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# RESTORING BIOGEOCHEMICAL FUNCTIONS IN DEGRADED URBAN STREAM ECOSYSTEMS

By
Dr. Emily S. Bernhardt[1,2], Elizabeth Sudduth[1], Peter Cada[2], and Christy Violin[3]

[1]Department of Biology
[2]Nicholas School of the Environment and Earth Sciences
Duke University
Durham, North Carolina

[3]Department of Biology
University of North Carolina at Chapel Hill
Chapel Hill, North Carolina

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Duke University
Durham, North Carolina

[3]Department of Biology
University of North Carolina at Chapel Hill
Chapel Hill, North Carolina

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**ABSTRACT:** A growing body of research demonstrates the important effect stream ecosystems have in altering the form, timing and magnitude of watershed nitrogen (N) losses. Most of this research has been conducted in minimally impacted watersheds. Streams in heavily urbanized watersheds may be functionally disconnected from upland soils, with a high proportion of precipitation routed over pavements and through storm drains directly into channels. Receiving streams, in turn, will become little more than gutters routing stormwaters towards the sea. Urban streams thus represent the worst case scenario, integrating a large number of simultaneous watershed insults. Several very recent studies suggest that these streams have very reduced capacities to transform and retain N. These same studies also demonstrate that N transformation and retention is closely tied to organic matter (OM) dynamics. For the last year we have examined differences between 12 focal stream reaches in the Raleigh-Durham metropolitan area, comparing streams from forested watersheds (n=4) with those in urban watersheds (n=8) in reaches that are degraded (n=4) or recently restored (n=4). We have found that stream restoration efforts do not appear to be restoring habitat or flow heterogeneity. The urbanized streams in our survey tend to have slower flows, more homogeneous substrate, and greater channel incision than their forested counterparts and indeed restored stream reaches are virtually identical to urban streams, with the exception of having reduced channel incision. Our efforts to document differences in ecosystem function across these twelve streams have proven less sensitive. Urbanization tends to shift stream ecosystems towards increasingly productive systems, with higher nutrients, slower flow and higher light levels stimulating algal growth. Restoration projects tend to eliminate riparian trees, thus the major effect of restoration on ecosystem function is warmer, more well lit streams that have higher algal production and higher nutrient uptake than their urban counterparts.

*Keywords:* Urbanization, river restoration, ecosystem function, habitat heterogeneity, nutrient uptake, stream metabolism

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SUMMARY AND CONCLUSIONS:

*Approach:* With the help (and additional financial support of ~$21K) of the NC Ecosystem Enhancement Program we identified 6 urban streams included in their existing program, four previously restored projects and 2 soon to be restored degraded urban streams. These 6 streams, along with 4 reference streams in Umstead Park and the Duke Forest and 2 additional urban streams (one in Raleigh and one in Durham) make up our set of 12 intensive field sites. Within the project period we have: (1) monitored water chemistry once monthly at all 12 streams; (2) developed GIS watershed analyses of land use for the watershed draining to each study reach; (3) performed nutrient injection experiments, measured whole ecosystem metabolism, and modeled transient storage in each reach using low level experimental enrichments of nutrients and hydrologic tracers (each of these measurements were made for each stream in June 2006 and February 2007); (4) conducted a detailed survey of stream and riparian morphology; (5) installed continuously recording water level sensors to develop hydrographs for each site and (6) intensively sampled benthic organic matter at all 12 sites.

*Objectives:* Our comparison of these 12 stream reaches was motivated by a desire to understand: (1) how urbanization changes both the structure (habitat heterogeneity, hydrologic connectivity, riparian characteristics) and function (metabolism, nutrient uptake) of stream ecosystems; and (2) the extent to which interventionist restoration approaches that use natural channel design to re-engineer degraded channels can move degraded urban ecosystems back towards "reference" conditions.

*Findings:* We are still in the midst of working up the entire dataset, and expect to submit at least two manuscripts arising from this work in fall 2007. One manuscript will focus on the structural and hydrologic changes in stream channels associated with urbanization and will report our findings that stream restoration efforts do not appear to be "restoring" habitat or flow heterogeneity. The urbanized streams in our survey tend to have slower flows, more homogeneous substrate, and greater channel incision. Restored streams are virtually identical to urban streams, with the exception of channel incision, likely reflecting the focus by restoration practitioners on channel geometry rather than habitat quality. A second manuscript will report our findings on nitrogen processing and metabolism across this urbanization gradient. Urbanization tends to shift streams towards increasingly productive systems, with higher nutrients, slower flow and higher light levels stimulating algal growth. Restoration projects tend to eliminate riparian trees, thus <u>the</u> major effect of restoration on ecosystem function is warmer, more well lit streams that have higher algal production and higher nutrient uptake than their urban counterparts.

Related work in these same stream reaches by PhD student Christy Violin has found that macroinvertebrate community composition is quite different between the urban and forested streams (with many more sensitive taxa found in the reference streams), but that macroinvertebrate communities in the restored stream reaches are not different from their urban degraded stream counterparts. We have found that simple measures of habitat heterogeneity are the best predictors of macroinvertebrate community composition, and suggest the lack of attention to creating fine scale habitat diversity in restored streams may limit their success.

RECOMMENDATIONS:

Our study to date has found that:

1) Streams in urban catchments have:
- Flashier hydrographs
- More highly incised stream channels
- Higher loads of both nitrate and total nitrogen (as well as $Cl^-$ and $SO_4^=$)
- Simplified flow and substrate defined habitats
- Less variable distributions of organic material
- Very low occurrences of sensitive macroinvertebrate taxa

2) Restored streams differ from their urban degraded counterparts by
- Having less incised stream channels
- Having higher summer uptake efficiencies for $NO_3^-$
- Having reduced canopy cover relative to unrestored urban streams targeted for restoration

3) Restored streams are indistinguishable from their urban degraded counterparts in
- Having little variation of bed and flow habitat types
- Having low variation in depth and velocity
- Having nitrogen concentrations that are higher than reference watershed streams
- Having identical macroinvertebrate community composition

These findings suggest that restoration efforts are failing to ameliorate many of the insults to urban stream ecosystems. We recommend that increasing attention be paid to reestablishing fine-scale variation in habitat heterogeneity (introducing a variety of substrate sizes and varying depths within restored stream reaches) in order to better mimic less impacted streams. We caution that all urban restoration efforts are unlikely to succeed without addressing the primary cause of channel degradation, the flash hydrographs associated with high watershed impervious cover. Restoration of channels without accompanying stormwater management efforts are unlikely to be successful at reaching the goals of “reestablishing ecosystem function”.

**Restoring Biogeochemical Functions In Degraded Urban Stream Ecosystems**

# 1. Introduction

## 1.1 Background

**Statement of Critical Water Resources Problem:**

**High levels of nitrogen are loaded to increasingly degraded streams:** Humans have roughly doubled the annual supply of nitrogen (N) to the planet. This has numerous detrimental impacts, including increased fluxes of nitrogen in rivers, leading to excessive nitrogen concentrations, harmful algal blooms, and regional hypoxia in many coastal waters and estuaries (Green, Vorosmarty et al. 2004). The streams that receive these increasingly high nitrogen inputs have a tremendous capacity to transform reactive N (available to plants and microbes) back into inert atmospheric $N_2$ through biological uptake and denitrification within river sediments (Peterson, Wollheim et al. 2001; Bernhardt, Likens et al. 2003; Bernhardt, Likens et al. 2005). Recent global modeling estimates have suggested that at least half of the nitrogen entering river systems appears to be lost to denitrification on its way to the sea (Galloway, Dentener et al. 2004). The smallest streams are the most effective at nitrogen removal (Alexander, Smith et al. 2000; Seitzinger, Styles et al. 2002), yet many of our smallest streams are poorly protected by current environmental regulations and are heavily impacted by pollution and channelization. Currently, over 130,000 km of U.S. streams are impaired by urbanization (USEPA 2003). This estimate will certainly increase over the next 30 years, as virtually all of the world's population growth is expected to occur in urban areas, with over 60% of the world's population in urban areas by 2030 (UNPD 2003). Urbanization and suburbanization of watersheds results in a series of predictable changes in streams, leading to radically altered channel forms (wide, shallow, straight channels with little depth or velocity variation) and hydrology (high peak flows, reduced base flows, and discontinuity between channel and subsurface sediments (Paul and Meyer 2001). Because urbanization simultaneously increases the loading of sediments and nutrients while simplifying the stream channel, urban rivers are effectively changed from functioning ecosystems to gutters. A number of recent papers demonstrate that urban streams have very reduced capacities for nutrient uptake and retention (Grimm, Crenshaw et al. *In Press;* Groffman and Dorsey *In Press;* Groffman, Law et al. *In Press;* Meyer, Paul et al. *In Press*), yet to date this work been primarily descriptive rather than mechanistic.

**Investments in river restoration attempt to reduce N export:** Concern over the impacts that land use changes may have on the ability of river systems to provide the ecological and social services upon which human life depends has resulted in the initiation of major investments in urban river restoration (Bernhardt, Palmer et al. 2005). More than one third of all river restoration projects in the U.S. are implemented to "manage and improve water quality", yet these projects are rarely evaluated to determine if this goal is achieved (Bernhardt, Palmer et al. 2005). In urban areas, multi-million dollar projects are aimed at "renaturalizing" these simplified channels back (hopefully) into functioning ecosystems (supporting of diverse fauna and capable of retaining sediments and nutrients) (Bernhardt and Palmer In review).

## Related Research and Justification:

### *Preliminary Data*

Recent work has demonstrated that rates of nitrogen uptake in urban streams are low compared to undisturbed systems (Grimm, Crenshaw et al. *In Press;* Meyer, Paul et al. *In Press*), Palmer & Bernhardt, in prep.), and that BOM levels are low (Meyer, Paul et al. *In Press*) and correlated with nitrogen uptake and denitrification (Groffman and Dorsey *In Press;* Meyer, Paul et al. *In Press*).

Efforts to reconnect stream channels with their floodplains and to slow flow via remeandering and placement of channel obstructions should lead to greater opportunities for inorganic nitrogen removal in riparian soils and hyporheic sediments. Preliminary surveys of four channel reconfiguration projects within urban watersheds near Durham suggest that these efforts are attenuating high $NO_3$ loads.

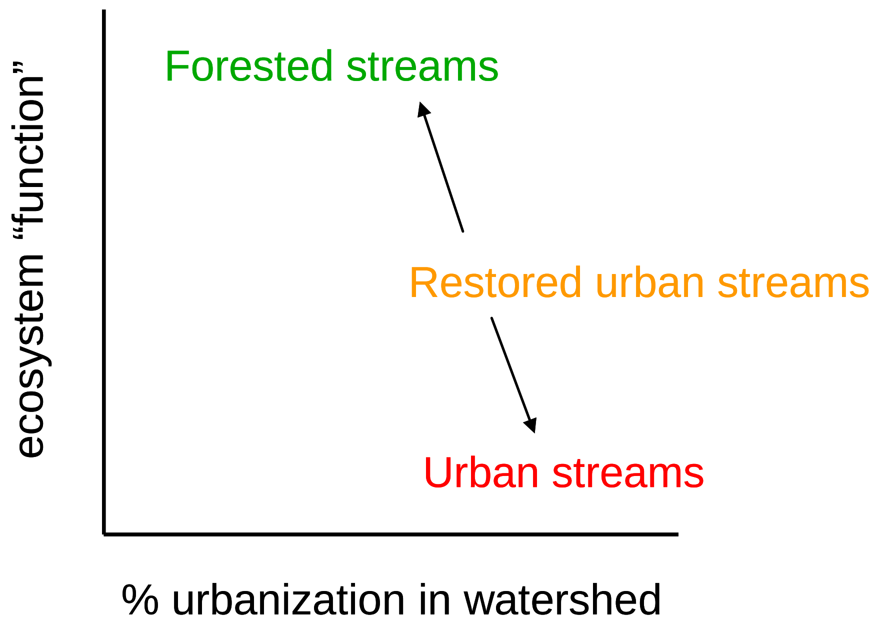
**Nitrogen uptake in streams is a function of labile C availability:** In the last decade, a growing body of research has documented the important role that stream ecosystems, particularly headwaters, play in influencing the downstream export of nitrogen (Alexander, Smith et al. 2000; Peterson, Wollheim et al. 2001; Bernhardt, Hall et al. 2002; Seitzinger, Styles et al. 2002). Efforts to understand the mechanisms that control nitrogen uptake have been less productive. Indeed, inter- and intra-biome studies of stream N cycling have tended to find that no measured variables are tightly correlated with nitrogen uptake (Webster, Mulholland et al. 2003). Exceptions to this trend are several lines of research that suggest carbon supply and carbon processing (metabolism) are good correlates of nitrogen uptake both within and among streams (Bernhardt and Likens 2002; Hall and Tank 2003; Meyer, Paul et al. *In Press*). Tight linkages between carbon and nutrient processing are expected -- given stoichiometric and thermodynamic constraints on organisms -- yet it can be difficult to conceive of small forested streams as carbon limited. However, carbon can be strongly limiting even in streams with high organic matter standing stocks. Experimental additions of labile carbon to: i) stream sediment samples (Strauss and Lamberti 2000); ii) hyporheic flowpaths (Baker, Dahm et al. 1999) and iii) entire streams (Bernhardt and Likens 2002) have been shown to: i) decrease nitrification; ii) stimulate N assimilation and denitrification; and iii) eliminate inorganic nitrogen export from an entire watershed.

**Urban stream microbial activity is likely to be C limited:** Geomorphic and hydrologic research in pristine streams demonstrates that structural elements in streams (e.g., debris dams) increase the deposition and storage of fine material(Bilby 1981). In heavily degraded urban streams, most of these structures have been removed, either through active management or due to frequent high, flashy stormflows. These simplified channels thus have a reduced capacity to trap organic matter (OM) and their beds are frequently scoured – reducing levels of deposited organic material as well as attached periphyton. Organic matter serves not just as an energy source but as a substrate for microbes; therefore, carbon limitation is likely to be particularly severe in urban stream ecosystems. This is unfortunate, since these same streams typically receive high nitrogen inputs (Paul and Meyer 2001; Groffman, Law et al. *In Press*). Even when urban impacted streams have intact riparian forests (and thus levels of litter inputs comparable to undeveloped sites), they will have a dramatically reduced capacity to retain these materials within the stream channel due to simplified channel structure and flashy storm hydrographs. Because restored streams frequently are engineered for increased channel complexity and sinuosity, they have the potential to increase OM retention and metabolism

**1.2 STUDY OBJECTIVES**

We predicted that streams in urban watersheds would have simplified habitat structure and be impaired in ecosystem function relative to their minimally impacted counterparts in predominantly forested watersheds (Figure 1). We also predicted that restoration efforts would lead to stream ecosystems that fell out intermediate in both structural and functional attributes relative to forested and urban watershed streams.

*Figure 1: Hypothetical predictions for the effects of urbanization and restoration on stream ecosystem function*



We examined these predictions through detailed comparison of 12 stream reaches distributed between 3 categories: forested watersheds (4 streams draining watersheds that were minimally impacted by urban development); urban degraded streams (4 streams draining heavily urbanized watersheds without any channel restoration); and urban restored (4 streams draining heavily urbanized watersheds that have undergone some form of natural channel design river restoration within the last eight years). For this set of 12 streams we made the following set of predictions in our original proposal (Table 1). In each case, we predicted that these factors would differ between the forested and the urban stream reaches, and hypothesized that successful restoration would lead to measurements that were intermediate to the urban and forested endpoints.

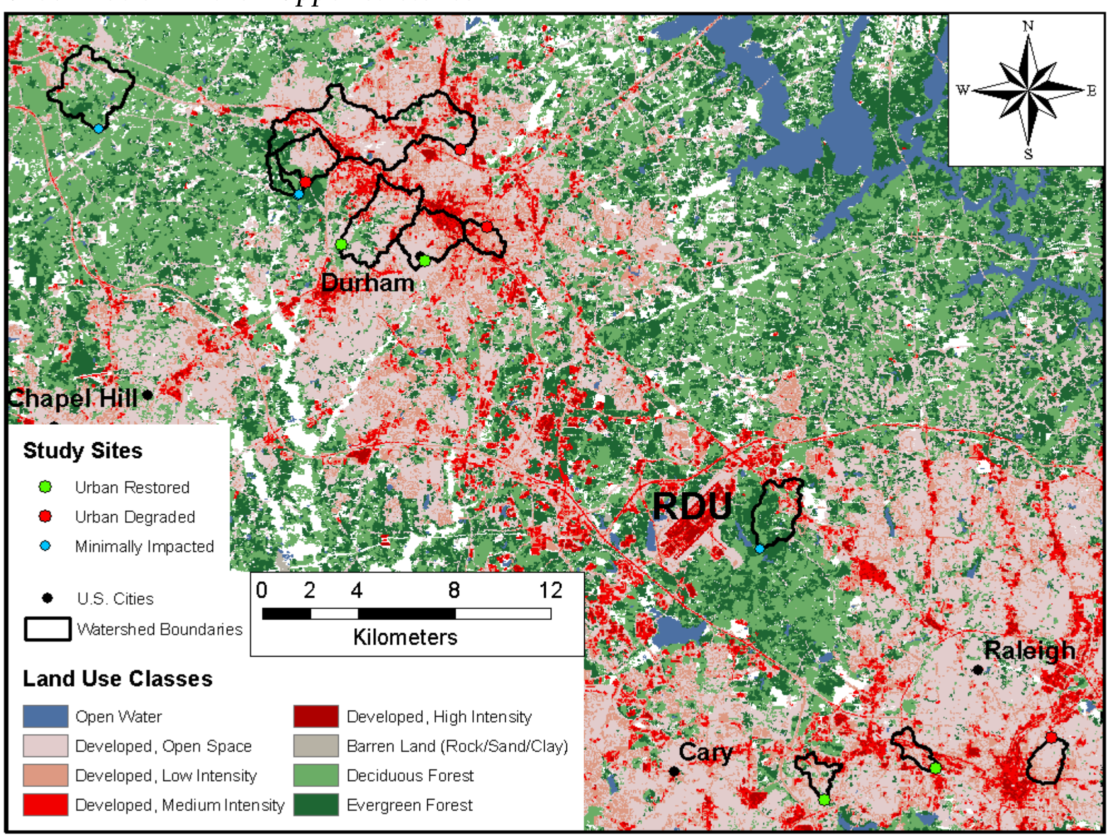
| **Table 1. Response Variables** | **Developed relative to undeveloped** | |
|---|---|---|
| | **Mean** | **Variance** |
| *Hydrologic* | | |
| Storm pulse amplitude | > | na |
| Transient storage | < | na |
| Hydraulic connectivity | < | < |
| *Geomorphic* | | |
| Channel Incision | > | < |
| Water depth | < | < |
| Channel width | > | < |
| *Biogeochemical* | | |
| Benthic Organic Matter (BOM) | < | < |
| Community Respiration (CR) | < | < |
| Denitrification potential (DEA) | < | < |
| Microbial biomass | < | < |
| DIN uptake velocities | < | < |
| Nitrification | > | < |

## 2. STUDY DESIGN

### 2.1 STUDY SITES

We set up a comparative study of streams from 12 watersheds within the Raleigh-Durham metropolitan area (see Figure 2). Four streams were in predominantly forested watersheds (<10% impervious cover) with our study reaches at least a kilometer downstream of any impervious cover (impacts in headwaters) (Table 1). Eight "urban" streams drained watersheds ranging from 11-40% impervious cover (Table 1). Four of our study reaches within these urban streams had been restored within the last decade and were recommended as the "best case scenarios" for restoration by staff of the NC EEP and the NC Stream Restoration Institute. In each stream we located an intensive study reach that was representative of local conditions and which allowed at least one hour of water travel time during summer baseflow. In the restored streams we chose reaches at the downstream end of the restored segments, operating on the assumption that these segments would benefit from both local and upstream effects of the restoration project. Our goal in this study was not to examine the average restoration project, but instead to examine the potential for restoration to achieve habitat improvement or ecosystem functional benefits, thus we chose the projects and the reaches that we expected would maximize restoration benefits.

*Figure 2: A map showing the distribution of study sites by land use category. Note that even our minimally impacted "forested" watershds have some level of urbanization in their upper stretches*



| Table 2: Watershed Characteristics | | | | | |
|---|---|---|---|---|---|
| Block | Status | Site Name | Watershed Size ($km^2$) | % Developed | % Impervious |
| A | Forested | Stony Creek | 6.9 | 24.4 | 3.4 |
| | Restored | Forest Hills | 4.4 | 99.5 | 32.4 |
| | Urban | Northgate Park | 7.6 | 88.7 | 20.8 |
| B | Forested | Potts Branch | 4.2 | 27.4 | 9.9 |
| | Restored | Abbott Creek | 1.7 | 84.5 | 17.8 |
| | Urban | Cemetary Creek | 2.2 | 98 | 19.1 |
| C | Forested | Mud Creek Tributary | 0.9 | 4.4 | 0.5 |
| | Restored | Rocky Branch | 1.5 | 99.2 | 34.8 |
| | Urban | Goose Creek | 1.7 | 100 | 39.4 |
| D | Forested | Mud Creek Reach 4 | 4.1 | 58.6 | 9.5 |
| | Restored | Sandy Creek | 6.7 | 76.9 | 16.8 |
| | Urban | Mud Creek Reach 1 | 3.5 | 66.9 | 11 |

## 2.2 SAMPLING METHODOLOGY

This research program will focus on measuring A) stream metabolism and inorganic nitrogen uptake in a series of degraded and restored urban streams as well as several reference streams (n=4 of each) and relating these vital ecosystem functions to two key structural attributes of stream channels; B) hydraulic connectivity between the stream channel and its riparian zone and between surface water and hyporheic groundwater; and C) organic matter retention and storage. We request funding for the initial year of research, but anticipate pursuing renewal funding from WRRI and additional funds from other sources (e.g., NSF, EPA, NC EEP) to continue this research for at least three years.

### A) Functional Measures: Metabolism and Nitrogen Uptake

**Metabolism**: Ecosystem metabolism is an expression of all heterotrophic and autotrophic activity in the stream and thus would be expected to be influenced by any change in shading, allochthonous input, thermal regime, or nutrient concentrations due to urbanization or stream restoration. Restoration efforts should slow streamflow and increase transient storage of surface water and exchange with hyporheic and shallow groundwater reservoirs. The resulting increase in water-sediment contact time and depositional habitats should lead to higher net ecosystem metabolism rates. Although metabolism rates may not be linearly affected by urbanization, ecosystem metabolism has been shown to control ammonium uptake in both relatively pristine (Hall and Tank 2003) and urban streams (Meyer, Paul et al. *In Press*).

*Methods:* Gross primary production (GPP), community respiration (CR), and net ecosystem metabolism (NEM=GPP-CR) will be estimated using the two-station method described by (Marzolf, Mulholland et al. 1994). This method uses oxygen probes at the top and bottom of a reach to measure oxygen change over the reach, and a propane and conservative tracer release to estimate transit time and oxygen exchange rate. We will also measure redox potential and respiration, using respiration chambers and redox probes, to determine the status of heterotrophic metabolism in riparian soils and hyporheic sediments.

*Expected Results:* Little structure and frequent disturbance due to flashy floods may limit the algal population in the urban streams, limiting GPP, and these effects may not be mitigated in the restored streams. CR is associated with stable, organic substrate, such as leaf packs, so we expect CR to be correlated with in-stream benthic organic matter. Naturally occurring stream complexity in the reference streams, and increased structure in the restored streams, will lead to larger transient storage zone volume, which could increase NEM.

**Nitrogen Uptake**
*Whole-stream uptake:* We will use standard methods(Newbold 1981; Bernhardt, Hall et al. 2002) to measure the rate at which inorganic nitrogen is removed from the water column. Briefly, we will perform back to back co-injections of $NaNO_3$ then $NH_4Cl$ with a hydrologic tracer (NaBr then NaCl). We will examine the downstream change in the concentration of the nutrient relative to the inert tracer. We will use the slope of the decline for each release to estimate, $NH_4$, $NO_3$ and total nitrogen uptake rates and whole-stream nitrification.

*Riparian and Hyporheic Denitrification Rates*: Denitrification is the only process by which nitrogen can be permanently removed from the stream channel and is thus the critical biogeochemical function that we would like to promote within restored stream reaches. We will measure denitrification potential by incubating stream and riparian sediment samples from each reach (**Groffman**, **Holland** et al. 1999). We will compare rates between streams to determine whether urbanization and/or restoration affects denitrification rates. We will also examine the relationship between BOM and denitrification potential for individual cores. In one representative stream within each category, we will supplement these estimates by measuring *in situ* denitrification rates in riparian and hyporheic sediments using $^{15}N$ single-well push-pull tests (Addy, Kellogg et al. 2002). Briefly, groundwater is extracted from a riparian or hyporheic well, supplemented with $^{15}NO_3$ along with hydrologic (NaBr) and gas (propane) tracers, and returned to the well. Samples are removed from the well 1, 3 and 8 hours following the injection and analyzed for $NO_3$, $N_2O$, Br, propane and $\delta^{15}N$ of $NO_3$ and $N_2O$. This technique provides a direct measure of biological uptake of labeled $NO_3$-N, as well as production rates of $N_2O$ through denitrification.

**B) Structural Measures: Hydraulic connectivity and organic matter storage**
**Stream Hydrographs:** We have continuously monitored stream height in all streams by installing a pair of datalogging Hobo© pressure transducers at the upstream end of each reach *[these were purchased with funds from the NC EEP Monitoring and Research program]*. We are still working to develop rigorous flow rating curves for each reach by calculating changes in instantaneous flow throughout at least one storm event in each stream (more rigorous rating curves will be developed through time, but are beyond the scope of this one year study). The stream height data will be used to calculate daily, seasonal, and annual flow statistics (e.g., flood frequency and magnitude, and “flashiness”).

**Hydraulic connectivity:** We consider hydraulic connectivity to be maximum in streams with: 1) less incised channels; 2) more variable water table depths (in riparian zone) and vertical hydraulic gradients (in channel); and 3) movement of solutes between riparian, hyporheic and surface water.

1) *Channel Incision*: We worked within the existing monitoring framework of the NC Ecosystem Enhancement Program (NC EEP) to assess channel incision by measuring bankfull channel shape and dimension at 5 transects in each study stream(Pizzuto, Hession et al. 2000). We also determined channel slope, grain-size distributions, channel sinuosity and created detailed habitat maps for each reach. These physical measurements are made annually by NC EEP for each of the restored streams in our survey. Thus we utilized many of the same approaches for the other 8 streams.

*2) Movement of Solutes Between Channel and Subsurface*: At each study site we conducted solute tracer releases once in summer 2006 and again in winter 2007, and continuously record solute breakthrough curves in the water column (to estimate water residence time and physical water storage) (Jones and Mulholland 2000).

**Organic Matter:** Organic matter (OM) in streams serves many functions, but it is especially important as a carbon source for the ecosystem. As a food source for macroinvertebrates, it serves as the base of the food web. As a food and substrate source for bacteria, algae, and fungi, it supports the ecosystem function of water quality improvement which these organisms provide. In particular, fine benthic organic matter (FBOM) in streams has been shown to be a highly correlated with nitrogen removal. In urban systems, OM levels are very low due to both reduced inputs from the riparian zone and reduced retention in the stream(Paul and Meyer 2001). Because organic matter is a cornerstone of several ecosystem functions which stream restoration targets, it could serve as a proxy for those functions in post-construction monitoring.

The first step in understanding OM dynamics in urban streams is to quantify the existing levels. In summer 2006, we sampled 10 transects for each study reach. All coarse benthic organic matter (CBOM) was first removed from 1-m long transect across the full width of the streambed at each transect. After surface CBOM was removed, a core sampler was inserted into the stream bed to measure FBOM, by mixing sediments to 10cm depth within the sampler, recording the volume within the core and removing a subsample. Each sample was weighed in the field and subsamples were returned to the lab. We characterized each sample for % wood and % leaves. All samples or subsamples were subsequently dried and ashed. This allows us to estimate both total dry mass and total ash-free dry mass for the stream bed CBOM and FBOM.

## 3. MAJOR RESULTS

### 3.1 ECOSYSTEM STRUCTURE

***Hypothesis 1: Streams in urban watersheds will have higher peak flows during similar storm events compared to their forested counterparts.***

We are still in the process of working through all of the hydrologic datasets for our 12 streams, but we clearly see reduced peakflows in our reference streams as compared to their urban counterparts. Shown here (Figure 3) is a comparison of two storm hydrographs for one urban and one forested stream within our survey. These streams are immediately adjacent and receive identical levels of precipitation, yet the urban stream hydrograph rises more rapidly and to a greater amplitude than its forested counterpart.

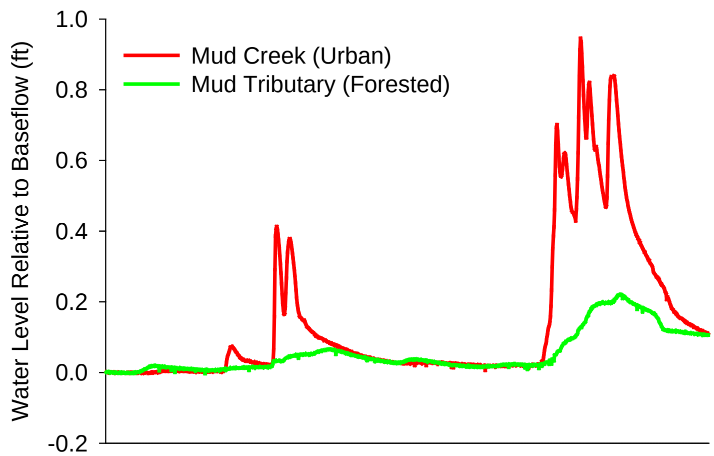


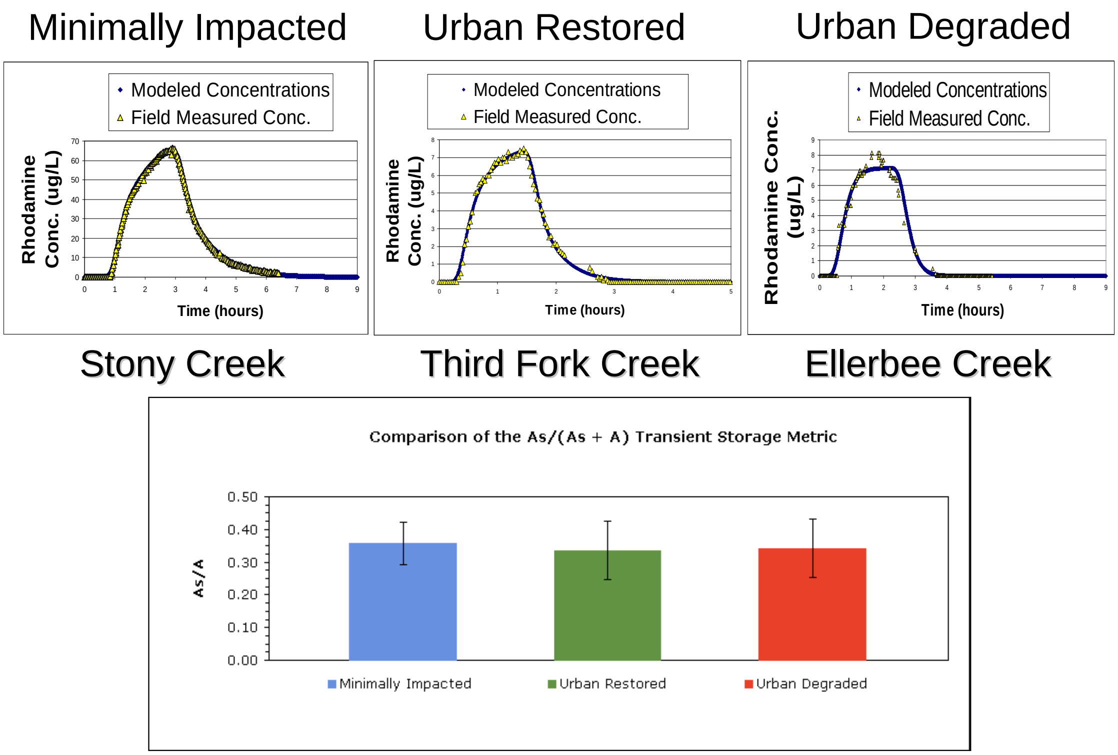

*Figure 3: A comparison of two April 2007 storm hydrographs between Mud Creek (an urban watershed) and its full forested tributary.*

***Hypotheses 2&3: Streams in urban watersheds will have significantly lower levels of hyporheic storage of water and hyporheic exchange (as measured through transient storage modeling of conservative tracer releases) as compared to their forested counterparts.***

We were surprised to find no differences in the transient storage metrics between our minimally impacted and urban streams from our 12 stream survey (Figure 4). We hypothesize that urbanization leads to dramatic reductions in hyporheic exchange and storage (through sedimentation and packing of interstitial spaces in the streambed) but simultaneously leads to large increases in within channel storage through the creation of streambeds that are low gradient, deeper and consisting primarily of slow moving pools and runs. This hypothesis is borne out in our geomorphic data (below), and the inability of current hydrologic models to resolve the differences between in channel and hyporheic storage is a commonly acknowledged flaw.

Similarly, because our model failed to differentiate between exchange within the channel (between fast and slow moving compartiments) and between the channel chan the subsurface (hyporheic exchange) we were unable to find any significant differences between stream types in hyporheic exchange (Table 3).

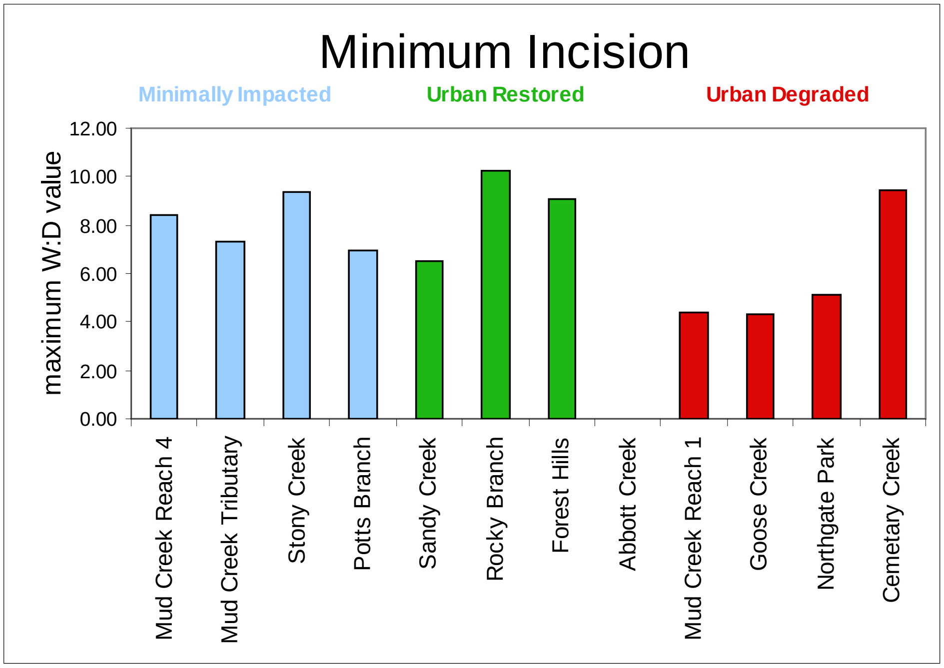
*Figure 4: Examples of conservative tracer breakthrough curves and model fits for calculating transient storage metrics for one block of stream reaches are shown above a summary graph showing the lack of differences in the % of total stream volume in transient storage ($A_s/A$) across stream types.*




| Table 3. Transient Storage Metrics | | | | | |
|---|---|---|---|---|---|
| **Block** | **Status** | **Site Name** | H | $A_s/A$ | **Fraction of Median Travel Time Due to Transient Storage ($F_{med}^{200}$)** |
| A | Forested | Stony Creek | 3.00E-04 | 0.714 | 41.65% |
| | Restored | Forest Hills | 8.71E-04 | 0.894 | 47.11% |
| | Urban | Northgate Park | 1.50E-03 | 0.201 | 14.37% |
| B | Forested | Potts Branch | 9.30E-04 | 0.422 | 28.53% |
| | Restored | Abbott Creek | 1.10E-04 | 0.451 | 30.98% |
| | Urban | Cemetary Creek | 1.00E-04 | 0.780 | 43.70% |
| C | Forested | Mud Creek Tributary | 5.90E-03 | 0.305 | 21.52% |
| | Restored | Rocky Branch | 5.80E-04 | 0.337 | 43.59% |
| | Urban | Goose Creek | 1.00E-04 | 0.752 | 42.91% |
| D | Forested | Mud Creek Reach 4 | 4.20E-04 | 0.937 | 48.37% |
| | Restored | Sandy Creek | 9.50E-04 | 0.285 | 19.52% |
| | Urban | Mud Creek Reach 1 | 9.80E-04 | 0.501 | 33.21% |

***Hypothesis 4: Streams draining urbanized watersheds will have higher degrees of channel incision than their forested counterparts, indicating less exchange of water and materials between the stream and its surrounding riparian zone.***

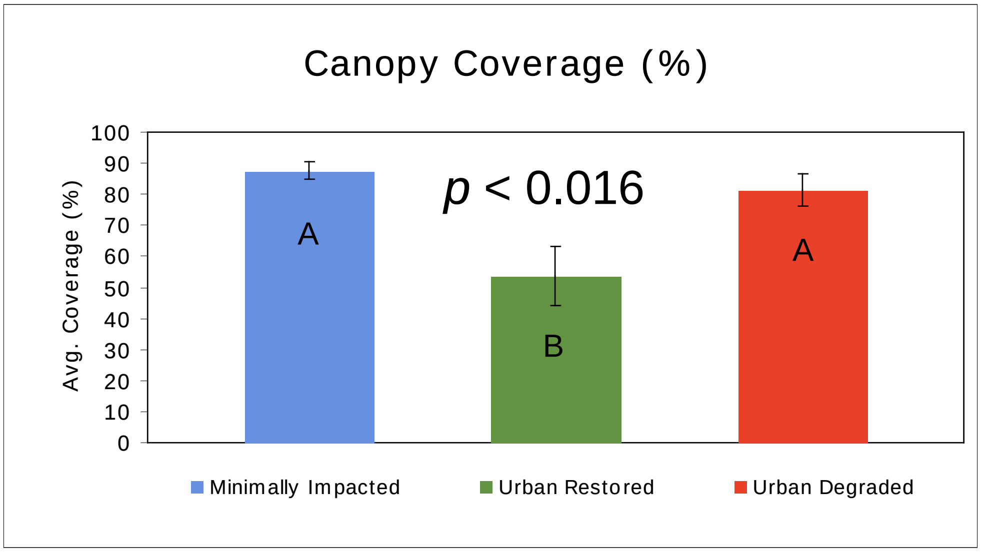
*Figure 5:Measures of channel width:depth ratios for 11 of our 12 streams. For this metric, higher width:depth ratios are indicative of less incised streams*




We found that with the exception of Cemetary Creek (a stream which is bedrock constrained throughout our study reach and for which channel incision is thus not possible) urban streams were more incised than either their forested or restored counterparts (Figure 5). Because creating less incised channel cross sections are one of the main goals of most natural channel design stream restoration projects it is not surprising to see that restoration does lead to decreased incision. However, because these projects have gone through several seasons or years since implementation, it is encouraging to find that the channels have held their new channel shape.

Despite the increased opportunity for hydrologic connectivity between restored urban stream channels and their riparian zones, we noted a discouraging trend towards dramatically reduced riparian canopy cover in all of our restored streams (Figure 6). In many cases mature trees were removed from the riparian zone in order to facilitate bank regarding and channel reconfiguration, leading to stream channels that have less canopy shading and reduced inputs of riparian leaf and wood material.

*Figure 6: Canopy cover over stream reach, measured with densitometer reading throughout each study segment.*

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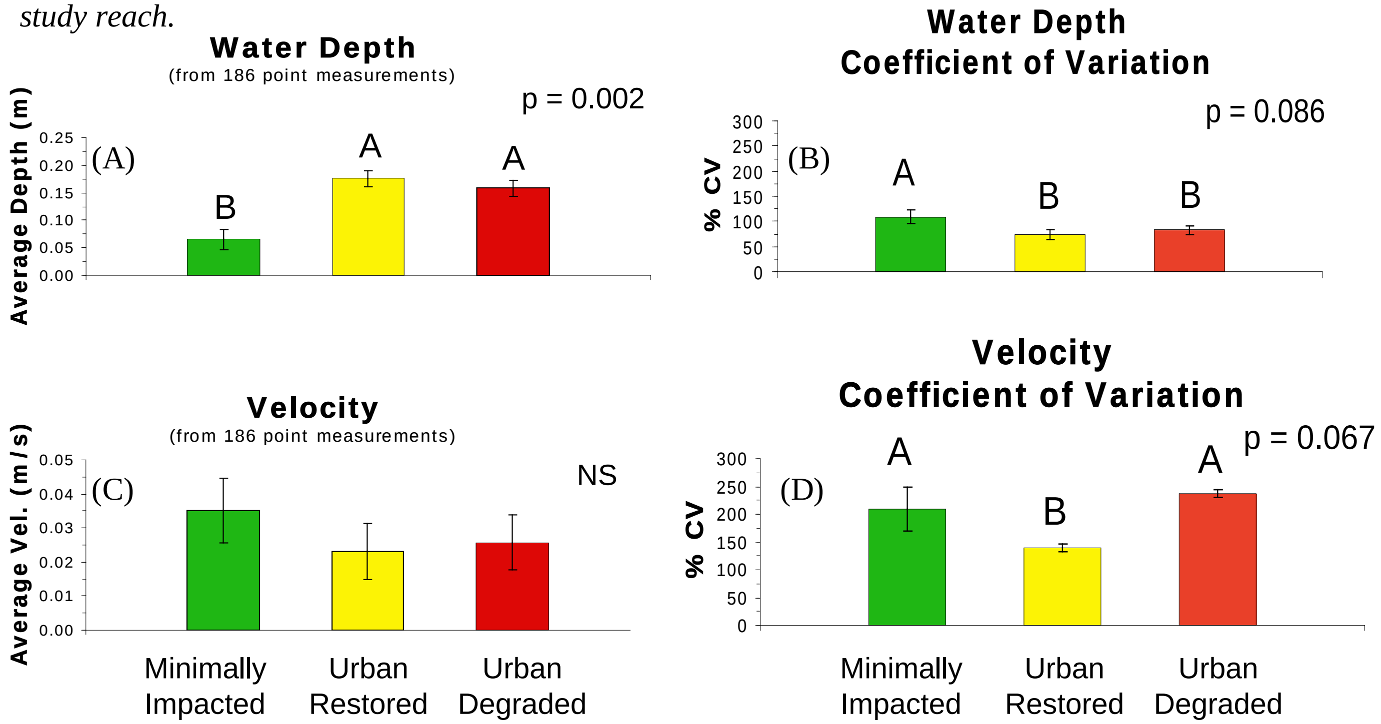
***Hypotheses 5&6: We predicted that streams draining urban watersheds would have wider channels with shallower and less variable flow habitats.***

We found no significant effects of urbanization on channel width (Table 4), although the wetted width of urban streams tended to be wider than their forested counterparts with similar drainage area. Urbanization tended to lead to streams with shallower channel slopes, deeper water columns with less variable depths and flows (Table 4 and Figure 7).

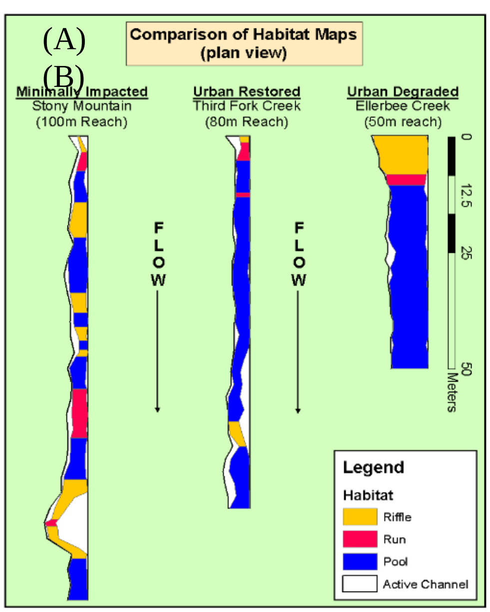
**Table 4. Additional Site Measurements**

| Site Characteristic | | Forested | Restored | Urban |
|---|---|---|---|---|
| Estimated Discharge (L/s) | | 5.1 ± 3.0 | 4.8 ± 1.5 | 8.7 ± 2.5 |
| Percent Dilution(%) | | -82.3 ± 14.8 | -103.6 ± 29.3 | -69.7 ± 11.9 |
| Flow Velocity (m/s) | | 0.02 ± 0.002 | 0.02 ± 0.009 | 0.01 ± 0.005 |
| Active Channel Width (m) | Avg | 4.1 ± 0.7 | 3.2 ± 0.4 | 5.4 ± 1.2 |
| | % CV | 22.7 ± 5.0 | 19.7 ± 4.8 | 18.0 ± 2.0 |
| Wetted Width (m) | Avg | 2.7 ± 0.5 | 2.5 ± 0.3 | 4.1 ± 1.5 |
| | % CV | 34.0 ± 2.7 | 28.4 ± 6.1 | 27.7 ± 5.8 |
| Longitudinal Slope (%) | Avg | 1.4 ± 0.7 | 0.3 ± 0.1 | 0.8 ± 0.6 |
| Degree of Incision D:W) | Avg | 0.17 ± 0.02 | 0.17 ± 0.03 | 0.22 ± 0.01 |
| | % CV | 35.5 ± 11.5 | 13.5 ± 2.6 | 17.0 ± 5.3 |

*Figure 7: Average and coefficient of variation of surveyed depths and velocities across stream types. In each stream we measured depth and velocity at ~100 points distributed throughout each study reach.*




These results led to some of the most interesting finding of our study that we thing are relevant to current restoration practices. Although natural channel design approaches are leading to reduced channel incision, they are not recreating the fine scale flow habitat variation that is characteristic of less disturbed watershed streams. Indeed habitat maps were made for each study reach and we documented dramatic differences in the extent and variation in flow habitats between our forested and urban stream categories, with restoration efforts having no measurable effect on habitat heterogeneity.



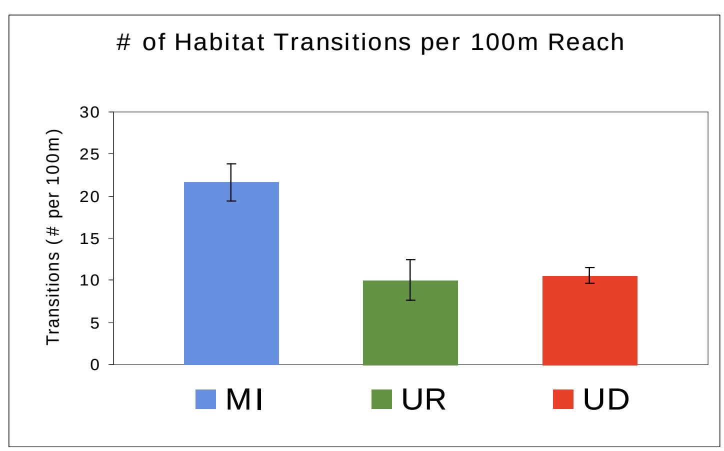




*Figure 8: (A) shows habitat maps for stream reaches within one study block, (B) shows the average # of habitat transitions found within 100m segments of each stream type*

## 3.2 ECOSYSTEM FUNCTION

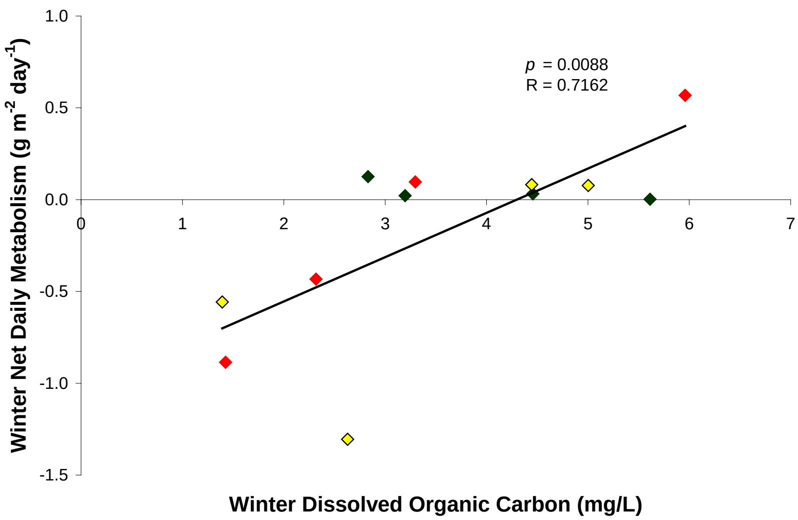
***Hypothesis 7: Benthic organic matter stocks will be lower and less variable in urban streams as a result of less retentive habitats to store organic materials as well as flashier hydrographs that significantly increase organic matter losses.***

We are still completing the analyses of benthic sediment samples in order to adequately understand the differences in organic matter storage between streams. We did not find significant differences in the standing stocks of surface organic matter (leaves and twigs collected off the stream bed) between our land use categories. However we did find significantly higher reach scale variation in where these materials were distributed within forested stream reaches than in their urban counterparts where surface OM tended to be evenly distributed. We are still waiting to determine the amount and quality of carbon stored within the streambed and expect to have those data by August 2007.

***Hypothesis 8: We expected Community Respiration to be reduced in urban streams as a result of dramatic reductions in organic matter storage.***

We were surprised that we were unable to detect significant differences in metabolic rates between our land use categories. Although restoration reaches tended to have higher rates of gross primary production these differences were not significant. We did find that winter rates of net daily metabolism (NDM) (NDM = NPP + CR) were strongly driven by water column DOC, a pattern driven almost exclusively by our urban stream datapoints (Figure 9). This correlation suggested to us that much of the metabolism of these urban streams may be driven by labile dissolved carbon in the water column, either produced by algae within these streams, or delivered from leaky sewer pipes and organic matter rich storm sewer outflows (as has been found for urban streams in Baltimore, MD (S. Kaushal, Baltimore LTER, personal communication)

Figure 9: Relationship between DOC and NDM Winter 2007




***Hypotheses 8&9 We expected denitrification potentials and microbial biomass to be reduced in urban streams.***

Sediment samples for these calculations have recently been collected and these data will be available by August 2007. We have no results to report at this time.

***Hypothesis 10 We expected to see higher efficiencies for nitrogen removal from the water column in our forested streams relative to their urban counterparts.***

Through repeated sampling we have established that the concentrations of both total and dissolved nitrogen is always higher in our urban streams than in their forested counterparts, with nitrogen concentrations in our restored stream reaches intermediate to these endpoints (Figure 10 A&B).

***Figure 10: Monthly streamwater nitrate concentrations across our 12 stream survey. On all but one date (Nov 2006), urban streams had significantly higher nitrate concentrations than forested streams.***

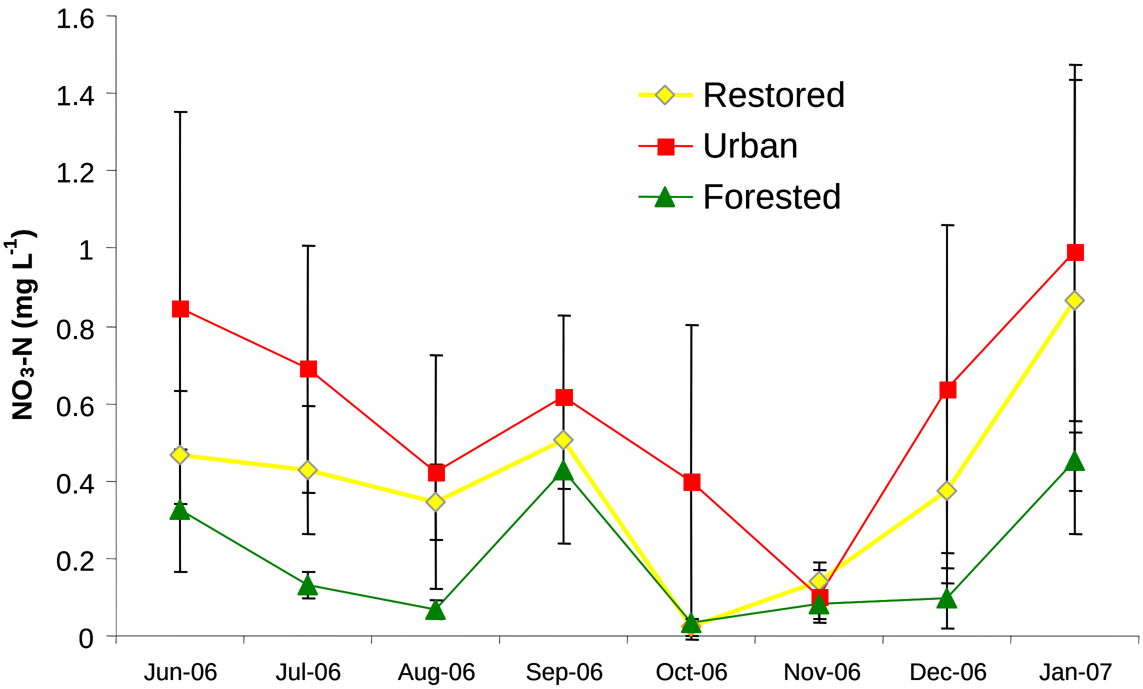
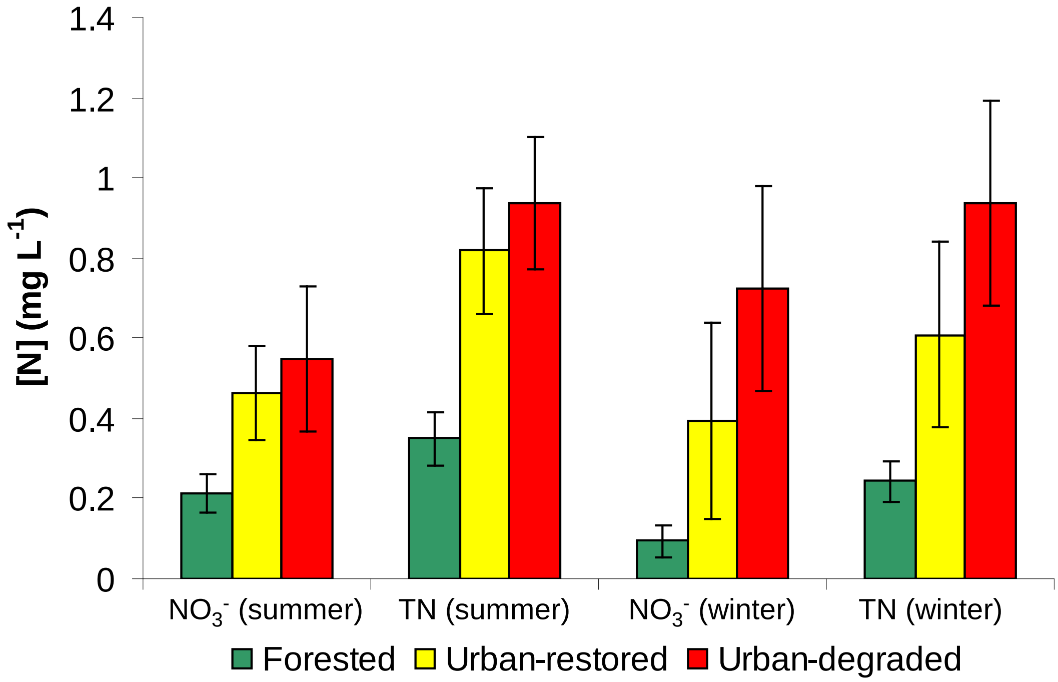
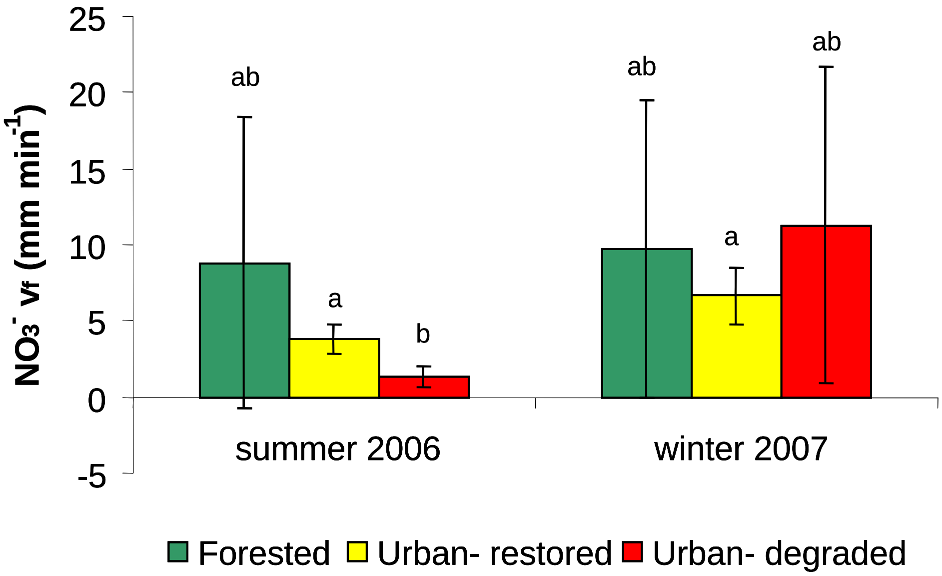


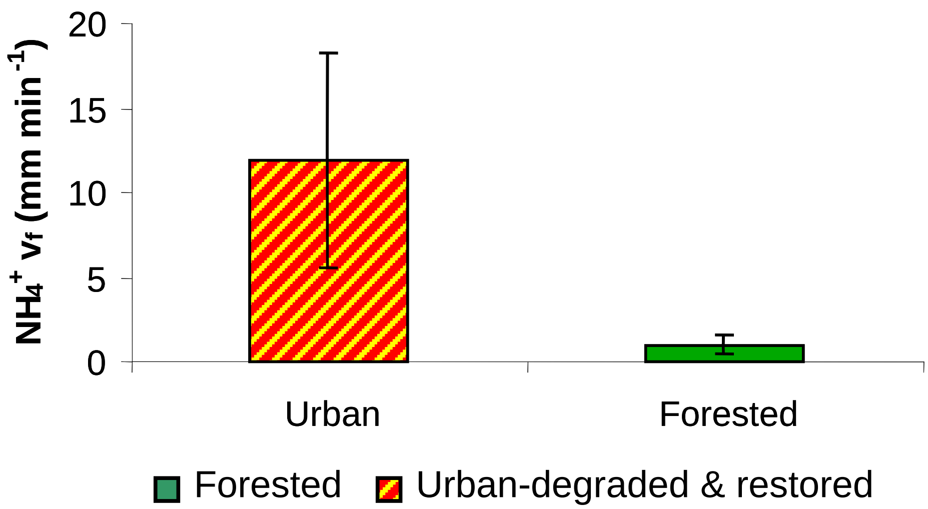
***Figure 11: Streamwater $NO_3^-$ and Total Dissolved Nitrogen concentrations as measured immediately prior to nutrient enrichment experiments in summer 2006 and winter 2007***




Contrary to our expectations there were no significant differences in nitrate uptake velocities between our forested and urban streams in either seasonal survey (although our restored reaches had significantly higher $NO_3^-$ uptake efficiencies than their urban degraded counterparts during the summer months) (Figure 11A). In contrast to our expectations we found significantly higher uptake efficiencies for $NH_4$ in both sets of urban streams (degraded and restored) as compared to our forested watershed streams (Figure 11B).

***Figure 12: (A) Summer vs. winter nitrate uptake velocities (the speed with which nitrate moves from the water column into the sediments) compared between land use categories. (B) Winter $NH_4^+$ uptake velocities are compared between the merged urban streams (no differences between restored and degraded sites) and their forested stream counterparts.***



***Hypothesis 11: We expect rates of nitrification to be higher in urban streams where supplies of both $NH_4$ and $NO_3$ are higher.***

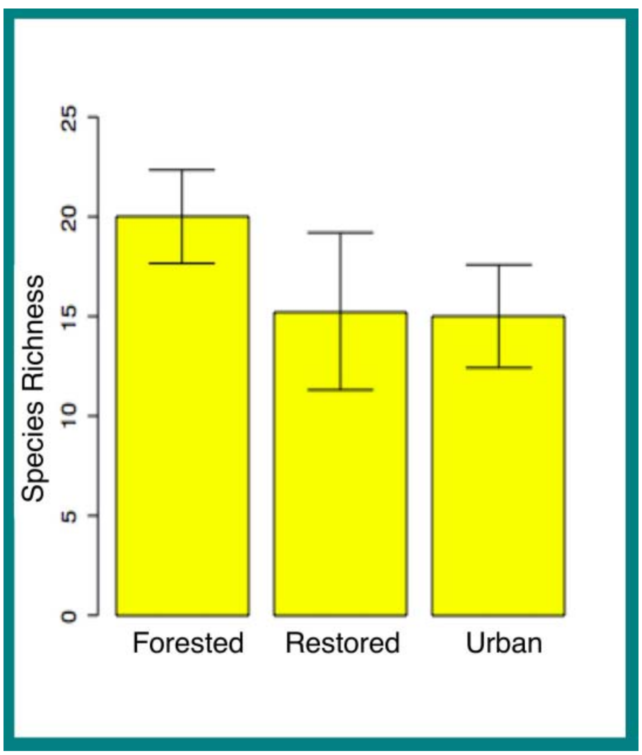
We are still working on the modeling aspect of answering this question from our winter releases, but preliminary data suggests that this hypothesis is correct. In many of our urban streams we see ambient increases in $NO_3^-$ concentrations through our study reaches, providing some evidence that nitrification is generating $NO_3^-$ within the reach. We expect this data analysis to be completed by August 2007.

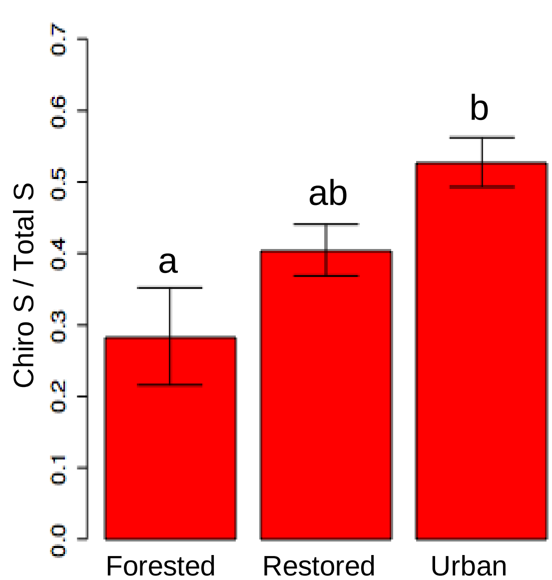
## 3.3. BIOTIC RESPONSES:

In work complementary to the efforts described here, UNC PhD student Christy Violin has been examining macroinvertebrate communities in each of our 12 study stream reaches. In summer 2006 she used the NCDWQ Qual-4 protocol to sample benthic macroinvertebrates in each stream. We predicted (as for the full study) that urban degraded stream reaches would have much lower macroinvertebrate diversity, and fewer sensitive taxa than their forested counterparts. We hoped that restored streams would fall out intermediate between the forested and urban degraded stream reaches.

Violin used several metrics for comparison. The first is a simple comparison of species richness (Figure 13). Although species numbers were not significantly different between sites, a variety of very tolerant chironomidae (midge larvae) made up the bulk of the species numbers in both the urban degraded and restored streams.

**Figure 13: (A) Species Richness (B) The proportion of total species #'s that are due to representatives of tolerant taxa of Chironomidae larvae**

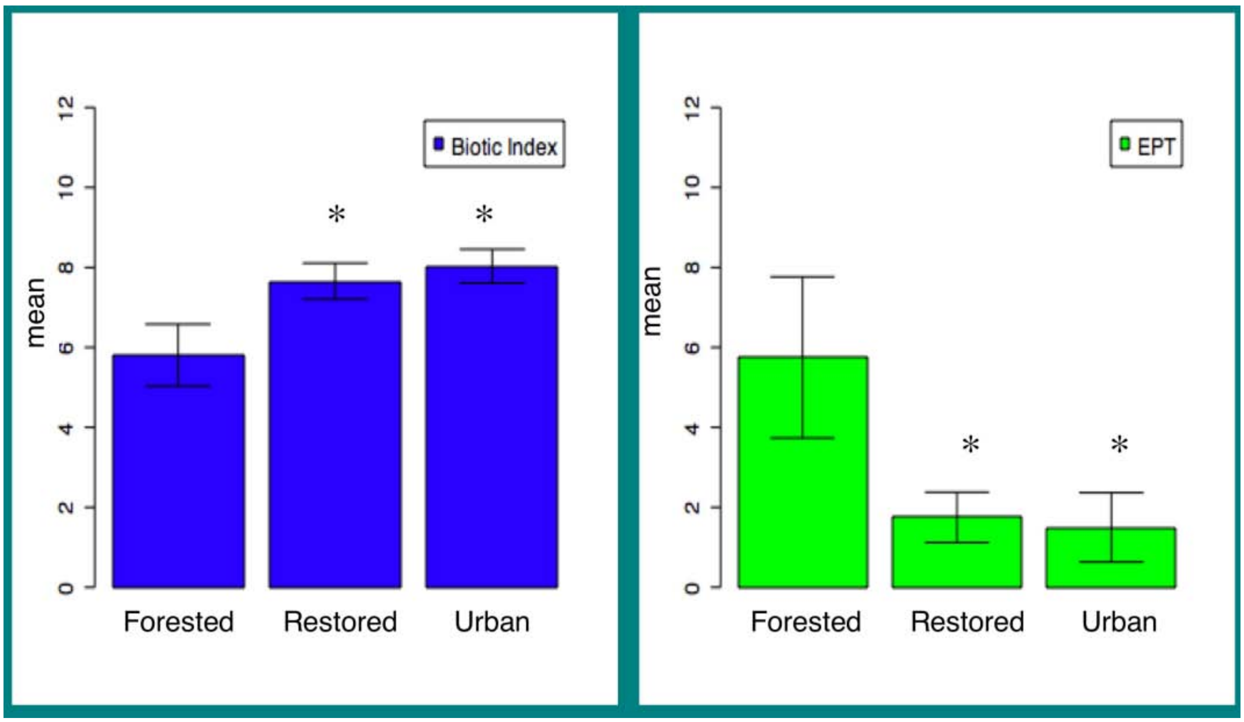


Comparisons are much clearer when examining two commonly used macroinvertebrate indices that are established as good correlates of water quality. The first is the EPT index which represents the total number of taxa within the Insect orders of Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies), represented by a wide diversity of organisms with varying life history strategies but typically sensitive to habitat and water quality degradation. Higher EPT scores are indicative of "healthier" communities. The IBI or Index of Biotic Integrity index, is calculated by summing the density of each taxa found in the community multipled by its tolerance value. High IBI scores indicate a community that is dominated by extremely tolerant taxa and are typical of polluted streams and rivers.

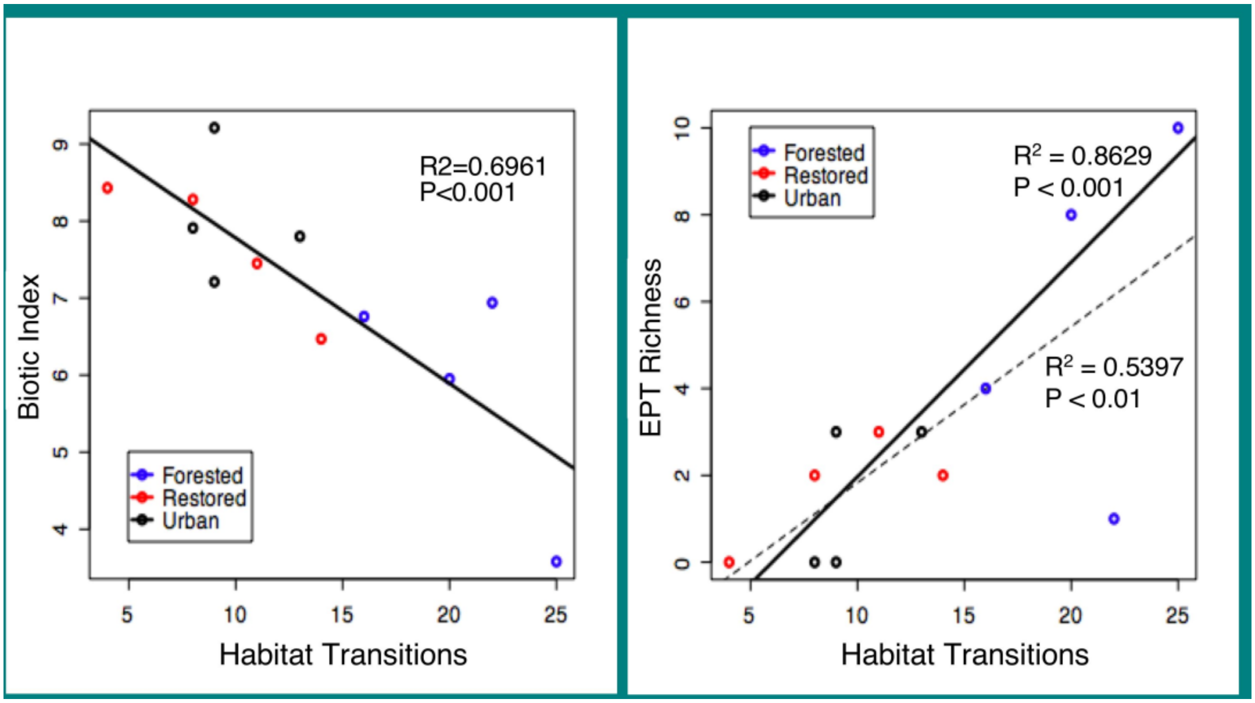
For both IBI and EPT indices, our forested stream reaches scored significantly better than either the urban degraded or urban restored streams, indicating they contain significantly more sensitive species of macroinvertebrates (Figure 14). There were no differences between the urban restored and urban degraded streams (Figure 14).

**Figure 14: Macroinvertebrate communities differ among stream types in both (A) IBI scores and (B) EPT scores**




Violin also found that the single best predictor of both IBI and EPT scores for each stream reach was the diversity of habitat transitions (as shown in Figure 8 above) (Figure 15). Note that there is a significant correlation for the relationship between IBI and EPT vs. habitat transitions for the 4 restored streams alone, suggesting that some projects are more successful than others at reestablishing this critical variation and supporting a macroinvertebrate community that is closer to "reference" conditions.

**Figure 15: Habitat Complexity and Macroinvertebrate Community Composition**




Biotic Index EPT

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# 5. Appendix

## 5.1 Public Presentations of this research

Results from this project have been (or will be) presented in the following forums:

Invited Keynote Address, Montana River Center Symposium: Assessing Stream Restoration Success: Developing Sustainable Ecological and Physical Systems. *"Ecological Systems and Renaturalization Success"* September 2006.

Invited Keynote Speaker, 2006 North Carolina Stream Restoration Institute Conference, *"Evaluating Restoration Effectiveness - Lessons from a National Synthesis"* October 2006.

**Cada, P., E.B. Sudduth, B.A. Hassett, and E.S. Bernhardt.** 2007. *Testing the 'Field of Dreams' Hypothesis: Stream Restoration Effects on Physical Structure.* NC Water Resources Research Institute Annual Conference, Raleigh, NC. *Peter won 2nd place for this research poster*

**Hassett, B.A., E.S. Bernhardt, E.B. Sudduth and P. Cada.** 2007. *Nitrogen cycling across an urbanization gradient.* 55th Annual Meeting of the North American Benthological Society, Columbia, SC. June 3-7 2007.

*******Invited talk***: Sudduth, E.B., P. Cada, B.A. Hassett, and E.S. Bernhardt.** 2007. *Escaping the urbanization cycle or expensive landscaping? Assessing ecosystem functional responses to natural channel design projects in urban catchments.* 55th Annual Meeting of the North American Benthological Society, Columbia, SC. June 3-7 2007.

**Cada, P., E.B. Sudduth, B.A. Hassett, and E.S. Bernhardt.** 2007. *Can we restore stream ecosystem structure in urban catchments?Potential recovery through stream restoration* 55th Annual Meeting of the North American Benthological Society, Columbia, SC. June 3-7 2007.

*******Invited talk*** : Violin, C., **E.B. Sudduth** and **E.S. Bernhardt**. 2007. *Can Reach Scale Restoration Ameliorate Watershed Scale Degradation? Macroinvertebrate Community Responses to Urbanization and Urban Restoration*. 55th Annual Meeting of the North American Benthological Society, Columbia, SC. June 3-7 2007.

**Sudduth, E.B., P. Cada, B.A. Hassett, C. Violin** and **E.S. Bernhardt.** 2007. *Restoration as Experimental Manipulation: Is channel structure or watershed condition more important in predicting ecosystem function in urban streams?* Ecological Society of America Meeting, San Jose, CA. August 2007.

***Invited Plenary Speaker* **E.S. Bernhardt.** *Stream ecosystems in urban landscapes.*Third International Symposium on Riverine Landscapes, Brisbane, Australia, Global change and river-floodplain ecosystems. August 2007.