AMMONIUM UPTAKE IN URBAN AND FORESTED HEADWATER STREAMS

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Abstract. Land-use can affect nutrient loading to streams; however, there is little information about how land-use affects nutrient uptake processes in streams. Because headwater streams serve as regulators of water chemistry, it is important to consider how land-use alters nutrient removal capacity. We measured ammonium uptake and mass transfer coefficients in four forested and four urban headwater streams within the Upper Etowah River Basin, GA, during summer baseflow. Although discharge did not differ between stream types, urban streams had longer water residence times, were wider, and had more algal biomass than forested streams. Despite these physical and biotic differences that normally result in greater nutrient uptake, no significant difference was observed in ammonium uptake length or mass transfer coefficient in urban and forested streams.

INTRODUCTION

Streams alter the form and amount of nutrients transported from terrestrial ecosystems to downstream ecosystems through uptake and transformation (Stream Solute Workshop 1990, Alexander et al. 2000). This retention and transformation can be important in regulating downstream fluxes of nutrients. For example, river retention of nitrogen due to denitrification and burial is generally around 30 percent (Caraco and Cole 1999).

Numerous studies have shown that land-use can affect nutrient loading to streams (Caraco 1995, Carpenter et al. 1998, Caraco and Cole 1999) and human population within a watershed is strongly related to mean annual nitrate concentration (Peierls et al. 1991). In addition, reports compiled by the USEPA state that 40% of streams or rivers surveyed in the US were impaired because of high nutrients (Dodds and Welch 2000). However, there is no information on how land-use affects nutrient uptake processes. Previous studies have shown that headwater streams are capable of retaining and transforming 50% of the inorganic N inputs from their watersheds (Peterson et al. 2001). In addition, because of their large surface-to-volume ratios, small streams are critical to regulating water chemistry (Alexander et al. 2000, Peterson et al. 2001).

Physical factors such as discharge, stream depth, and current velocity have been demonstrated to be important factors in determining ammonium uptake (Peterson et al. 2001, Wollheim et al. 2001). Therefore, changes in land-use that affect the physical characteristics of the stream could influence uptake lengths.

Urban land-use affects streams in a variety of ways (Paul and Meyer 2001). Increased impervious surfaces lead to increased peak discharges, which can create larger channels through in-channel scour and bank erosion (Paul and Meyer 2001). In addition, urban streams are frequently straightened, forced through culverts underground, or modified in other ways (e.g concrete channels) that remove typical in-channel structures (e.g. meanders, pools, debris dams) that temporally retain water. These retention areas are called transient storage zones. It is possible that these areas are important to the retention of nutrients. However, transient storage zone size only explained 35% of the variation in ammonium mass transfer coefficients in the summer in 13 streams at Hubbard Brook Experimental Forest (Hall et al. 2002).

Urban streams typically have higher ammonium concentrations than forested streams. These increased nutrient inputs may decrease the ability of streams to retain and transform nutrients, leading to longer uptake lengths (Wollheim et al. 2001). Thus, streams draining catchments with land-uses that increase nutrient inputs to streams may have longer uptake lengths than other streams of similar physical characteristics.

We examined the impacts of land use on ammonium dynamics by measuring ammonium uptake lengths and mass transfer coefficients in four urban and four forested headwater streams in the Upper Etowah River Basin, GA. We hypothesized that urban streams would have longer uptake lengths and lower mass transfer coefficients because of higher background ammonium concentrations and less physical retention.

BACKGROUND

In streams, the transport and transfer of nutrients are tightly linked with the physical movement of water. In flowing waters, nutrient cycles are longitudinally extended to become spirals (Webster and Ehrman 1996). The length of the spiral is primarily determined by uptake length (Newbold et al. 1983, Webster and Ehrman 1996). Uptake length is a measure of the distance it takes the average nutrient molecule to be incorporated into biomass or a particle. It is measured by following the decline in concentration of added nutrients after the added nutrients and chloride are in equilibrium in the channel. Uptake length is the negative inverse of the slope of the regression of the natural logarithm of the nutrient:specific conductivity ratio measured at each sampling site (after background correction) and the distance between the specific sampling site and the site of nutrient input. Uptake length is positively related to discharge (Butterini and Sabater 1998). Mass transfer coefficients of uptake correct for the effect of discharge and make it possible to compare uptake between different streams (Stream Solute Workshop 1990). Mass transfer coefficients represent the demand for nutrients relative to the supply in the water column, and can be thought of as the vertical velocity of nutrients (Stream Solute Workshop 1990, Hall et al. 2002).

METHODS

Study Site

We used eight streams in the Upper Etowah River watershed. The four forested streams were located in the Dawson Forest Management Area in southwest Dawson County. Watershed area for the forested stream ranged from 0.3 to 1.8 km^2 (Table 1). The four urban streams were located within the city limits of Kennesaw or Acworth, GA and drained a mixture of residential and industrial land uses. Watershed areas for the urban streams ranged from 0.4 to 1.8 km^2 (Table 1).

Nutrient Uptake Length

Nutrient uptake length was measured using the methods described by Webster and Ehrman (1996) and Stream Solute Workshop (1990). We performed short-term nutrient additions using sodium chloride as a conservative tracer to measure discharge and travel time at each site during baseflow conditions in summer of 2002. Nutrients and salt were dissolved in water and simultaneously injected at a known constant rate by using a Watson-Marlow peristaltic pump. Target concentrations varied based on background concentrations, but we typically increased conductivity by 30 μScm^{-2} and NH_4-N concentrations by 15 μgL^{-1}. Reach length varied between 100 and 150 m depending on travel time and accessibility. We calculated ammonium uptake length using the equation: $\ln C_x = \ln C_o - ax$ where C_x and C_o are ammonium concentrations x m downstream from the addition site, and a is the per meter uptake rate (Newbold et al. 1983, Hall et al. 2002). Uptake length, S (m), is equal to $-a^{-1}$. We calculated mass transfer coefficients, V_f, using the equation: $V_f = Q/(wS)$, where Q is discharge, w is width, and S is uptake length (Stream Solute Workshop 1990, Hall et al. 2002). Uptake rate per meter, U ($\mu g\ m^{-1}\ min^{-1}$), of stream length is calculated by multiplying the mass transfer coefficient by the average concentration in the stream during the release and dividing by reach length

We used a YSI recording multiprobe (YSI 6920) to measure change in relative salt concentration with time at a point in the thalweg. Once salt concentrations had reached a plateau, we sampled ammonium and conductivity at 10 m intervals. For ammonium, we took three grab samples across each transect and immediately filtered the sample using Whatman GFF glass fiber filters. Specific conductivity was measured using the conductivity meter. Ammonium samples were analyzed using the methods of Holmes et al. (1999).

Algal biomass was measured by scraping a known area from three surfaces on 10 transects in the reach. Algal biomass (mg chlorophyll *a* m^{-2}) was calculated using the methods of Wetzel and Likens (1992). Canopy cover of the channel was measured using a spherical densiometer at each algal sampling location.

We used t-test with unequal variances (Welch's t) to test for differences in discharge, travel time, width, algal biomass, canopy cover, ammonium uptake length, and ammonium mass transfer coefficients between the urban and forested streams (Zar 1999).

Table 1. Forested and Urban Stream Data. All t-test assumed unequal variances and a = 0.05.

	Forest mean	*Urban mean*	*p value*
Watershed area (km^2)	0.78	1.11	0.49
Discharge ($L\ s^{-1}$)	2.4	1.5	0.18
Water residence time (min)	38	84	0.03
Width (m)	1.39	2.17	0.008
Canopy cover (% cover)	61	47	0.03
Ammonium concentration ($\mu g\ L^{-1}$)	14	45	0.02
Uptake length (m)	86	57	0.35
Mass transfer coefficient ($mm\ min^{-1}$)	1.37	0.96	0.4
Chlorophyll *a* ($mg\ m^{-2}$)	5.6	10.9	0.03

RESULTS

Background concentrations of ammonium were higher in the urban sites than in the forested site. Discharge did not differ significantly between the two stream types (Table 1). However, water residence time was two times greater in the urban streams than in the forested stream (Table 1). In addition, urban streams were 1.5 times wider than forested streams (Table 1). Forested streams had more canopy cover than urban streams ($p = 0.03$).

Uptake length ranged from 53 to 162 m in the forested streams and from 26 to 89 m in the urban streams, but there was no significant difference between the two stream types (Table 1). Mass transfer coefficients in the urban streams were highly variable, with three of the four streams ranging from 0.55 to 0.69 $mm\ min^{-1}$ and one site's mass transfer coefficient three times higher at 2.07 $mm\ min^{-1}$. This site was located in a conservation subdivision. Mass transfer sites in the forest streams ranged from 0.73 to 2.22 $mm\ min^{-1}$, with a much more even distribution within the range. There was no significant difference in mean mass transfer coefficients between the two stream types (Table 1). Algal biomass was almost two times higher in the urban sites than in the forested sites ($p = 0.03$). These results indicate that the urban streams remove an average of 0.3 $\mu g\ m^{-1}\ min^{-1}$, while the forested sites remove an average of 0.26 $\mu g\ m^{-1}\ min^{-1}$.

DISCUSSION

We hypothesized that nutrient uptake lengths would be longer in the urban streams than in the forested streams due to less physical retention and higher background concentrations. In fact, water residence time was greater in the urban streams than in the forested streams. Background ammonium concentrations were higher in the urban streams, but there was no difference in either ammonium uptake length or ammonium mass transfer coefficient.

Variation in uptake length can be caused by hydrologic, geomorphologic, and biotic characteristics. For example, longer water residence time typically leads to shorter uptake lengths (Valett et al. 1996, Butterini and Sabater 1998). In addition, high algal abundance increases the demand for nutrients and decreases uptake lengths (Marti et al. 1997). Since urban streams had both longer water residence time (a function of both increased depth and decreased velocity) and greater algal biomass we would have expected shorter uptake lengths and higher mass transfer coefficients. However, this was not the case. One potential reason for uptake lengths longer than expected is the high background concentrations of ammonium (Dodds et al. 2002).

Mass transfer coefficients for the forested and urban streams were at the low end of the range of coefficients found in forested streams with similar discharge at Hubbard Brook Experimental Forest (Hall et al. 2002). Mean ammonium mass transfer coefficient for the Hubbard Brook stream was 3.21 $mm\ min^{-1}$ and ranged from 0.81 to 10.81 $mm\ min^{-1}$. Only two of the Hubbard Brook streams had mass transfer coefficients less than the average mass transfer coefficient for the urban Etowah sites. Again, this suggests that ammonium uptake in the urban streams is less than we would expect given the high retention and algal biomass.

The increased water residence time in these urban channels is a function of channel shape. Urban channels had fewer debris dams than forested streams, but did have large scour pools that are created and maintained by the high peak discharges. Contrary to our expectation, these streams maintained the channel structures such as meanders and pools that enable retention of water at baseflow, and this physical retention is likely important in nutrient retention as well.

These data illustrate the importance of small streams in regulating nutrients. Small streams are frequently lost in urbanized areas as they are piped, thereby reducing drainage area (Paul and Meyer 2001, Meyer and Wallace 2001). These urban streams are capable of retaining nutrients because they have maintained channel structure and in-channel substrates that have not been silted and can still serve as attachment sites for algae. Interestingly, the urban stream with the highest mass transfer coefficient and the shortest uptake length had the highest canopy cover and the most algal biomass. This stream was located in a conservation subdivision, and had a wide riparian buffer zone. This suggests urban headwater streams are capable of retaining nutrients and helping to regulate water chemistry if they are maintained as functioning ecosystems by not piping or channelizing them.

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