Effects of Small Dams on Fish and Mussels in the Chowan, Neuse, Roanoke and Tar River Basins

Report to

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Summary

In 2010 with support from the Albemarle-Pamlico National Estuarine Program (APNEP) we completed the second year of a 3-year collaborative project between researchers at Appalachian State University and the NC Wildlife Resources Commission aimed at assessing the effects of small dams on freshwater mollusk and fish populations and stream habitats in the Chowan, Neuse, Roanoke and Tar drainages in North Carolina and Virginia. Both large and small dams are widespread in low-to mid-order Piedmont and Coastal Plain streams. The objectives of this study are 1) Quantify effects of small dams on mollusk and fish assemblages and stream habitats in biologically diverse low-to-moderate gradient Piedmont and Coastal Plain streams 2) Provide baseline estimates of mollusk and fish population sizes near small dams and 3) Provide resource managers with an empirical system for evaluating and prioritizing dams for removal or preservation. We sampled three 150 m study sites associated with each dam. We selected sites in an upstream free-flowing reach, a reach immediately downstream of the dam (mill reach), and a reach ~0.5-2.0 km downstream from the dam. In 2009 and 2010 we identified and mapped 79 of 108 focal sites associated with 28 dams across the study basins. At each site we conducted fish, mollusk, and habitat measurements, quantified land-use within the upstream catchment and measured a suite of physicochemical habitat parameters, including channel width, depth, and velocity, substrate composition, conductivity, pH, and DO. We deployed temperature loggers at each site and within the impoundment of intact dams. In 2010 we sampled fish and computed land-use parameters at 48 sites associated with 16 dams. Additionally, we measured habitat parameters at 45 of these sites (15 dams) and sampled mollusk populations at 27 sites (9 dams). We identified and measured 12,565 fish (73 taxa) and 18,705 mussels (16 taxa). Analysis of survey data reveal that both mussels and fish were more abundant and diverse immediately downstream of intact small dams compared to up and downstream reaches. Additionally, four families of fish were significantly more abundant in the mill reach of intact dams relative to up-or-downstream reaches. No significant differences were observed between mussel or fish metrics at sites associated with breached or relict dams. Associations between fish and mussel assemblages revealed what may be the first evidence linking fish and mussel abundance and richness. Land use and physical habitat parameters revealed few consistent relationships but urban, pasture and forest land cover were frequently associated with mussel or fish assemblage metrics. In 2011 we will complete mussel and fish sampling and conduct more comprehensive analyses of this extensive data set.

Introduction

Dams may have profound effects on stream habitats, biota and ecosystem function. Many authors have reported that large dams are a major cause of freshwater mollusk extinction and imperilment (Bogan, 1993; Parmalee & Bogan, 1998; Lydeard *et al.*, 2004; Gangloff & Feminella, 2007; Strayer, 2008; Williams, Bogan & Garner, 2008). Impacts of large dams are well-documented (Fraley, 1979; Holden, 1979; Armitage, 1984; Ward & Stanford, 1987; Jensen, 1987; Vaughn & Taylor, 1999; Lessard & Hayes, 2003). However, effects of more ubiquitous small dams are more poorly understood because many undergo less scientific or regulatory scrutiny than dams on larger streams (Shuman, 1995; Dean *et al*., 2002).

Intact dams strongly alter upstream community and habitat structure (within impoundments) by altering substrate composition, water flow rate, and temperature profile. Impoundments typically support few mussel taxa (Williams, Fuller & Grace 1992; Parmalee & Bogan, 1998; Dean *et al*., 2002; Gangloff & Feminella, 2007; Tiemann *et al*., 2007). Dams also typically alter downstream flow and substrate conditions with dramatic consequences for stream biota and ecosystem processes (Downward & Skinner, 2005; Maxted, McCready & Scarsbrook, 2005; Haxton & Findlay, 2008).

Stream communities may not recover from the effects of intact dams for many km downstream (Vaughn & Taylor, 1997). Additionally, un-regulated dam breaching may radically alter stream morphology, destabilize streambeds, and displace mussels and other benthic macroinvertebrates (Dean *et al*., 2002; Lessard & Hayes, 2003; Sethi *et al*., 2004; Downward & Skinner, 2005; Gangloff *et al*., In Review; Hartfield *et al.*, In Review).

Freshwater pearly mussels (Bivalvia: Unioniformes) are imperiled globally due to in large part to the effects of impoundments (Bogan, 1993; Riccardi & Rasmussen, 1999; Lydeard *et al*., 2004; Poole & Downing, 2004; Brainwood, Burgin & Bryne, 2006; Strayer, 2008). Few lotic unionids tolerate lentic habitats (Parmalee & Bogan, 1998; Haag, 2010). Moreover, cold hypolimnetic releases from many high dams can dramatically reduce mussel gametogenesis and effectively sterilize downstream reaches. Adult mussels may persist in a senescent, non-reproductive state downstream for decades (Layzer, Gordon & Anderson, 1993; Heinricher & Layzer, 1999; Parmalee & Bogan, 1998; Rehn, 2009). Dams may also limit passage of migratory fish hosts and thereby alter mussel distributions by excluding host fishes or fragmenting populations (Bogan, 1993; Watters, 1996; Williams *et al*., 2008).

Although the effects of larger dams on freshwater mussel populations are well-documented and dramatic, less is known about how smaller dams affect mussel populations. Dams are widespread in southeastern U.S. and are widely believed responsible for the extinction and extirpation of many riverine fish and mollusk taxa. In North Carolina many of the larger rivers are impounded by dams used for high-capacity hydro-electrical power production. Large (>10 m) dams fragment habitat across very broad (e.g., entire basin) scales and inundate thousands of river km under reservoir habitat unsuitable for many fluvial species.

Smaller dams, including mill dams and other low-head structures used in local scale power or mechanical production, are concentrated along in a band along the transition between the Piedmont and Atlantic Coastal Plain physiographic provinces (M. Gangloff, unpublished data). Unlike large dams, many of these smaller structures have been in place for more than a century and date to a time before widespread electrification was common. These dams impound small stretches of small-to-moderate sized streams and are frequently overtopped during large flood events. Although small dams may not be primary barriers to diadramous migratory or resident fishes, they do appear to restrict gene flow in both mussel and crayfish populations (Hartfield et al. In Review; Abernethy et al., unpublished data).

Technological obsolescence has promoted the neglect and abandonment of many small dams in North Carolina and across the Southeastern U.S. As a result there is a need for an objective system to evaluate the risks or benefits of removing small dams. Without an empirical understanding of how small dams impact stream systems and imperiled biota, there is a risk that incompletely thought-through projects may further degrade of already imperiled mollusk and fish stocks and their habitat. This is critical because North Carolina's mollusk populations have exhibited some of the highest recent rates of local population extirpation in North America (Neves et al. 1997; Haag 2010). More than 10 regionally endemic mussels have become alarmingly rare in the last 2 decades and several are being considered for threatened or endangered status by the U.S. Fish and Wildlife Service (Bogan 2002; Bogan & Alderman 2004). Recent studies suggest these losses are strongly linked to changes in landuse including expansion of low-intensity residential (i.e., ex-urban) development into formerly forested or agricultural areas along the southern Atlantic Slope (Bogan 2002; Bogan & Alderman 2004, Alderman & Adams 1993)

The objectives of this study are to generate and analyze quantitative mussel, fish, habitat and landuse data at sites associated with small dams in streams of the Albemarle Pamlico Basin (APB). Baseline information obtained about the status of at-risk freshwater fish and mollusk resources near these structures will provide an important point of comparison for evaluating the success of subsequent habitat restoration projects.

Methods

Study site selection

From 2009-2010 we scouted numerous potential sites in the Neuse, Roanoke and Tar drainages and conferred with NCWRC personnel to identify priority dam sites for sampling (Appendix 1). We attempted to identify 3 intact, 3 breached, and 3 relict dam sites in each drainage. However, if sites were deemed a priority by NCWRC personnel, then we included these as well. In 2009 and 2010, we mapped study reaches at 79 sites associated with 28 dams (Appendix A). An additional 29 sites remain un-mapped. Ongoing scouting work will identify these sites prior to 2011 sampling.

Fish surveys

We examined how dams alter fish habitat and assemblage structure up-and downstream from dams to both assess effects of dams on fish community metrics (richness, diversity) and to test the hypothesis that mussel aggregations below dams are associated with increased host fish aggregations. In 2010 we quantified fish community structure at 16 dams (N = 48 sites) using 9-20 replicate (100 s) sampling passes per site. At each site we first identified 3 replicates of each of four stream meso-habitats (riffle, run, pool and stream-bank). If the third replicate yielded a previously undetected fish taxon, we sampled additional replicates for 50 s or until no new taxa were detected. We used a seine to isolate meso-habitats and then drove fish into the net using a backpack electrofishing unit. In deeper pools we occasionally used a seine. Seine haul data were excluded from statistical analyses.

We computed fish assemblage metrics at the site and pass scale. We computed site-scale mean fish catch per unit effort (CPUE) as number of fish caught per hour of sampling, number of fish species and families present at each site, Shannon diversity (H’), the number and proportion of fishes present at each site that have been reported to be mussel hosts and the total number and proportion of fish caught that are reported to be mussel hosts. We additionally computed pass-scale fish CPUE and species richness at each site. Pass scale means were used in mixed-model ANOVAs for total abundance, CPUE and richness and site-scale means were used in mixed-model ANOVAs for H' and fish assemblage metrics. Site scale means were used in correlation analyses.

A tertiary goal was to examine how small dams affect the distribution of invasive fish species including flathead catfish (*Pylodictis olivaris*), a large and potentially dominant apex predator that is expanding its range along the Atlantic Slope. Dan Walker, an undergraduate working in the Gangloff lab is examining dietary habitats and growth rate of flathead catfish in the Tar River and will be the focus of his undergraduate honors thesis. In 2010 Dan and NCWRC biologists collected 75 flathead catfish for diet and growth analyses. Data collection and processing for that study is on-going.

Mollusk surveys

We conducted mollusk surveys at 7 dams (n = 21 sites) during summer 2010 and 3 dams (n = 9 sites) during fall 2009. For each dam, we sampled one site upstream from the impoundment (or former site of the impoundment), a second site immediately downstream from the dam, and a third site $\geq$500 m downstream of the dam (Appendix A). At each site we sampled mussels using quantitative (0.25 m^2 quadrats, 80 per site) and qualitative sampling (15 replicate timed-searches). This 2-tiered sampling approach provides a robust density and demographic data while maximizing detection of rare mussel taxa. All mussels were identified to species, measured (total length), and sexed when possible. We also quantified gastropod, fingernail clam (Sphaeriidae) and *Corbicula fluminea* (Asian clam) densities during quadrat sampling.

Habitat measurements

We measured habitat and water chemistry parameters at 36 sites (12 dams) in 2010 and 9 sites (3 dams) in 2009. We measured depth, current velocity and substrate composition (12 particles per point) at regularly-spaced points along 16 cross-channel transects per site. Habitat parameter measurement points coincided with quadrat excavation points at sites that were quantitatively sampled for mussels. All habitat variables were measured under summer-fall baseflow conditions and data were collected soon after fish or mollusk sampling occurred. We measured water temperature, pH, specific conductance, and DO during habitat surveys. We computed multiple substrate metrics for each site including the mean and median substrate diameter and the proportion of the substrate at each site comprised of silt, sand, bedrock, wood and organic material (i.e., aquatic vegetation, leaf packs, small woody debris). Temperature is being monitored continuously using iButton temperature loggers at 4 sites (upstream, mill pond, mill reach, downstream) at intact dams and 3 sites at breached or relict dams. Temperature loggers are deployed during initial site scouting trips and retrieved periodically. We do not include water chemistry/temperature data in preliminary analyses because data collection at many sites is still on-going.

Landuse parameters

We used ArcGIS to obtain landscape-scale habitat and landuse classification data including upstream catchment area (km^2), rank and link magnitude (the number of upstream first order tributaries), and percentage of surface cover comprised of 12 landuse classes (Open water, wetland, high-intensity urban, low-intensity urban, pasture, row-crop agriculture, shrubs, coniferous, deciduous and mixed forest, grassland and barren ground). In 2010 we delimited watersheds and calculated landuse for 79 sites associated with 28 dams (Appendix A).

Mollusk size and shell growth

Previous research suggests that mussels located immediately downstream from small dams are larger because they grow faster than conspecifics living further up-or downstream (Singer and Gangloff, In Review). Small dams apparently enhance both the quantity and quality of organic material exported downstream. Alternatively, dams may promote streambed stability and larger mussels may be larger simply because they are longer-lived. To test these hypotheses, we measured lengths of all live mussels found in quadrats and determined if mean size and demographic parameters (number of juveniles, number of year classes, etc.) were different between sites. We did not use data from timed-searches because timed-searches are biased towards larger mussels. Analysis of demographic data is on-going. In 2011 we will complete collection of quantitative mussel data and demographic analyses.

Mussel population fragmentation

Alternatively, genetic differences may explain the dramatic differences in mussel size and abundance observed near some small dams. We are examining mtDNA fragments to assess genetic diversity between mussel populations occurring up-and down-stream of several intact and relict dams. We are using cosmopolitan species (*Elliptio complanata*) to ensure adequate sample sizes and to avoid impacting more sensitive mussel taxa. Initially, mitochondrial DNA will be used to examine population level differences but if these makers prove to be too invariant, we will consider other, more sensitive markers (e.g., microsatellites). This work is underway and will be the focus of an undergraduate honors thesis by Erin Abernethy to be completed in May 2011.

Statistical Analyses

We used mixed-model ANOVAs to examine differences in mussel and fish assemblages across site. Mixed models allow an investigator to include the effect of random factors (e.g., streams or drainages) in models. This allows us to account for differences attributable to factors including biogeography and historical landuse. We coded data to account for stream (random factor), site (up, mill, or downstream) and dam status. To account for differences in sample sizes between intact, relict and breached dams, we grouped breached and relict sites together prior to analyses. A priori analyses revealed no significant differences between mussel or fish assemblage metrics between breached and relict dams. We used Pearson correlations to examine associations between stream habitat conditions (site means), land-use parameters, and mussel or fish assemblage metrics. Finally, we used Pearson correlations to examine associations between fish and mussel assemblages to test the hypothesis that mussel aggregations below some dams may be related to fish abundance or community structure. To account for differences that may result from underlying geology, we examined all sites together and segregated analyses by physiography.

Results and Discussion

All data presented here are preliminary and should be treated as such. This project is ongoing (here we discuss results from years 1 and 2: 2009 & 2010) and APNEP funds helped to support 2 graduate and 2 undergraduate research projects. Final analyses will include additional landuse data as well as mussel, fish and habitat data to be collected during the 2011 field season. These data will likely lead to multiple peer-reviewed publications and will also be used to construct an empirical ranking system to evaluate the costs and benefits of dam-removal and prioritize restoration sites based on management objectives.

Mussels and Dams

We processed (identified and enumerated) >18,000 mussels in 2009-2010 and obtained measurements on >8000 individuals in 16 taxa (Appendix B). Surveys revealed moderately diverse Atlantic slope mussel assemblages ranging from 1 to 9 species (total richness = 16 taxa, mean richness = 4.1 taxa) at most sites. Mussel assemblages were dominated by *Elliptio complanata* and diversity (Shanon H’) was low (overall mean = 0.25, range 0-1.14). Abundance ranged from 66 to 9861 mussels per site (mean = 1187 per site) and CPUE ranged from 3.7 to 386 mussels per hour (mean = 80.3 per hour). We found populations of 9 state-or-federally-listed mussels (*Alasmidonta undulata*, *Elliptio lanceolata*, *Elliptio roanokensis*, *Fusconaia masoni, Lampsilis cariosa, Lampsilis radiata, Pleurobema collina, Strophitus undulatus and Villosa constricta*) in study reaches (Appendix B).

ANOVAs detected significant interactions between dam status and site location so we analyzed data from intact and relict/breach dams separately. ANOVA revealed no significant differences among site-scale mussel assemblage metrics at relict/beach dams. However, at intact dams, mussel CPUE and richness were significantly higher in the mill reach compared to up-and-downstream sites (both $p<0.001$, Figure 1). We speculate these counter-intuitive patterns may result from impoundment-derived mussel food and temperature subsidies or habitat degradation near relict/breach dams.

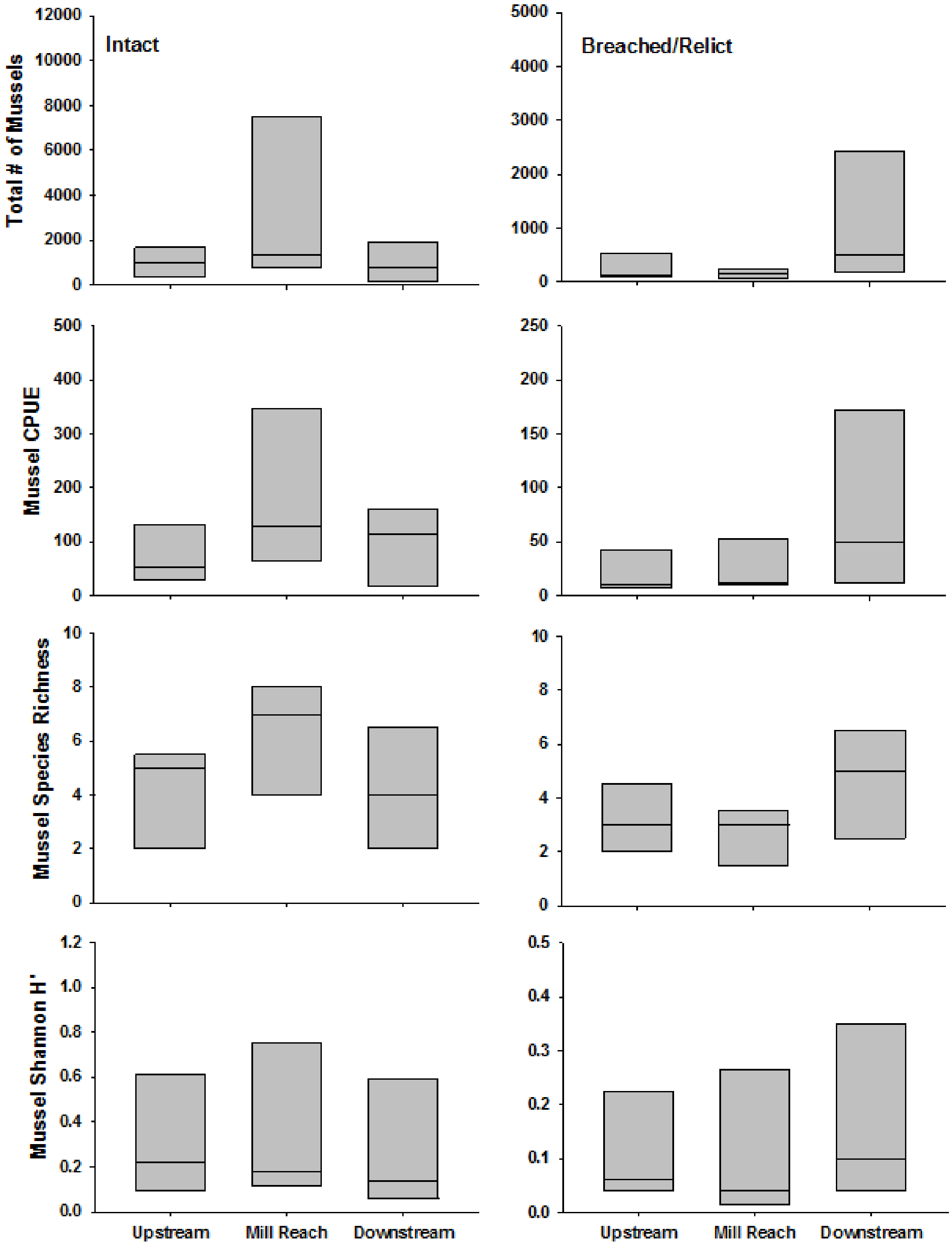


Figure 1. Box-plots of mussel abundance, catch-per-unit-effort (CPUE), species richness and diversity (Shannon H') at sites located upstream, immediately downstream (Mill Reach) and 500-650 m downstream of intact and breached/relict small dams in the Roanoke and Tar river drainages in 2009 and 2010. The center line represents the median, the box upper and lower bounds the 25th and 75th percentiles of the data.

Mussels and Habitat

We observed few statistically significant associations between freshwater mussel assemblage metrics and stream physical habitat parameters. However, the relationships we did observe suggest that dam-mediated changes in substrate conditions may affect mussel assemblages. Mussel richness was negatively associated with current velocity suggesting more swiftly-flowing sites had fewer mussels (Table 1). Moreover, mussel CPUE, richness and H’ were all negatively associated with mean particle size suggesting that sites with larger particles had fewer total mussels, lower species richness and diversity (Table 1). Finally, mussel H’ was positively correlated with percent sand and percent organic matter (Table 1).

Mussels and Landuse

Associations between freshwater mussel assemblage metrics and basin landuse revealed numerous counter-intuitive or difficult to explain patterns. Not surprisingly, we found a significant positive relationship between mussel abundance, CPUE, richness and diversity and both link magnitude and area across all sites (Table 2). This is because larger streams typically support more abundant and diverse mussel assemblages than do smaller streams. All mussel metrics were negatively associated with the percent of pasture in a catchment, yet positively associated with the proportion of row-crops, deciduous forest, wetland, and barren ground. Additionally, mussel CPUE, richness and H’ were positively associated with percent shrubland and richness was positively associated with proportion grassland at all sites (Table 2).

When we examined landuse associations at Coastal Plain and Piedmont sites, we found fewer significant relationships, likely because of reduced statistical power.

However, the relationships appear more intuitive. Coastal Plain site mussel abundance and H’ were positively related to link magnitude and area. Coastal Plain mussel H’ was significantly negatively associated with low-intensity urban development, pasture, and mixed forest but positively related to evergreen forest and wetland, the two historically dominant land cover categories in the Coastal Plain (Table 2). Piedmont mussel richness and H’ were negatively associated with deciduous forest and total forest cover but positively associated with evergreen forest, wetland, barren land, shub, and grassland cover (Table 2). Although we expected mussels to be positively associated with all forest cover metrics and wetland cover (likely a proxy for beaver-dominated headwater streams), associations with cropland, barren ground, shrubs and grassland are problematic.

These somewhat contradictory patterns may suggest that historical landuse may have a more important effect on mussel assemblages than do current conditions. Upland habitats in the Piedmont as well as the Coastal Plain were historically dominated by extensive stands of longleaf pine (*Pinus palustrus*) that stretched from Virginia to Texas. However, very little of the region’s original forest persists; much of the original longleaf pine has been replaced by pine plantations (primarily Loblolly Pine, *Pinus taeda*) or mixed deciduous forests. This may explain negative associations between forest and mussels. However, it is still unclear why mussel metrics were positively correlated with crop, barren, shrub and grassland cover. Additional sites and more sophisticated treatment of the data may help resolve these contradictory patterns.

Table 1. Statistically significant (p<0.05) Pearson correlation coefficients for associations between freshwater mussel assemblage and physical habitat parameters at 30 sites associated with 10 dams in the Roanoke and Tar river drainages sampled in 2009 and 2010. Channel width, depth, percent silt, percent bedrock and percent wood are excluded from the table because we did not observe any statistically significant associations with mussel parameters. Missing data (-----) indicate non-significant correlations.

Habitat Parameter	**Total Mussels**	**Mussel CPUE**	**Mussel Richness**	**Mussel H'**
Mean Velocity (m/s)	-----	-----	r = -0.418 p = 0.02 n = 30	-----
Mean Particle Size (mm)	-----	r = -0.414 p = 0.02 n = 30	r = -0.438 p = 0.02 n = 30	r = -0.406 p = 0.03 n = 30
Median Particle Size (mm)	-----	-----	r = -0.364 p = 0.048 n = 30	-----
Percent Sand	-----	-----	-----	r = 0.358 p =0.05 n = 30
Percent Organic	r = 0.403 p = 0.03 n = 30	-----	r = 0.393 p = 0.03 n = 30	r = 0.604 p < 0.001 n = 30

Table 2. Statistically significant ($p<0.05$) Pearson correlations between freshwater mussel assemblage and landuse parameters at all 30 sites and at sites associated with 4 Coastal Plain and 6 Piedmont dams in the Roanoke and Tar river drainages in 2009 and 2010. Percent open water was excluded from the table because we did not observe any statistically significant associations with mussel parameters. Additionally, we excluded Mussel Richness for Coastal Plain sites and Total Mussels and Mussel CPUE for Piedmont sites. Missing data (-----) indicate non-significant correlations.

	Rank Magnitude	**Link Magnitude**	**Area**	**Urban-low**	**Urban-high**	**Pasture**	**Crop**	**Deciduous Forest**	**Evergreen Forest**	**Mixed Forest**	**Total Forest**	**Wetland**	**Barren**	**Shrub**	**Grass**
All Sites															
Total Mussels	-----	r = 0.514 p = 0.004 n = 30	r = 0.499 p = 0.005 n = 30	-----	-----	r = -0.528 p = 0.003 n = 30	r = 0.552 p = 0.002 n = 30	-----	r = 0.411 p = 0.024 n = 30	-----	-----	r = 0.478 p = 0.008 n = 30	r = 0.368 p = 0.05 n = 30	-----	-----
Mussel CPUE		r = 0.400 p = 0.03 n = 30	r = 0.382 p = 0.04 n = 30			r = -0.504 p = 0.004 n = 30	r = 0.504 p = 0.004 n = 30		r = 0.421 p = 0.02 n = 30	-----	-----	r = 0.504 p = 0.005 n = 30	r = 0.426 p = 0.02 n = 30	r = 0.375 p = 0.04 n = 30	-----
Mussel Richness		r = 0.368 p = 0.05 n = 30	r = 0.356 p = 0.05 n = 30			r = -0.424 p = 0.02 n = 30	r = 0.514 p = 0.004 n = 30	r = -0.530 p = 0.003 n = 30	r = 0.532 p = 0.002 n = 30	-----	r = -0.380 p = 0.04 n = 30	r = 0.584 p = 0.001 n = 30	r = 0.550 p = 0.002 n = 30	r = 0.483 p = 0.007 n = 30	r = 0.480 p = 0.007 n = 30
Mussel H'	r = 0.381 p = 0.04 n = 30	r = 0.705 p <0.001 n = 30	r = 0.698 p <0.001 n = 30			r = -0.719 p <0.001 n = 30	r = 0.696 p <0.001 n = 30	r = 0.563 p = 0.001 n = 30	r = 0.741 p <0.001 n = 30	-----	-----	r = 0.765 p <0.001 n = 30	r = 0.665 p <0.001 n = 30	r = 0.462 p = 0.01 n = 30	-----
Coastal Plain															
Total Mussels	-----	r = 0.580 p = 0.05 n = 12	r = 0.572 p = 0.05 n = 12	-----	-----	-----	-----	-----	-----	-----	-----	r = 0.597 p = 0.04 n = 12	-----	-----	-----
Mussel CPUE	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	r = 0.580 p = 0.05 n = 12	-----	-----	-----

	Rank Magnitude	**Link Magnitude**	**Area**	**Urban-low**	**Urban-high**	**Pasture**	**Crop**	**Deciduous Forest**	**Evergreen Forest**	**Mixed Forest**	**Total Forest**	**Wetland**	**Barren**	**Shrub**	**Grass**
Mussel H’	r = 0.616 p = 0.03 n = 12	r = 0.774 p = 0.003 n = 12	r = 0.778 p = 0.003 n = 12	r = -0.614 p = 0.03 n = 12	-----	r = -0.648 p = 0.02 n = 12	-----	-----	r = 0.620 p = 0.03 n = 12	r = -0.697 p = 0.003 n = 12	-----	r = 0.756 p = 0.004 n = 12	-----	-----	-----
Piedmont															
Mussel Richness	-----	-----	-----	-----	-----	-----	r = 0.575 p = 0.01 n = 18	r = -0.557 p = 0.02 n = 18	r = 0.526 p = 0.03 n = 18	-----	r = -0.544 p = 0.02 n = 18	r = 0.537 p = 0.02 n = 18	r = 0.481 p = 0.04 n = 18	r = 0.547 p = 0.02 n = 18	r = 0.589 p = 0.01 n = 18
Mussel H’	-----	-----	-----	-----	r = 0.481 p = 0.04 n = 18	-----	r = 0.636 p = 0.01 n = 18	r = -0.657 p = 0.01 n = 18	r = 0.548 p = 0.02 n = 18	-----	r = -0.703 p = 0.001 n = 18	r = 0.626 p = 0.01 n = 18	r = 0.611 p = 0.01 n = 18	r = 0.637 p = 0.01 n = 18	r = 0.639 p = 0.004 n = 18

Fishes and Dams

We processed >12,000 fish in 2010 and obtained length measurements for all 12,423 fish and weights on 1804 fish. Mixed-model ANOVAs revealed that fish were significantly more abundant and assemblages were significantly more species-rich and diverse (higher Shannon H') immediately downstream of intact dams compared to up and downstream sites. However, models revealed no differences between fish community metrics at sites associated with breached/relict dams (Figure 2). ANOVA also revealed that fish CPUE and taxa richness were significantly higher in the mill reach of intact dams. However, we found no between-reach differences in any fish community metrics at breached or relict sites. We examined differences in fish community composition between sites and found that CPUE data for the fish families Centrarchidae (sunfishes), Catostomidae (suckers), Percidae (darters) and Anguillidae (eels) were all significantly higher in the mill reach compared to up-or-downstream reaches at intact dams but not at relict dams.

Anguillids are catadramous and highly migratory. It appears that intact dams may aggregate these fishes within the mill reach. However, the other three groups are primarily comprised of resident fish taxa in these streams. Thus it appears that dams may be augmenting conditions for these fishes within the mill reach. Few of the sites sampled during 2010 were primary barriers (first barriers upstream from saltwater) to fishes and we collected very few anadramous taxa (e.g., shad and herring). This is likely an artifact of site selection and time of year sampled. In 2011 we will be sampling several primary barriers in March and April to assess effects of these structures on fish communities in streams with anadramous runs.

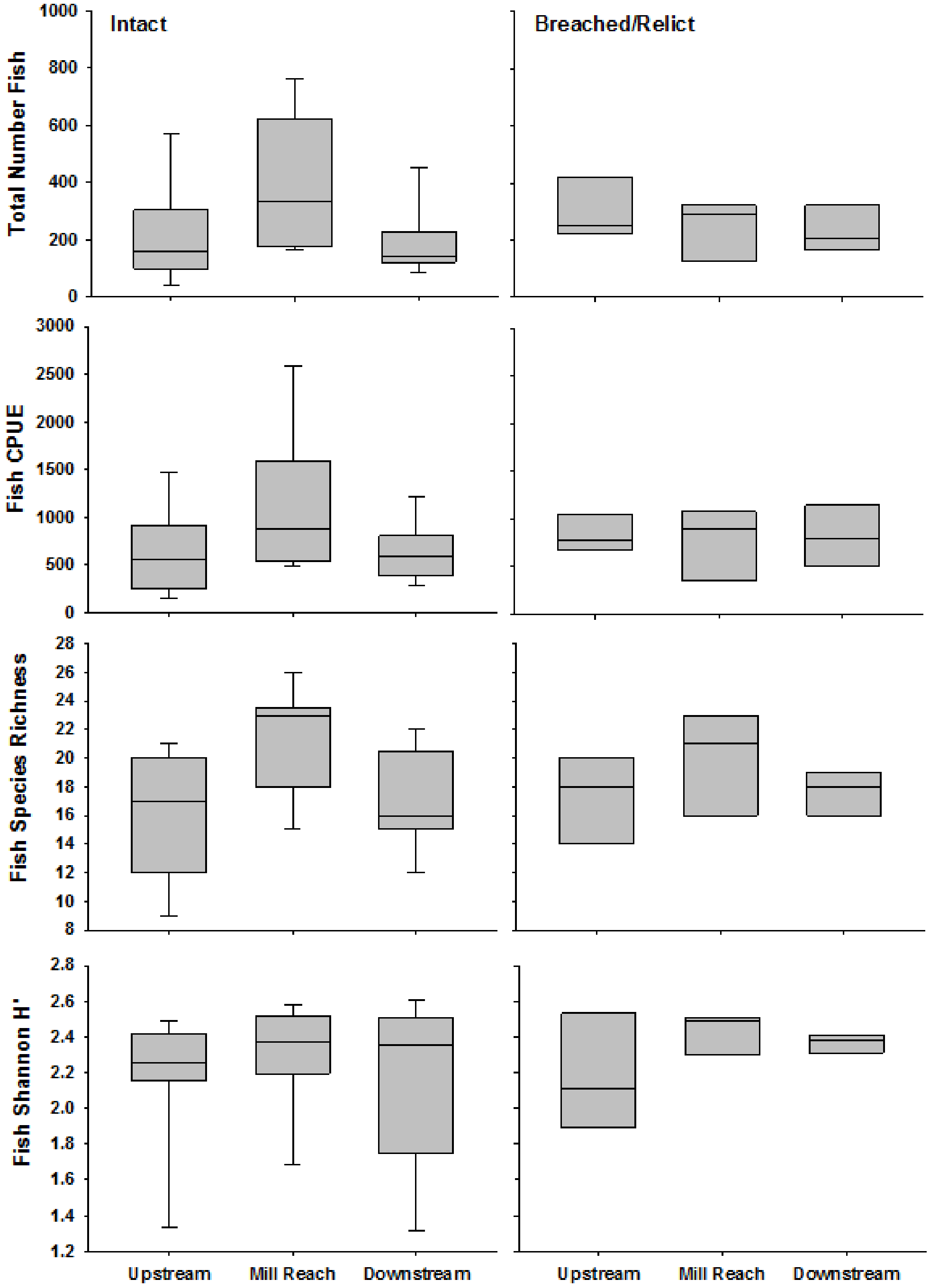


Figure 2. Box-plots of fish abundance, catch-per-unit-effort (CPUE), species richness and diversity (Shannon H') at sites located upstream, immediately downstream (Mill Reach) and 500-650 m downstream of intact and breached/relict small dams in the Neuse, Roanoke and Tar river drainages in 2009 and 2010. The center line represents the median, the box upper and lower bounds the 25th and 75th percentiles of the data. Error bars represent the 5th and 95th percentiles.

Fishes and Mussels

ANOVA revealed that both the number of mussel host fish taxa and the total number of mussel hosts present at a site was significantly higher in the mill reach of intact dams. No significant differences in reported mussel host abundance or assemblage structure were reported from relict/breached dams (Figure 3). Interestingly, both the total number of fishes and fish CPUE were significantly positively correlated with mussel abundance, CPUE, richness and H' (Table 4). We observed few significant correlations between mussel and fish assemblages. However, mussel abundance, CPUE and richness were all positively associated with the total number of host fishes present at each site (Table 4). Curiously, mussel H' was negatively associated with the percentage of fish taxa that were reported to be mussel hosts.

These are among the first data to demonstrate a link between host fish and mussel abundance in the field and should be considered highly preliminary. Although previous studies have demonstrated that mussel and fish species richness are frequently correlated, this association is largely believed to be a function of stream size. Because both mussel and fish richness typically increase with stream size it is therefore difficult to separate effects of biogeography from effects of dams (and dam condition). Subsequent analyses will examine this relationship in more detail and will attempt to account for the effects of stream size on mussel and fish assemblages using multivariate modeling techniques.

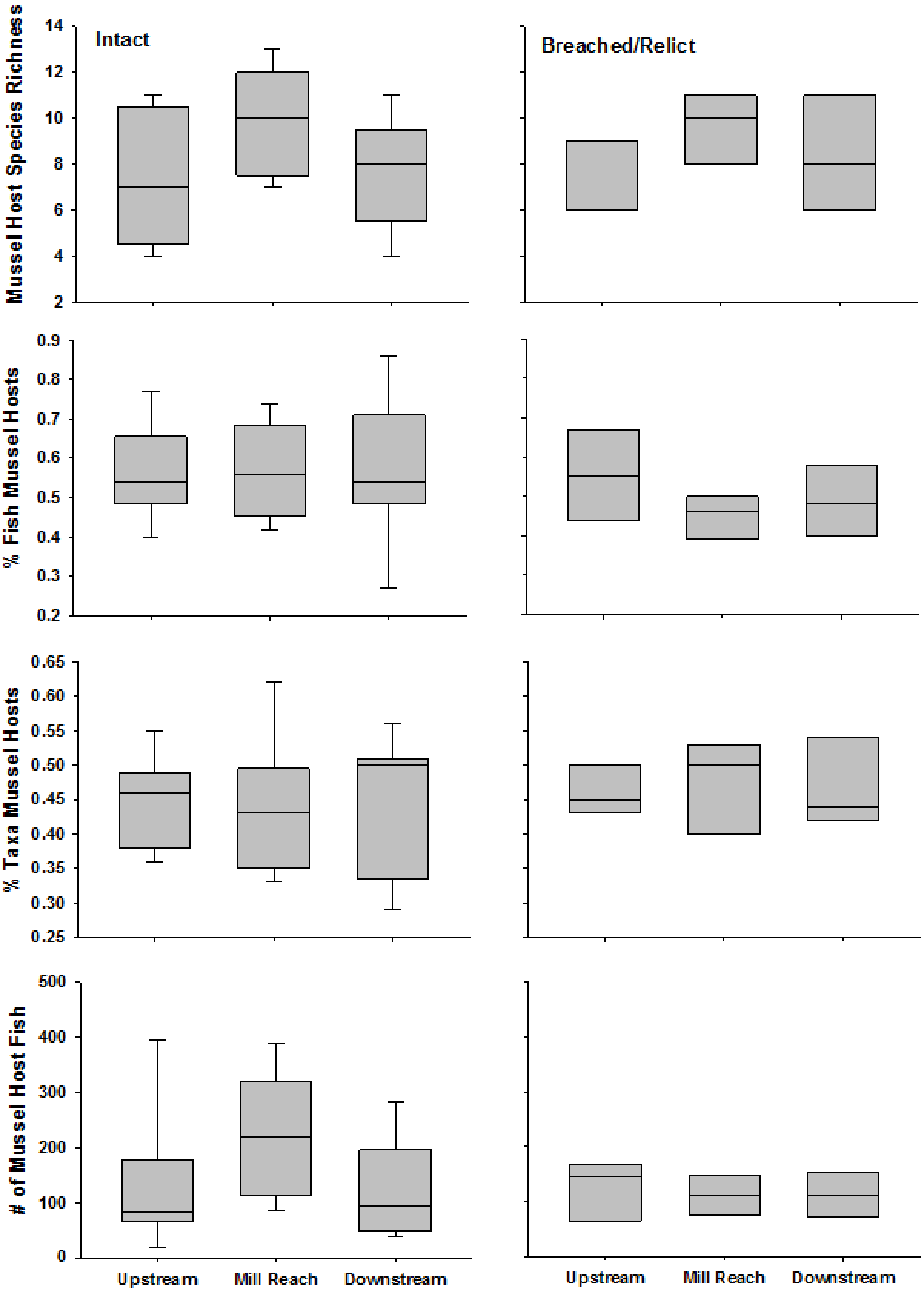


Figure 3. Box-plots of mussel host fish richness, the percent of total fish captured that are mussel hosts, the percent of all taxa that are hosts and the total number of host fish captured at sites located upstream, immediately downstream (Mill Reach) and 500-650 m downstream of intact and breached/relict small dams in the Neuse, Roanoke and Tar river drainages in 2009 and 2010. The center line represents the median, the box upper and lower bounds the 25th and 75th percentiles of the data. Error bars represent the 5th and 95th percentiles.

Table 3. Pearson correlations between mussel and fish assemblage metrics at 30 sites where fish and mussels were sampled during 2009-2010 in the Tar and Roanoke river drainges. We excluded Fish species richness, Fish diversity, Number of host fish taxa and the Percent of the fish assemblage comprised of mussel hosts from the table because we did not observe any statistically significant associations between these parameters and mussel assemblage metrics. Missing data (-----) indicate that no statistically significant associations were found between parameters.

Mussel Parameter	**Total Fish**	**Fish CPUE**	**Fish Family Richness**	**Percent Taxa Mussel Hosts**	**Number Host Fishes**
Total Mussels	r = 0.514 p = 0.004 n = 30	r = 0.539 p = 0.002 n = 30	-----	-----	r = 0.465 p = 0.01 n = 30
Mussel CPUE	r = 0.376 p = 0.04 n = 30	r = 0.389 p = 0.03 n = 30	r = 0.372 p = 0.04 n = 30	-----	r = 0.407 p = 0.03 n = 30
Mussel Richness	r = 0.421 p = 0.02 n = 30	r = 0.432 p = 0.02 n = 30	-----	-----	r = 0.482 p = 0.007 n = 30
Mussel H'	r = 0.369 p = 0.05 n = 30	r = 0.438 p = 0.02 n = 30	-----	r = -0.442 p = 0.02 n = 30	-----

Fishes and Habitat

Fish abundance was significantly positively correlated with stream width and proportion bedrock (Table 4). Fish species and family richness were negatively correlated with depth (species richness) and velocity (both). Family richness was negatively correlated to percent silt but positively correlated with percent wood. The proportion of fish taxa that are reported to be mussel hosts was negatively correlated with depth and organic matter (Table 4). Finally, the total number of host fishes was negatively associated with depth and velocity but positively associated with bedrock. These associations illustrate that mussels and fish may have different habitat requirements and that factors that appear to favor mussel production (proportion of organic matter in substrate) may not necessarily benefit fishes. Similarly, factors that are positively associated with fish production, including the proportion of substrate at a site comprised of bedrock are not frequently associated with high-density or diversity mussel assemblages. These relationships hint at the problematic nature of a one-size-fits-all approach to stream biodiversity management.

Table 4. Pearson correlations between fish assemblage metrics and stream physical habitat parameters at 45 sites sampled during 2010 in the Neuse, Roanoke and Tar river drainages. We excluded Mean and median particle size, percentage sand and Fish CPUE and H' (Shannon Diversity) from the table because we did not observe any statistically significant associations. Missing data (-----) indicate associations were not statistically significant (p > 0.05).

	Channel Width	**Channel Depth**	**Current Velocity**	**Percent Silt**	**Percent Bedrock**	**Percent Wood**	**Percent Organic**
Total Fish	r = 0.298 p = 0.047 n = 45				r = 0.347 p = 0.02 n = 45		
Fish Species Richness		r = -0.312 p = 0.037 n = 45	r = -0.307 p = 0.04 n = 45				
Fish Family Richness			r = -0.463 p = 0.001 n = 45	r = -0.301 p = 0.04 n = 45		r = 0.380 p = 0.01 n = 45	
Percent Taxa Mussel Hosts		r = -0.345 p = 0.02 n = 45					r = -0.318 p = 0.03 n = 45
Percent Host Fish			r = -0.502 p <0.001 n = 45				
Total Number Host Fish		r = -0.374 p = 0.01 n = 45	r = -0.401 p = 0.006 n = 45		r = 0.317 p = 0.03 n = 45		

Fishes and Landuse

Associations between fish assemblage metrics and landuse parameters revealed both intuitive and problematic trends. Coastal Plain fish species richness was negatively associated with drainage area and fish H' was negatively associated with open water and wetland cover (Table 5). More intuitively, Coastal Plain H' was negatively associated with cropland and positively associated with deciduous forest, mixed forest, total forest and shrub cover. Coastal Plain mussel host metrics were primarily driven by stream size (rank magnitude, link magnitude, and area).

At Piedmont sites, fish abundance, CPUE, and richness were all positively associated with stream size variables. Fish abundance, CPUE and H' were negatively associated with pasture but CPUE and richness were positively associated with high-intensity urban development (Table 5). Piedmont fish H' was negatively associated with open water, mixed forest and grassland cover. The proportion of fish taxa that have been reported to serve as mussel hosts was negatively associated with open water, low-intensity urban development, pasture and crop lands and mixed forest but positively associated with deciduous forest, total forest, and shrub cover (Table 5).

These data suggest that physiography has a strong influence on how landuse and habitat factors mediate the effects of dam on stream biota. Fish and mussel assemblage metrics were not consistently correlated with the same physical or landuse parameters. However some parameters, including pasture and forest cover, were frequently associated with biotic metrics. More comprehensive analyses will elucidate the underlying mechanisms driving these patterns in an attempt to understand how dams affect imperiled Atlantic Slope mussel and fish assemblages.

Table 5. Statistically significant ($p<0.05$) Pearson correlations between freshwater mussel assemblage and landuse parameters at all 30 sites and at sites associated with 4 Coastal Plain and 6 Piedmont dams in the Roanoke and Tar river drainages in 2009 and 2010. Percent open water was excluded from the table because we did not observe any statistically significant associations with mussel parameters. Additionally, we excluded Mussel Richness for Coastal Plain sites and Total Mussels and Mussel CPUE for Piedmont sites. Missing data (-----) indicate non-significant correlations.

	RM	**LM**	**Area**	**Open Water**	**Urban Low**	**Urban High**	**Pasture**	**Crop**	**Deciduous Forest**	**Evergree n Forest**	**Mixed Forest**	**Total Forest**	**Wetland**	**Barren**	**Shrub**	**Grass**
Coastal Plain																
Fish Species Richness	-----	-----	r= -0.466	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
			p=0.05													
			n=18													
Fish Diversity (Shannon H')	-----	-----	-----	r= -0.482	-----	-----	-----	r= -0.617	r=0.519	-----	r=0.550	r=0.567	r= -0.649	-----	r=0.543	-----
				p=0.043				p=0.006	p=0.027		p=0.018	p=0.014	p=0.004		p=0.020	
				n=18				n=18	n=18		n=18	n=18	n=18		n=18	
Percentage Taxa Fish Hosts	r= -0.487	r= -0.541	r= -0.540	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	p=0.040	p=0.020	p=0.021													
	n=18	n=18	n=18													
Piedmont																
Fish Abundance	r=0.585	r=0.710	r=0.706	-----	-----	-----	r= -0.486	-----	-----	-----	-----	-----	-----	-----	-----	-----
	p=0.001	p=0.000	p=0.000	-----	-----	-----	p=0.007	-----	-----	-----	-----	-----	-----	-----	-----	-----
	n=30	n=30	n=30	-----	-----	-----	n=30	-----	-----	-----	-----	-----	-----	-----	-----	-----
Fish CPUE	r=0.615	r=0.680	r=0.675	-----	-----	r= 0.406	r= -0.463	-----	-----	-----	-----	-----	-----	-----	-----	-----
	p=0.000	p=0.000	p=0.000	-----	-----	p=0.026	p=0.010	-----	-----	-----	-----	-----	-----	-----	-----	-----
	n=30	n=30	n=30	-----	-----	n=30	n=30	-----	-----	-----	-----	-----	-----	-----	-----	-----
Fish Species Richness	-----	r=0.451	r=0.439	-----	-----	r=0.448	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
		p=0.012	p=0.015			p=0.013										
		n=30	n=30			n=30										

	RM	LM	Area	Open Water	Urban Low	Urban High	Pasture	Crop	Deciduous Forest	Evergreen Forest	Mixed Forest	Total Forest	Wetland	Barren	Shrub	Grass
Fish Family Richness	r= -0.637 p=0.000 n=30	-----	r= -0.366 p=0.046 n=30	r=0.610 p=0.000 n=30	r=0.397 p=0.030 n=30	-----	r=0.366 p=0.046 n=30	r=0.655 p=0.000 n=30	r= -0.689 p=0.000 n=30	r= 0.466 p=0.009 n=30	r=0.439 p=0.015 n=30	r= -0.712 p=0.000 n=30	r=0.668 p=0.000 n=30	r= -0.464 p=.010 n=30	-----	r=0.604 p=0.000 n=30
Fish Diversity (Shannon H')	-----	-----	-----	r= -0.454 p=0.012 n=30	-----	-----	r= -0.593 p=0.001 n=30	-----	-----	-----	r= -0.521 p=0.003 n=30	-----	-----	-----	-----	r= -0.370 p=0.044 n=30
Percentage Taxa Fish Hosts	r=0.395 p=0.031 n=30	-----	-----	r= -0.644 p=0.000 n=30	r= -0.693 p=0.000 n=30	-----	r= -0.488 p=0.006 n=30	r= -0.479 p=0.007 n=30	r=0.467 p=0.009 n=30	-----	r= -0.474 p=0.008 n=30	r=0.481 p=0.007 n=30	-----	-----	r=0.368 p=0.046 n=30	-----

Table 5 continued

References

Alderman, J.M. & Adams, W.F. (1993) Conservation of critical habitat for freshwater mussels in North Carolina. pp.81-82. In K.S. Cummings, A.C. Buchanan & L.M. Koch (eds.) Conservation and Management of Freshwater Mussels. Proceedings of a UMRCC Symposium.

Armitage P.D. (1984) Environmental changes induced by stream regulation and their effect on lotic macroinvertebrate communities. In: *Regulated Rivers* (Eds. A. Lillehammer & S.J. Saltveit), pp. 139-165. Oslo University Press, Oslo, Norway.

Bogan A.E. (1993) Freshwater bivalve extinctions (Mollusca: Unionoida): a search for causes. *American Zoologist*, **33,** 599-609.

Bogan A.E. (2002) Workbook and key to the freshwater bivalves of North Carolina, 101 p + 10 plates

Bogan A.E. & Alderman, J.M. (2004) Workbook and key to the freshwater bivalves of South Carolina. 64 p + 10 plates.

Brainwood M., Burgin S. & Byrne M. (2006) The impact of small and large impoundments on freshwater mussel distribution in the Hawkesbury-Nepean River, Southeastern Australia. *River Research and Applications,* **24,** 1325-1342.

Dean J.D., Edds D., Gillette D., Howard J., Sherraden S. & Tiemann J. (2002) Effects of lowhead dams on freshwater mussels in the Neosho River, Kansas. *Kansas Academy of Science Transactions*, **105,** 232-240.

Downward S. & Skinner K. (2005) Working Rivers: the geomorphological legacy of English freshwater mills. *Royal Geographical Society*, **37,** 138-147.

Fraley J.J. (1979) Effects of elevated stream temperatures below a shallow reservoir on cold-water macroinvertebrate fauna. In: *The Ecology of Regulated Streams* (Eds J.V. Ward & J.A. Stanford), pp. 257–272. Plenum Press, New York, NY.

Gangloff M.M. & Feminella J.W. 2007. Distribution and status of freshwater mussels (Bivalvia: Unionidae) of the lower Coosa and Tallapoosa river drainages in Alabama. Bulletin of the Alabama Museum of Natural History, **25,** 24-70.

Gangloff M.M., Hartfield E.E., Werneke D.C. & Feminella J.W. (In Review) Associations between small dams and mollusk assemblages in Alabama streams. Submitted to Journal of the North American Benthological Society, 1 July 2010

Gangloff M.M., Hartfield E.E., Singer E.E., Helms B., Werneke D., White K. & Feminella J.W. (2009) Alabama Mill Dam Inventory. Final Report to ADCNR. Available Online at: http://www.outdooralabama.com/research-mgmt/State%20Wildlife%20Grants/projectsfunded.cfm.

Haag W.R. (2010) Past and future patterns of freshwater mussel extinctions in North America during the Holocene. In: *Holocene Extinctions* (Ed. S.T. Turvey), pp 107-128. Oxford University Press, Oxford, UK.

Hartfield E.E., Gangloff M.M., Santos S.R. & Feminella J.W. (In Review) Consequences of low-head dams to crayfish assemblages and gene flow in Alabama streams. Submitted to: Journal of the North American Benthological Society.

Haxton T.J. & Findlay C.S. (2008) Meta-analysis of the impacts of water management on aquatic communities. *Canadian Journal of Fisheries and Aquatic Science,* **65,** 437-447.

Heinricher J.R. & Layzer J.B. (1999) Reproduction by individuals of a non-reproducing population of *Megalonaias nervosa* (Mollusca: Unionidae) following translocation. *American Midland Naturalist,* **141,** 140-148.

Holden P.B. (1979) Ecology of riverine fishes in regulated stream systems with emphasis on the Colorado River. In: *The Ecology of Regulated Streams* (Eds. J.V. Ward & J.A. Stanford), pp. 57–74. Plenum Press, New York, NY.

Jensen A.J. (1987) Hydropower development of salmon rivers: Effect of changes in water temperature on growth of brown trout (*Salmo trutta*) presmolts. In: *Regulated Streams Advances in Ecology* (Eds. J.F. Craig & J.B. Kemper), pp. 207–218. Plenum Press, New York, NY.

Layzer J.B., Gordon M.E. & Anderson R.M. (1993) Mussels: the forgotten fauna of regulated rivers. A case study of the Caney Fork River. *Regulated Rivers: Research and Management*, **8,** 63-71.

Lessard J.L. & Hayes D.B. (2003) Effects of elevated water temperatures on fish and macroinvertebrate communities below small dams. *River Research and Applications*, **19,** 721-732.

Lydeard C., Cowie R.H., Bogan A.E., Bouchet P., Cummings K.S., Frest T.J., Herbert D.G., Hershler R., Gargominy O., Perez K., Ponder W.F., Roth B., Seddon M., Strong E.E. & Thompson F.G. (2004) The global decline of nonmarine mollusks. *BioScience*, **54,** 321-330.

Maxted J.R., McCready C.H. & Scarsbrook M.R. (2005) Effects of small ponds on stream water quality and macroinvertebrate communities. *New Zealand Journal of Marine and Freshwater Research*, **39,** 1069-1084.

Neves, R. J.*,* A. E. Bogan*,* J. D. Williams*,* S. A. Ahlstedt*,* P. W. Hartfield*.* 1997*.* Status of aquatic mollusks in the southeastern United States: a downward spiral of diversity. *Pages* 43 85 *in* G. W.Benz D. E.Collins*, editors.* Aquatic fauna in peril: the southeastern perspective*. Southeastern Aquatic Research Institute, Lenz Design and Communications, Decatur, Georgia.*

Parmalee P.W. & Bogan A.E. (1998) *The Freshwater Mussels of Tennessee.* The University of Tennessee Press. Knoxville, TN.

Poff N.L. & Hart D.D. (2002) How dams vary and why it matters for the emerging science of dam removal. *BioScience*, **52,** 659-668.

Poole K.E. & Downing J.A. (2004) Relationship of declining mussel biodiversity to stream-reach and watershed characteristics in an agricultural landscape. *Journal of the North American Benthological Society*, **23,** 114-125.

Rehn A.C. (2009) Benthic macroinvertebrates as indicators of biological condition below hydropower dams on west slope Sierra Nevada streams, California, USA. *River Research and Applications,* **25,** 208-228.

Ricciardi A. & Rasmussen, J.B. (1999) Extinction rates of North American freshwater fauna. *Conservation Biology*, **13**, 1220-1222.

Sethi S.A., Selle A.R., Doyle M.W., Stanley E.H. & Kitchel H.E. (2004) Response of unionid mussels to dam removal in Koshkonong Creek, Wisconson (USA). *Hydrobiologia*, **525,** 157-165.

Shuman J.R. (1995) Environmental considerations for assessing dam removal alternatives for river restoration. *Regulated Rivers: Research and Management,* **11,** 249-261.

Strayer D.L. (2008) *Freshwater mussel ecology: a multifactor approach to distribution* *and abundance.* University of California Press. Los Angeles, CA.

Tiemann J.S., Dodd H.R., Owens N. & Wahl D.H. (2007) Effects of lowhead dams on unionids in the Fox River, Illinois. *Northeastern Naturalist*, **14,** 125-138.

Vaughn C.C. & Taylor C.M. (1999) Impoundments and the decline of freshwater mussels: a case study of an extinction gradient. *Conservation Biology*, **13,** 912-920.

Ward J.V. & Stanford J.A. (1987) The ecology of regulated streams: past accomplishments and directions for future research. In: *Regulated Streams Advances in Ecology* (Eds. J.F. Craig & J.B. Kemper), pp. 391-409. Plenum Press, New York, NY.

Watters T.G. (1996) Small dams as barriers to freshwater mussels (Bivalvia, Unionioda) and their hosts. *Biological Conservation*, **75,** 79-85.

Williams J.D., Fuller S.L.H. & Grace R. (1992) Effects of impoundments on freshwater mussels (Mollusca: Bivalvia: Unionidae) in the mainstem of the Black Warrior and Tombigbee rivers in western Alabama. Bulletin of the Alabama Museum of Natural History, **13,** 1-10.

Williams J.D., Bogan A.E. & J.T. Garner. (2008) *Freshwater Mussels of Alabama and the Mobile Basin in Georgia, Mississippi, and Tennessee.* University of Alabama Press, Tuscaloosa, AL.

Appendix A. List of study sites in the Chowan, Neuse, Roanoke and Tar river drainages in North Carolina and Virginia.

Drainage	Stream	Dam	Status	Site	Latitude	Longitude
Roanoke	Dan River	Jessup Mill	Intact	Upstream	36.53001	-80.38033
Roanoke	Dan River	Jessup Mill	Intact	Impoundment	36.52689	-80.37451
Roanoke	Dan River	Jessup Mill	Intact	Dam	36.52686	-80.37380
Roanoke	Dan River	Jessup Mill	Intact	Downstream	36.52465	-80.36691
Roanoke	Dan River	George Mill	Relict	Upstream	36.51708	-80.30866
Roanoke	Dan River	George Mill	Relict	Dam	36.51576	-80.30387
Roanoke	Dan River	George Mill	Relict	Downstream	36.51025	-80.30115
Roanoke	Dan River	Joyce Mill	Relict	Upstream	36.53772	-80.40422
Roanoke	Dan River	Joyce Mill	Relict	Dam	36.53711	-80.40073
Roanoke	Dan River	Joyce Mill	Relict	Downstream	36.53403	-80.39467
Roanoke	Mayo River	Avalon Dam	Intact	Dam	36.42838	-79.94685
Roanoke	Mayo River	Avalon Dam	Intact	Downstream	36.42384	-79.94936
Roanoke	Mayo River	Mayo Dam	Intact	Upstream	36.42299	-79.95358
Roanoke	Mayo River	Mayo Dam	Intact	Dam	36.41800	-79.96292
Roanoke	Mayo River	Mayo Dam	Intact	Downstream	36.41397	-79.96297
Roanoke	Dan River	Walnut Cove Power Dam	Relict	Upstream	36.37701	-80.12864
Roanoke	Dan River	Walnut Cove Power Dam	Relict	Dam	36.37003	-80.12714
Roanoke	Dan River	Walnut Cove Power Dam	Relict	Downstream	36.36642	-80.12740
Roanoke	Grassy Creek	Dalton Mill	Intact	Dam	36.49060	-78.61629
Roanoke	Grassy Creek	Dalton Mill	Intact	Downstream	36.48979	-78.62120
Neuse	Little River	Atkinson Mill	Intact	Upstream	35.69106	-78.26328
Neuse	Little River	Atkinson Mill	Intact	Dam	35.66785	-78.25991
Neuse	Little River	Atkinson Mill	Intact	Downstream	35.66285	-78.25529
Neuse	Little River	Lizard Lick Mill	Intact	Upstream	35.83554	-78.35867
Neuse	Little River	Lizard Lick Mill	Intact	Dam	35.82253	-78.35219
Neuse	Little River	Lizard Lick Mill	Intact	Downstream	35.81856	-78.35291
Neuse	Little River	Lowell Mill	Relict	Upstream	35.60095	-78.19739
Neuse	Little River	Lowell Mill	Relict	Dam	35.56589	-78.16013
Neuse	Little River	Lowell Mill	Relict	Downstream	35.56335	-78.15397
Neuse	Little River	Mitchell Mill	Breach	Upstream	35.93044	-78.39571
Neuse	Little River	Mitchell Mill	Breach	Dam	35.91402	-78.38745
Neuse	Little River	Mitchell Mill	Breach	Downstream	35.91110	-78.38607
Neuse	Contentnea Creek	Wiggins Mill	Intact	Upstream	35.69034	-78.02986
Neuse	Contentnea Creek	Wiggins Mill	Intact	Dam	35.68800	-77.94872
Neuse	Contentnea Creek	Wiggins Mill	Intact	Downstream	35.68125	-77.93287
Neuse	Contentnea Creek	Buckhorn Mill	Breach	Upstream	35.68715	-78.09457

Drainage	Stream	Dam	Status	Site	Latitude	Longitude
Neuse	Contentnea Creek	Buckhorn Mill	Breach	Dam	35.69789	-78.06197
Neuse	Contentnea Creek	Buckhorn Mill	Breach	Downstream	35.69275	-78.05753
Neuse-	Little River	Cherry Hospital Dam	Relict	Dam	35.39387	-78.02666
Neuse	Little River	Cherry Hospital Dam	Relict	Downstream	35.38984	-78.02567
Tar	Tar River	Gooch Mill	Intact	Upstream	36.29545	-78.73116
Tar	Tar River	Gooch Mill	Intact	Dam	36.29269	-78.70781
Tar	Tar River	Gooch Mill	Intact	Downstream	36.28939	-78.70186
Tar	Tar River	Oxford City Dam	Breach	Upstream	36.26927	-78.67831
Tar	Tar River	Oxford City Dam	Breach	Dam	36.26756	-78.66902
Tar	Tar River	Oxford City Dam	Breach	Downstream	36.26241	-78.66904
Tar	Tar River	Day’s Mill	Breach	Upstream	36.32603	-78.76938
Tar	Tar River	Day’s Mill	Breach	Dam	36.32037	-78.76478
Tar	Tar River	Day’s Mill	Breach	Downstream	36.31909	-78.75903
Tar	Tar River	Cannady Mill	Relict	Upstream	36.19144	-78.56664
Tar	Tar River	Cannady Mill	Relict	Dam	36.19041	-78.55904
Tar	Tar River	Cannady Mill	Relict	Downstream	36.18819	-78.55316
Tar	Fishing Creek	Bellamy Mill	Intact	Upstream	36.14561	-77.84164
Tar	Fishing Creek	Bellamy Mill	Intact	Dam	36.15500	-77.74274
Tar	Fishing Creek	Bellamy Mill	Intact	Downstream	36.13498	-77.71776
Tar	Fishing Creek	Powell Mill	Relict	Upstream	36.34110	-78.13358
Tar	Fishing Creek	Powell Mill	Relict	Dam	36.33895	-78.12939
Tar	Fishing Creek	Powell Mill	Relict	Downstream	36.33649	-78.12657
Tar	Fishing Creek	Hamme Mill	Intact	Upstream	36.37429	-78.16712
Tar	Fishing Creek	Hamme Mill	Intact	Impoundment	36.36876	-78.15419
Tar	Fishing Creek	Hamme Mill	Intact	Dam	36.36908	-78.15382
Tar	Fishing Creek	Hamme Mill	Intact	Downstream	36.36666	-78.14844
Tar	Sandy Creek	Laurel Mill	Intact	Upstream	36.21032	-78.22669
Tar	Sandy Creek	Laurel Mill	Intact	Dam	36.17804	-78.19111
Tar	Sandy Creek	Laurel Mill	Intact	Downstream	36.17361	-78.18958
Tar	Tar River	Spring Hope Mill	Breach	Dam	35.93617	-78.14868
Tar	Tar River	Spring Hope Mill	Breach	Downstream	35.93214	-78.14801
Tar	Savage Mill Run Creek	Savage	Relict	Dam	35.98290	-77.41776
Chowan	Bennett's Creek	Merchant’s Mill	Intact	Upstream	36.43741	-76.67028
Chowan	Bennett's Creek	Merchant’s Mill	Intact	Dam	36.43214	-76.69926
Chowan	Bennett's Creek	Merchant’s Mill	Intact	Downstream	36.42844	-76.70068

Drainage	Stream	Dam	Status	Site	Latitude	Longitude
Chowan	Nottoway River	Fort Pickett Dam	Intact	Upstream	37.01751	-78.02908
Chowan	Nottoway River	Fort Pickett Dam	Intact	Dam	36.99044	-77.96323
Chowan	Beaverpond Creek	Garners Mill	Intact	Upstream	36.56970	-77.67974
Chowan	Beaverpond Creek	Garners Mill	Intact	Dam	36.55556	-77.67123
Chowan	Reedy Creek	Webb's Mill	Intact	Upstream	36.74380	-77.70227
Chowan	Reedy Creek	Webb's Mill	Intact	Dam	36.73629	-77.69501
Chowan	Reedy Creek	Webb's Mill	Intact	Downstream	36.73298	-77.69238
Chowan	Indian Creek	Dillard’s Mill	Breach	Upstream	36.25635	-76.63962
Chowan	Indian Creek	Dillard’s Mill	Breach	Dam	36.22917	-76.22917
Chowan	Indian Creek	Dillard’s Mill	Breach	Downstream	36.22608	-76.67790

Appendix B. Live mussels encountered during surveys at mill dams in North Carolina during summer 2010.

Site	**N**	Taxa Richness	*Alasmidonta undulata*	*Elliptio cistellaformis*	*Elliptio complanata*	*Elliptio congaraea*	*Elliptio icterina*	*Elliptio lanceolata*	*Elliptio mediocris*	*Elliptio roanokensis*	*Elliptio sp.*	*Elliptio viridulus*	*Fusconaia masoni*	*Lampsilis cariosa*	*Lampsilis n.s.*	*Lampsilis radiata*	*Pyganodon cataracta*	*Strophitus undulatus*	*Villosa constricta*
Tar River Days Mill Upstream	111	3			102						5					4			
Tar River Days Mill- Mill Reach	64	1			64											38			
Tar River Days Mill Downstream	3878	8	2		3816	5					4		4				7		2
Tar River Goochs Mill- Upstream	1808	5			1735		26						7		37				3
Tar River Goochs Mill- Mill Reach	1307	6			1276		12		13	4						1		1	
Tar River Goochs Mill Downstream	784	4			766		15		2			1							
Tar River Cannadys Mill Upstream	785	6		6	771		3	1	1					3					
Tar River Cannadys Mill- Mill Reach	138	3		4	133					1									
Tar River Cannadys Mill Downstream	219	5		2	198				1	16				2					
Fishing Creek Hamme Mill Upstream	75	2			72							2							
Fishing Creek Hamme Mil- Mill Reach	5171	7			4779	20	129		88	146		7				2			
Fishing Creek Hamme Mill Downstream	1429	8			1234	7	91	5	75	7		9	1						

Site	**N**	Taxa Richness	*Alasmidonta undulata*	*Elliptio cistellaformis*	*Elliptio complanata*	*Elliptio congaraea*	*Elliptio icterina*	*Elliptio lanceolata*	*Elliptio mediocris*	*Elliptio roanokensis*	*Elliptio sp.*	*Elliptio viridulus*	*Fusconaia masoni*	*Lampsilis cariosa*	*Lampsilis n.s.*	*Lampsilis radiata*	*Pyganodon cataracta*	*Strophitus undulatus*	*Villosa constricta*
Fishing Creek Powell Mill Upstream	286	2			285			1											
Fishing Creek Powell Mill- Mill Reach	181	4			159	2	19	1											
Fishing Creek Powell Mill- Downstream	500	5			463		31	2		2		2							
Fishing Creek Bellamy Mill Upstream	1525	6			609		13		888			1	4	10					
Fishing Creek Bellamy Mill- Mill Reach	9861	9	3		3815		50		2338	3593		41		2		41	2		
Fishing Creek Bellamy Mill Downstream	2335	5			1992	9	56		113	165									
Sandy Creek Laurel Mill Upstream	663	5			590		30		41				1						1
Sandy Creek Laurel Mill- Mill Reach	937	7			892	3	34			5			1			1			1
Sandy Creek Laurel Mill Downstream	211	3			205	1	5												
Total N	**32078**	**104**	**5**	**12**	**23956**	**37**	**514**	**10**	**3560**	**3939**	**9**	**63**	**18**	**17**	**37**	**87**	**9**	**1**	**7**

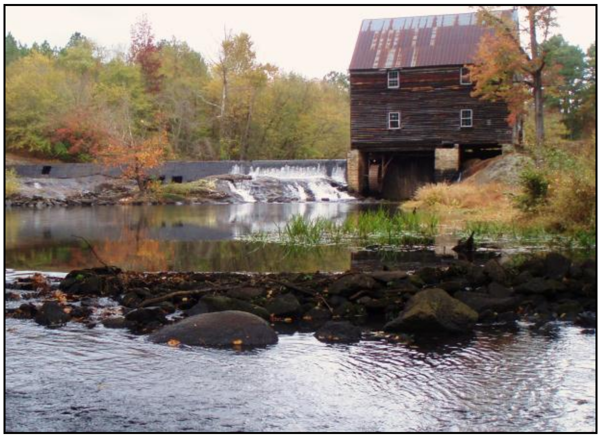
Appendix C. Fish assemblage metrics at 45 sites sampled in the Neuse, Roanoke and Tar river drainages in 2010.

Stream	**Dam**	**Status**	**Site**	**Total Fish**	**CPUE**	**Species Richness**	**Family Richness**	**H'**
Neuse Basin								
Little River	Atkinson Mill	Intact	Up	263	692.2	20	8	2.40
			Mill	163	502.1	20	9	2.12
			Down	109	281.1	22	9	2.35
Little River	Lizard Lick Mill	Breach	Up	84	245.3	9	6	1.33
			Mill	332		24	9	2.27
			Down	213		12	7	1.30
Little River	Lowells Mill	Relict	Up	248		22	8	2.55
			Mill	366		23	7	2.57
			Down	323		19	8	2.34
Contentnea Creek	Buckhorn Mill	Breach	Up	420		15	6	2.11
			Mill	297		22	9	2.38
			Down	934		16	7	2.19
Contentnea Creek	Wiggins Mill	Intact	Up	114		14	7	2.18
			Mill	427		23	10	1.69
			Down	236		16	6	1.63
Roanoke Basin								
Dan River	Georges Mill	Relict	Up	104		18	5	2.24
			Mill	100		15	5	2.33
			Down	337		13	5	2.26

Stream	**Dam**	**Status**	**Site**	**Total Fish**	**CPUE**	**Species Richness**	**Family Richness**	**H’**
Dan River	Jessups Mill	Intact	Up	157		13	4	2.25
			Mill	144		15	7	2.30
			Down	127		16	6	2.42
Dan River	Joyce Mill	Relict	Up	224		18	5	2.07
			Mill	293		22	6	2.32
			Down	203		18	6	2.38
Mayo River	Washington Mill	Intact	Up	570		20	5	2.24
			Mill	753		26	5	2.58
			Down	452		20	5	2.51
Tar Basin								
Fishing Creek	Bellamys Mill	Intact	Up	43		11	6	2.13
			Mill	765		23	7	2.45
			Down	84		16	7	2.36
Fishing Creek	Hammes Mill	Intact	Up	181		20	8	2.41
			Mill	167		22	9	2.34
			Down	218		21	7	2.51
Fishing Creek	Powell Mill	Relict	Up	238		20	8	2.56
			Mill	283		19	8	2.56
			Down	195		16	7	2.27
Tar River	Cannady Mill	Relict	Up	440		19	5	2.14
			Mill	308		19	5	2.19
			Down	449		25	7	2.59

Stream	**Dam**	**Status**	**Site**	**Total Fish**	**CPUE**	**Species Richness**	**Family Richness**	**H’**
Tar River	Day’s Mill	Breach	Up	237		14	7	1.89
			Mill	124		16	7	2.42
			Down	165		17	7	2.40
Tar River	Gooch Mill	Intact	Up	345		21	8	2.43
			Mill	490		21	7	2.35
			Down	133		16	7	2.35
Sandy Creek	Laurel Mill	Relict	Up	155		17	8	2.48
			Mill	327		23	8	2.50
			Down	141		14	8	1.89

Appendix D. Field Site Pictures



1. Sandy Creek at Laurel Mill. Example example of an intact dam on a Piedmont stream.

2. Former site of Powell Mill, Fishing Creek. Example of a relict dam site on a Piedmont stream.

3. Little River at Mitchell Mill. Example of a breached dam on a Piedmont stream.

4. Jessups Mill on Dan River. Example of an intact dam site on a Piedmont stream in the Roanoke River Drainage.

5. Sampling fish on the Mayo River near Washington Mills (Roanoke River Drainage)

6. Field Crew en route to sites on the Mayo River.

7. Katie Rifenburg with bowfin Lowell Mill, Little River.

8. Daniel Walker with flathead catfish Tar River near Pinetops, NC

9. *Fusconaia masoni* from Tar River upstream of Gooches Mill (Granville Co.)

10. *Elliptio viridula* from Fishing Creek at Bellamy Mill Dam (Halifax Co.)

11. Lampsilis cariosa from Fishing Creek at Bellamy Mill.

12. Elliptio lanceolata from Fishing Creek downstream From Hammes Mill Dam.