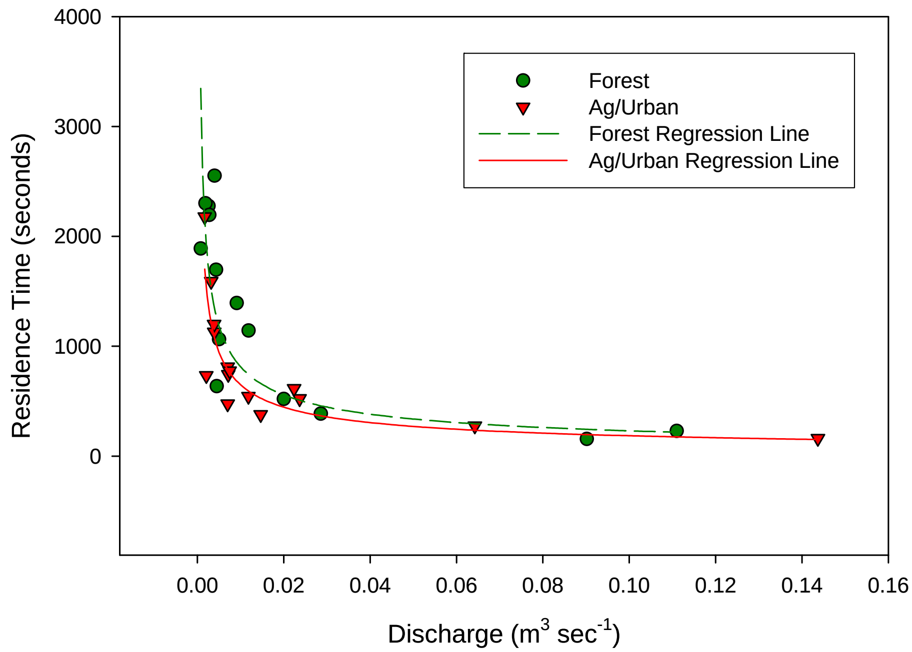

Figure 1. The 50-meter residence time (sec) and discharge (m^3 sec^{-1}) for each reach type. Forested reaches (circle) have a significantly higher residence time than agricultural/urban reaches (triangles) using discharge as a covariate ($p = 0.034$, ANCOVA).

Loss rates of NO_3^- were not significantly different between reach types in any of the 3 sampling seasons ($p = 0.458$, ANOVA; Figure 2). On the other hand, there were significant differences in NO_3^- loss rates between seasons ($p = 0.024$, ANOVA; Figure 2). This finding was expected as temperatures, rain events, and in-stream NO_3^- concentrations do vary seasonally. Residence time has little ability to explain nitrogen removal in these systems ($R^2 = 0.012$, $p = 0.569$; Figure 3). Nitrate concentration in the water column of our headwater reaches does explain a majority of the variation in the nitrogen removal data ($R^2 = 0.603$, $p < 0.001$; Figure 4). Further, the data suggest that our sites are saturated with NO_3^-, limiting the capability of these systems to process NO_3^- (Figure 4). This finding has been found in other agricultural systems as well (Bernot et al., 2006; Davis and Minshall, 1999).

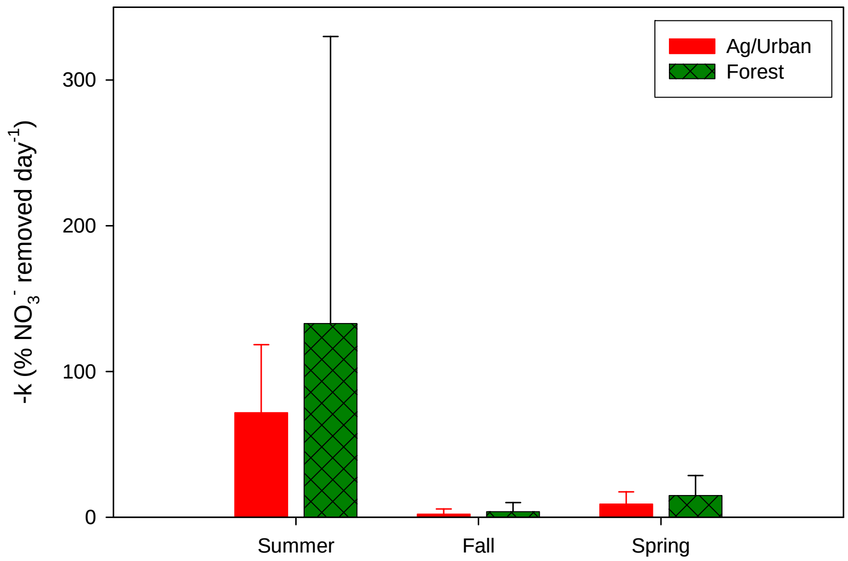

Figure 2. Nitrate loss rates (-k) for the agricultural/urban sites (solid bars) and the forested sites (hashed bars) for the Summer and Fall of 2005 and the Spring of 2006. There are no significant differences between reach types ($p = 0.458$) but there is a significant seasonal effect ($p = 0.024$). Error bars are standard deviations.

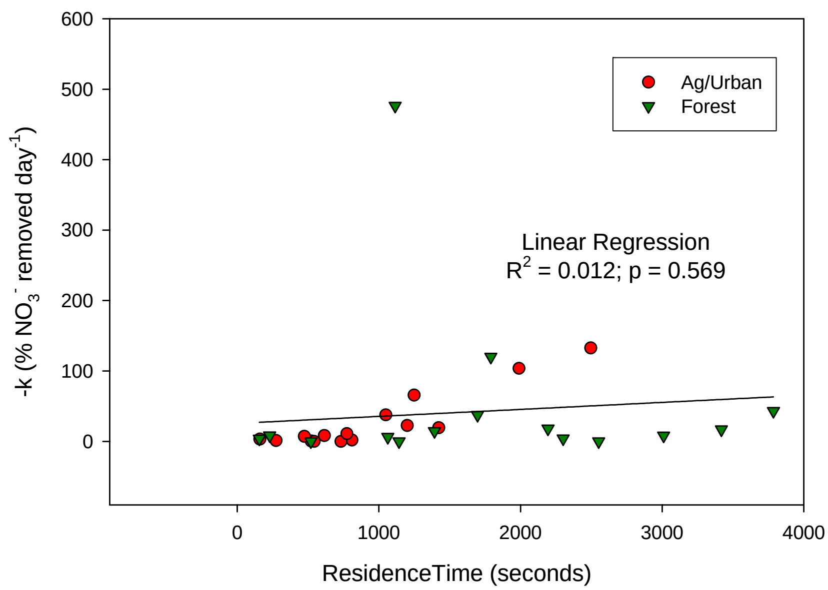

Figure 3. Nitrate loss rate (-k) and residence time (sec) for the agricultural/urban sites (circles) and the forested sites (triangles). The linear regression was run on all sites and was not significant ($p = 0.569$).

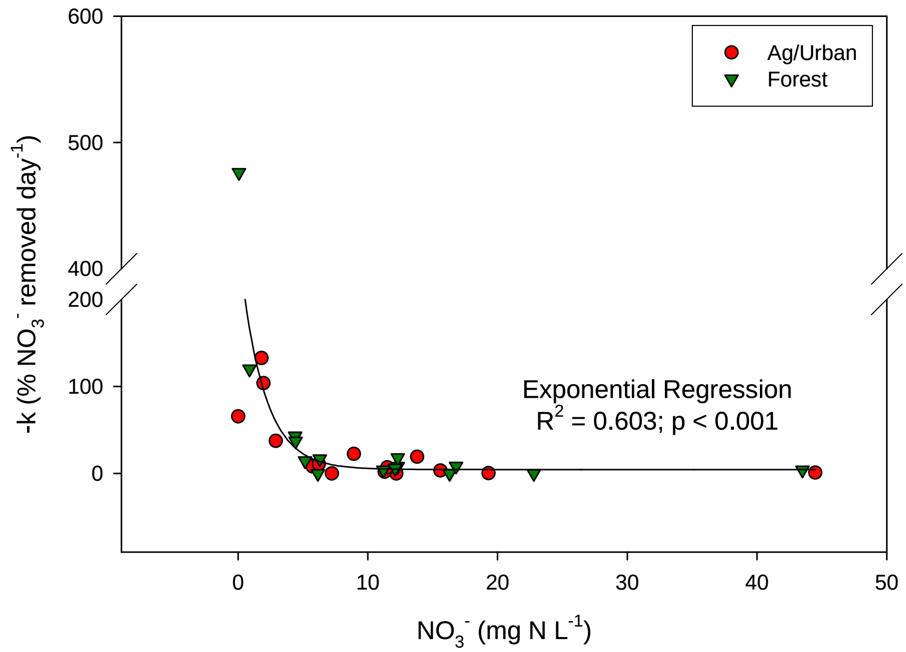

Figure 4. Nitrate loss rate (-k) and the water column NO_3^- concentration (mg N L^{-1}) for the agricultural/urban sites (circles) and the forested sites (triangles). The exponential regression was run on all sites and was significant ($p < 0.001$).

Significance

Our overall objective was to determine the effect of residence time on nitrogen removal via denitrification in agricultural headwater streams. We identified 2 stream reach types (agricultural/urban and forested) with significantly different residence times along 5 headwater streams in the Upper Sugar Creek Watershed. These 2 subsets did not, however, have significantly different nitrogen removal rates. A closer examination of the regression between the NO_3^- loss rate and residence time from the study sites determined that residence time has little ability to explain nitrogen removal. On the other hand, NO_3^- concentrations do explain a large amount of variability in the nitrogen removal data in our study. The data suggest that nitrogen removal is NO_3^- saturated and above concentrations of ~6 mg N L^{-1} these streams have no ability to remove NO_3^-. Although residence time may have some ability to control nitrogen removal in aquatic systems, our streams most likely do not represent a wide enough separation in residence times to show significant differences in nitrogen removal.

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