Report as of FY2007 for 2006NC63B: "Restoring Biogeochemical Functions in Degraded Urban Stream Ecosystems"

Publications

- Other Publications:
    - Bernhardt,E.S., 2006. Ecological Systems and Renaturalization Success, Montana River Center Symposium: Assessing Stream Restoration Success: Developing Sustainable Ecological and Physical Systems.
    - Bernhardt,E.S., 2006, Evaluating Restoration Effectiveness - Lessons from a National Synthesis, 2006 North Carolina Stream Restoration Institute Conference.

Report Follows

Title

Restoring biogeochemical functions in degraded urban stream ecosystems

Project Summary

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).

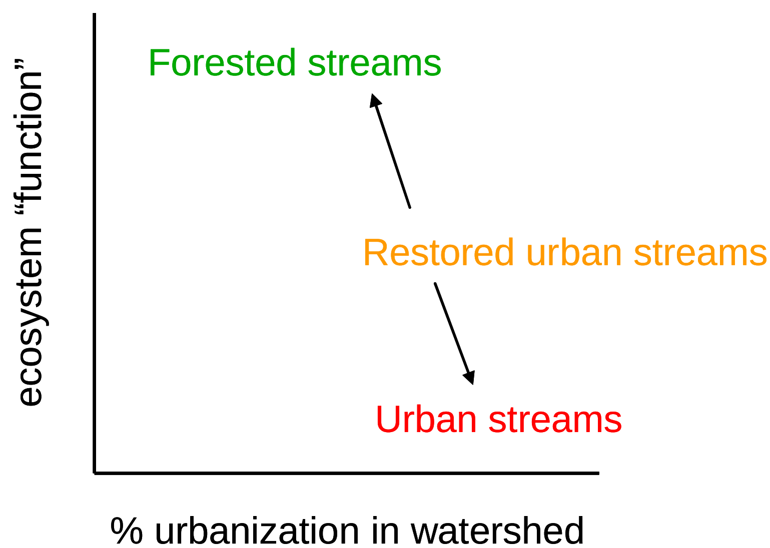
A growing body of research demonstrates the important effect stream ecosystems have in altering the form, timing and magnitude of watershed nitrogen (N) losses. Most of this research has been conducted in minimally impacted watersheds. Streams in heavily urbanized watersheds may be functionally disconnected 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.

Methodology

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	>	<

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" watersheds have some level of urbanization in their upper stretches

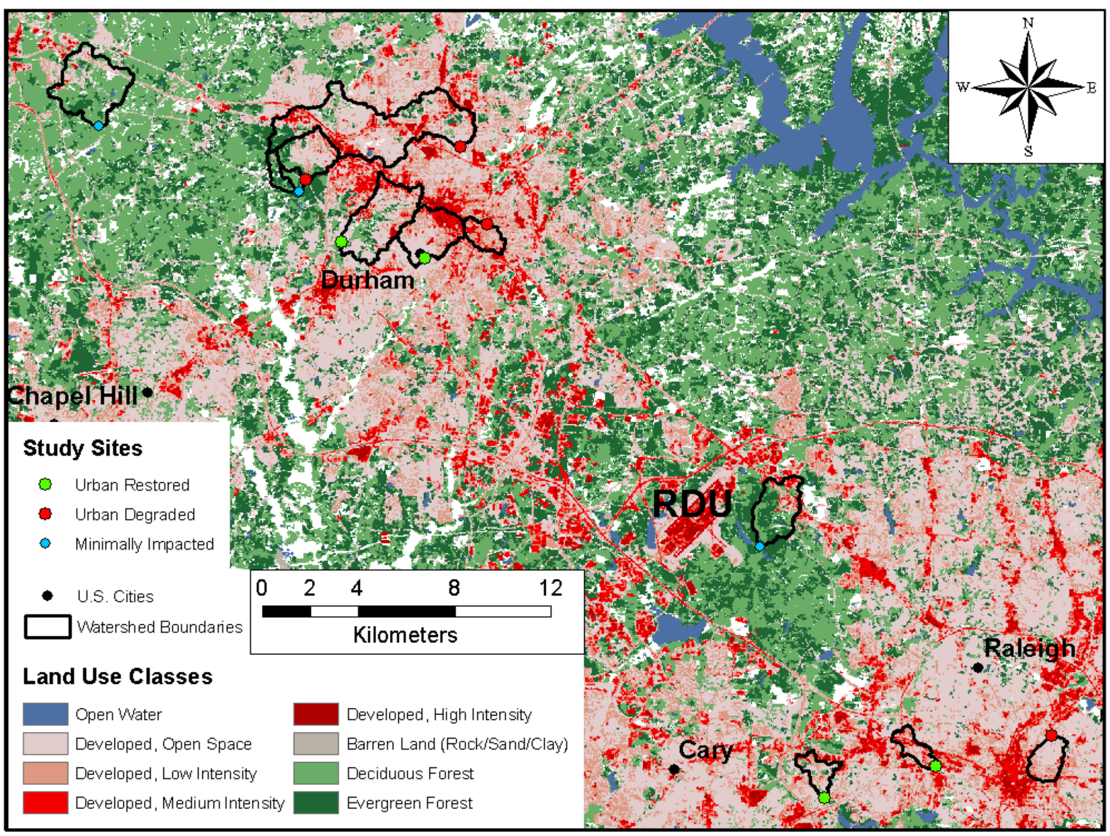


Table 2: Watershed Characteristics					
Block	**Status**	**Site Name**	**Watershed Size (km^2)**	**% Developed**	**% Impervious**
A	Forested	Stony Creek	6.9	24.4	3.4
	Restored	Forest Hills	4.4	99.5	32.4
	Urban	Northgate Park	7.6	88.7	20.8
B	Forested	Potts Branch	4.2	27.4	9.9
	Restored	Abbott Creek	1.7	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

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.

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.

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.

Principle Findings

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.

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.

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 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.

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.

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".

Significance

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

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