The Impact of Urbanization on Benthic Macroinvertebrates in Southern Appalachian Streams

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ABSTRACT

Macroinvertebrate assemblage structure was compared from 12 streams differing in urbanization type and degree. Urbanization, both historical and current, was measured using several variables generated from GIS overlays of land cover, aerial photographs, and field exploration in the study watersheds. Quantitative benthic macroinvertebrate samples were taken, and a variety of physicochemical characteristics were measured. Increasing urbanization resulted in a decline in diversity and abundance of intolerant organisms. Streams in industrial areas had greater invertebrate density due to large increases in a few tolerant groups. Urbanization in the watersheds was coupled with changes in the physical and chemical structure of the streams suggesting some possible mechanisms for urbanization impact on stream biota. Multivariate analysis grouped streams based on a number of pollution-sensitive taxa suggesting the utility of this type of approach in analyzing community data.

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Introduction

Watershed properties dictate the chemical and physical template of streams and, thus, determine the structure and function of stream ecosystems (Cummins 1974). Anthropogenic disturbance of watersheds (logging, farming, recreation, and development) alters the natural condition of streams by reducing allochthonous sources of detritus, increasing nutrients and light, adding sediments, and changing channel morphology and substrate complexity (Resh et al. 1988, Webster et al. 1992).

Urbanization poses a unique opportunity for ecological study. McDonnell and Pickett (1990) define urbanization as “the ecological forcing functions created by the growth of cities and associated human activities.” Ecologists can quantify the influence of urban and natural environmental factors for the study of disturbance theory along the complex gradient of conditions resulting from land development.

Urbanization is particularly damaging to aquatic processes and biota due to the vast array of .types and sources of impact on the land and on receiving waters. Urban areas range from cleared land for recreation and low-density residential housing (e.g., golf courses, public parks) to high density industrial development with marked changes in the landscape as you increase the amount of urbanization (Benke et al. 1981). Specific impacts of urbanization on streams include nutrients in runoff or sewer discharge (Duda et al. 1979, Penrose et al. 1980, Hachmöller et al. 1991), toxic chemicals often associated with sediment (Wilber and Hunter 1977, Pitt and Bozeman 1980, Medeiros et al. 1983), reductions in substrate size and heterogeneity (Cordone and Kelly 1961, Richards and Host 1994), unstable flow regime with increased severity of floods (Changnon and Demissie 1996), and loss of organic matter inputs (Jones and Clark 1987, Richards and Host 1994). Changes in the chemical and physical template of streams are reflected in the biological community, but identifying specific causal relationships is difficult given the scope and complexity of the disturbance (Klein 1979, Lenat et al. 1981). Many microcosm experiments have been done manipulating some aspect of streams that could have resulted from watershed land use (Chutter 1969, Williams and Mundie 1978, Lenat et al. 1981, Medeiros et al. 1983), but these are short term and often contradictory (Richards et al. 1997). However, without doing a multitude of physical and chemical manipulations, relationships linking land use and macroinvertebrate assemblages can be inferred through changes of in-stream conditions brought about by land use (Townsend et al. 1983, Richards and Host 1993).

The composition and other attributes of benthic macroinvertebrate assemblages change in response to factors operating at different spatial scales. Micro-scale differences of geology and climate may affect the diversity and production of invertebrates, but other larger scale influences such as ecoregion and elevation cause other changes (Minshall et al. 1985, Wohl et al. 1995). Changes due to anthropogenic land use at different scales affect specific parts of the physicochemistry of streams (Allan et al. 1997, Johnson et al. 1997, Richards et al. 1997). For example, allochthonous sources of detritus can be long distances upstream yet still reach impacted areas of streams (Johnson and Covich 1997). Therefore, Allan and Johnson (1997) recommend using both land use and geologic characteristics at large spatial scales to attribute causal factors properly. Studying sites within the same ecoregion and with similar underlying geologic formation is important in minimizing background differences in chemistry and substrate, so differences among streams can be attributed to land use changes in the watershed (Benke et al. 1981).

Due to the complex impact of land use change, choosing sites along a gradient of watershed land use has been favored by a number of researchers (Benke et al. 1981, Townsend et al. 1983, Ellis and Schneider 1997). When working with land use changes on a gradient, it is especially important to choose sites without underlying, non-human induced changes in the stream properties by choosing sites in the same region (Benke et al. 1981). The southern Appalachian mountain region of western North Carolina has been identified as an area of relatively uniform geology and background water chemistry (Simmons and Heath 1979) and thus serves as a good place for gradient studies of human impact.

Historically, urbanization in western North Carolina is not as extensive as other areas of the country, but it does have a dramatic impact on aquatic life. Harding and Benfield (in press) showed that some streams currently in forest where the land was more agricultural 40 years ago have invertebrate assemblages similar to currently agricultural streams. While this legacy of land use impact on stream biota complicates the picture a bit, urbanization (defined here as increasing buildings and roads) has been on the rise in western North Carolina. Much of the land along streams in western North Carolina has long been used for agriculture and pasture land, but recently, many local farms are being sold to developers (SAMABC 1996). Many residential developments in the area have been constructed in the early successional forests growing on land previously used for agriculture. Many towns in the region have been spreading into the outskirts where there was once agriculture, and many streams previously in suburban areas are now in more densely developed areas. To investigate the specific land use changes associated with urbanization, it is necessary to account for historical changes in watershed land use over time.

The variety of human influences on streams in western North Carolina includes alterations at many scales ranging from acid deposition in rain water over the entire region to local effects of sedimentation and organic enrichment. Human land use activities are particularly dangerous to aquatic biodiversity in this region due to a high degree of endemism and large numbers of rare and threatened species (Morse et al. 1993). Streams in the mountain region of North Carolina are typically more diverse and support more sensitive species than streams from other areas (Penrose et al. 1982), and land use impacts usually cause dramatic changes in community structure and biodiversity (Lenat and Eagleson 1981, Lenat and Crawford 1994).

In this study, benthic macroinvertebrates were sampled in 12 streams that differed in the amount and type of urbanization. The goal of my project was to study the response of benthic macroinvertebrates to watershed urbanization and to investigate physical and chemical changes in the stream possibly related to changes in the macroinvertebrate assemblage.

Methods

Site Description

The streams studied here are located in the Little Tennessee, Tuckaseegee, Pigeon, and French Broad River drainages, all tributaries of the Tennessee River, in the southern Appalachian mountains of western North Carolina, USA (Fig. 1). This area lies in the Blue Ridge physio-graphic province and is characterized by micaceous schist and granitic gneiss geology resulting in naturally acidic water with low dissolved ions (Simmons and Heath 1979). Average rainfall in Asheville, the main urban center for most of the area, is 94 cm per year, and much of the land is covered by mixed deciduous forest.

Twelve streams were selected to represent the various degrees and types of urbanization in the area. These streams flow through a variety of land use upstream of the sampling reaches, but all sampling locations are downstream of urban areas (Table 1). Latitude, longitude, and altitude of the study sites were found using a Magellan GPS-2000 global positioning unit and were verified with USGS topographic quadrangles (1:24,000 scale). Stream discharge was calculated seasonally by measuring current velocity with a Marsh-McBirney Flo-Mate Model 2000 portable flowmeter at ten points on a transect. The depth and width at each point along a transect were multiplied by velocity to compute the contribution of each stream section, and the ten values were added to get total stream discharge. Stream gradient was measured as the change in elevation over the entire length of the stream to the sampling reach (m elevation/m stream length). These general site characteristics are shown in Table 1.

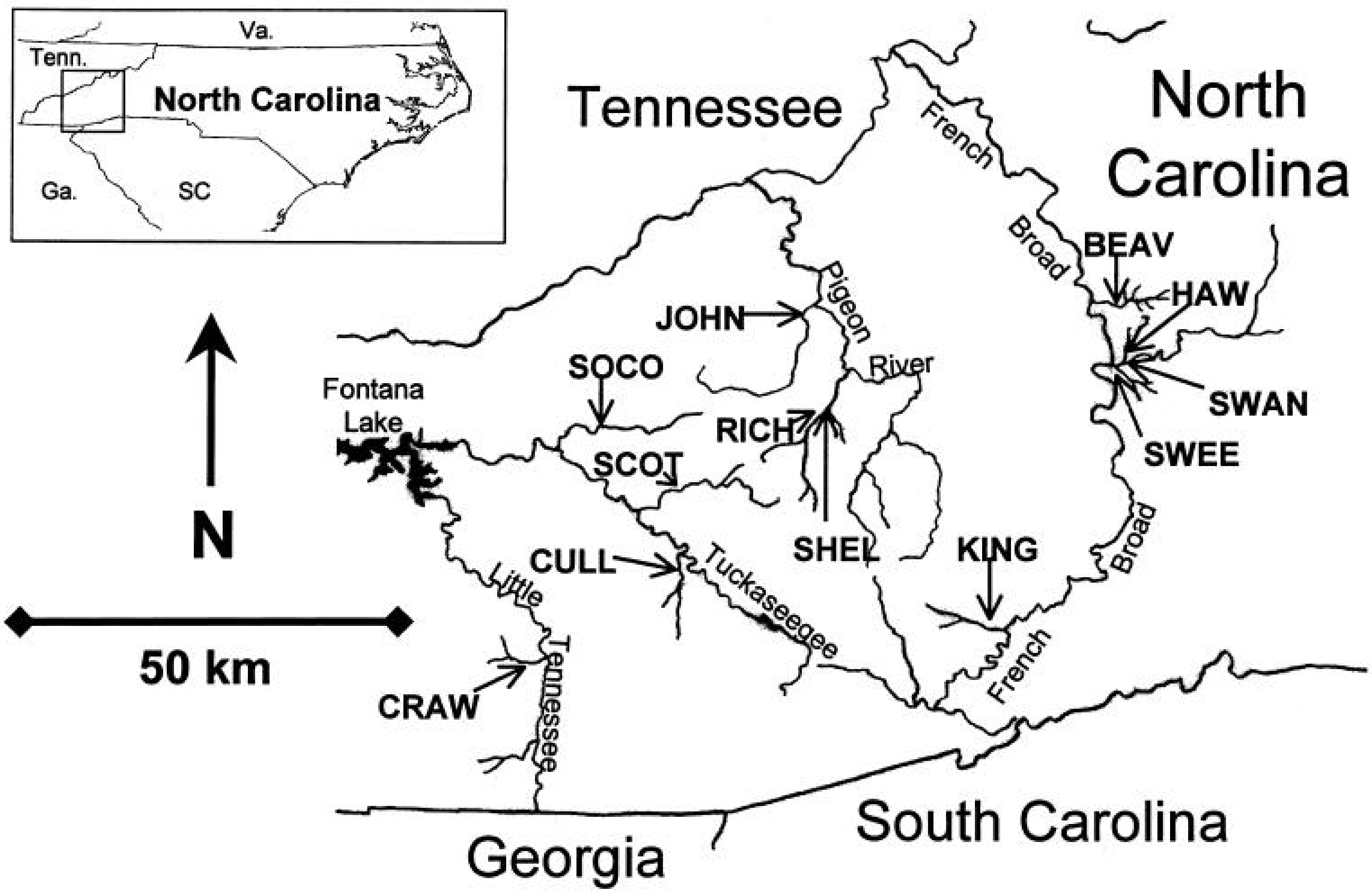

Figure 1: Site map of the study area in western North Carolina including major river drainages. Arrows indicate sampling locations.

Table 1: Location and general information of sampling sites on 12 streams in western North Carolina. Discharge is mean annual with range from four samples (October 1996, January 1997, March 1997, July 1997). See Fig. 1 for a geographic distribution of the sites.

	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
Stream Name	Beaverdam Creek	Crawford Branch	Cullowhee Creek	Haw Creek	Jonathan Creek	King Creek	Richland Creek	Scott Creek	Shelton Branch	Soco Creek	Swannanoa River	Sweeten Creek
County	Buncombe	Macon	Jackson	Buncombe	Haywood	Transylvania	Haywood	Jackson	Haywood	Jackson	Buncombe	Buncombe
City/Town	N. Asheville	Franklin	Cullowhee	Asheville	Maggie Valley	Brevard	Waynesville	Sylva	Waynesville	Cherokee	Asheville	Asheville
Latitude	35°38.25’N	35°11.00’N	35°18.37’N	35°35.20’N	35°30.87’N	35°14.39’N	35°29.27’N	35°22.57’N	35°30.07’N	35°28.27’N	35°39.70’N	35°33.98’N
Longitude	82°32.92’W	83°22.54’W	83°11.15’W	82°31.18’W	83°04.11’W	82°43.77’W	82°59.03’W	83°13.54’W	82°58.75’W	83°18.71’W	82°29.87’W	82°32.29’W
Elevation (m)	644	628	631	619	836	647	799	616	802	610	607	604
Watershed Area (ha)	1927.2	598.6	5895.7	1137.9	8688.1	974.6	11593.2	14377.1	511.4	9819.8	32125.1	1400.9
Discharge (m^3/sec)	0.18 (0.07-0.31)	0.13 (0.08-0.19)	1.47 (0.87-1.91)	0.15 (0.05-0.36)	3.52 (1.19-7.97)	0.30 (0.18-0.52)	2.84 (1.31-4.62)	4.20 (2.11-7.01)	0.08 (0.07-0.12)	3.32 (1.3-7.02)	4.21 (1.61-6.14)	0.17 (0.12-0.24)
Gradient (m/m)	0.058	0.019	0.044	0.065	0.048	0.030	0.050	0.037	0.020	0.055	0.009	0.036

Quantifying Urbanization as a Land Use

Urbanization was measured in the watershed upstream of each sampling location using a combination of GIS overlays, aerial photography, and field reconnaissance. GIS overlays were used to find cleared land, building density, and road density for each watershed in the 1970's and the 1990's. The data used to construct the GIS overlays were obtained from aerial photographs, satellite images, and USGS topographic quadrangles (1:24,000 scale) and include the land in the watershed upstream of the sampling reach. The percent of cleared land is the proportion of watershed area that is not forested. Building density was measured by digitizing buildings from topographic maps for original (pre-1970) and revised (post 1990) map years. Road density includes all roads in the watershed (from heavy duty to unimproved roads). These three variables were measured in 1970 and in 1990 to compare urbanization histories of the watersheds.

At a finer scale, building type and impervious surface area were measured within a 100-m wide riparian area on both sides of the stream for 2 km upstream of the sampling sites. Type of urbanization was found by driving to every building in this area and recording building type (residential, commercial, or industrial). These data are represented and discussed as the percent of industrial buildings in this area upstream of the sampling reaches. Impervious surface area was measured within the 200-m by 2 km area by overlaying a grid on the aerial photographs. Each line junction represented a random plot, and all junctions falling on buildings or paved areas constituted impervious areas. For this metric,

$$\% \text{ impervious surface} = (\text{no. impervious plots} / \text{total number of plots}) * 100,$$

and the total number of plots was greater than 100 for all sites.

In-Stream Physical and Chemical Characteristics

Water chemical measurements were taken seasonally from October 1996 through July 1997. Field chemistry included measurements of temperature, pH, dissolved oxygen, alkalinity, hardness, and conductivity. Alkalinity, hardness, and pH were measured using a Hach field kit. Dissolved oxygen and conductivity were measured using YSI field probes. More detailed chemical analyses were done at Coweeta Hydrologic Laboratory. Nutrients (NO_3-N, NH_4-N, and O-PO_4), sulfate (SO_4), and chloride were measured using ion chromatography. Various cations (Ca, Mg, Na, and K) were measured by atomic absorption spectrophotometry. Tables 3 and 4 show means and ranges for the variety of measured water chemistry.

Physical measurements of stream characteristics were made either once during the study (Pfankuch stability index and substrate size and heterogeneity) or seasonally (total suspended solids and inorganic epilithic sediment). I calculated the Pfankuch index (Pfankuch 1975) which categorizes physical stream stability by investigating the geomorphic properties of the stream banks and substrate. In-stream habitat was calculated by categorizing 70 random individual substrate particles in the 50m sampling reach using a modified Wentworth classification (Cummins 1962). A substrate index using the sum of weighted substrate percentages was then calculated (Jowett and Richardson 1990).

Total suspended solids (TSS) were collected from three 1-L grab samples taken at mid-channel. Samples were filtered onto pre-ashed and weighed Whatman glass fiber filters. Filters were then dried at 50°C overnight, weighed, ashed at 500°C for 1 hour, wetted, re-dried, and re-weighed to measure the organic fraction of suspended solid (Gurtz et al. 1980).

Inorganic epilithic sediment (IES) is a measure of the sediment deposited on the stream bed (epilithon). IES was measured for twenty rocks in each stream by carefully placing each rock into a submerged bag to avoid losing sediment. Rocks were then scrubbed in water with a toothbrush and measured. The scrub water, containing the sediment from the rock surface, was diluted up to 1-L, stirred vigorously to create a homogeneous sediment suspension, and subsampled by removing 100-ml with a syringe. These subsamples were filtered onto pre-ashed and weighed glass fiber filters. Filters were then dried at 50°C overnight, weighed, ashed at 500°C for 1 hour, wetted, dried, and re-weighed to measure the inorganic fraction of epilithic solids. The scrubbed rocks were wrapped in aluminum foil which was then weighed to find rock surface area using a weight-area conversion. The amount of inorganic sediment in each subsample was multiplied by a factor of ten and divided by the corresponding rock surface area to find the inorganic material per unit surface area of stream bottom.

Along with water chemistry and stream physical properties, benthic organic matter (BOM) standing stock was measured. BOM was collected along with the macroinvertebrate samples (as in Egglishaw 1964). After removing the macroinvertebrates from samples, the remaining material was dried at 50°C for 1 week, ground in a mill, and weighed. Ground material was then ashed at 500°C until all organic matter was burned and re-weighed to determine total ash free dry mass (g AFDM) of organic matter in each sample.

Benthic Macroinvertebrate Sampling and Metrics

Macroinvertebrate samples were taken in October 1996 and March 1997. Macroinvertebrates were collected from the streams by a quantitative kick-net procedure. This technique uses a 44.7 x 89.5 cm (0.4 m^2) rectangular frame to mark the sampling area and a driftnet (353-μm mesh) placed at the downstream end of the frame to catch the macroinvertebrates (see Appendix 3 for visual representation of the sampling apparatus). The area within the frame was disturbed to a depth of 10 cm for three minutes, and all large rocks were hand-wiped to remove attached and stubborn animals. The animals were washed into a bottle at the bottom of the net and preserved in formalin. In the lab, samples were washed in a 500-μm sieve, and macroinvertebrates were removed and preserved in 70% ethanol for identification.

Samples with a large amount of sediment, organic matter, or animals were subsampled using a sample splitter. The sample splitter was constructed from a round 15-cm wide, 7.5-cm deep plastic tub divided in half with a piece of Plexiglas (Appendix 3). Samples requiring splitting were poured into the dish, diluted to flow over the Plexiglas, and mixed to spread them homogeneously between each side. One side was emptied into a 500-μm sieve and preserved in 70% ethanol. Macroinvertebrates were removed from the remaining half-sample and preserved in 70% ethanol for identification.

Macroinvertebrates were identified to the lowest possible taxonomic level using standard keys (Appendix 1). A complete taxa list is in Appendix 2. On each date, five samples were taken, and the data from each were pooled for analysis of the complete assemblage data set. Using the pooled macroinvertebrate data, a variety of diversity and tolerance metrics were calculated. Macroinvertebrate density (no./m^2) was calculated by dividing total number of animals collected by total area sampled at each site. Taxa richness is defined as the total number of taxa found at each site. Diversity was also measured with indices that use population numbers and the distribution of animals among the taxa present. I calculated Margalef's diversity (Clifford and Stevenson 1975, D_{Mg}) and Simpson's evenness index (Simpson 1949, 1/D). In order to characterize the macroinvertebrate assemblage based on pollution-tolerant organisms, I calculated the

North Carolina Biotic Index (Lenat 1993; NCBI), which uses tolerance values and the proportional abundance of taxa in the streams. Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa richness were also counted and used as a tolerance metric as members of these aquatic insect orders are typically pollution sensitive. I also calculated the Multimetric Aggregated Index for Streams (Smith and Voshell 1997; MAIS), which combines rated scores for several diversity and tolerance metrics using family-level identification. Finally, I calculated the percent of the invertebrate assemblage in EPT orders and in the five most abundant taxa.

Statistical Analyses

For the different data sets (land use, chemistry, and macroinvertebrates), I ran correlations of variables with others in the same group to identify and eliminate variables giving repetitive information. This step was taken primarily to reduce the number of individual regressions while maintaining the information of greatest importance.

To look for the impact of urbanization on the benthic assemblage, I tested invertebrate metrics (dependent variables) against watershed land use (independent variables) using least-squares linear regression. Regression analysis was also used to test the response of stream physical and chemical characteristics to changing watershed urbanization. Regression analyses of macroinvertebrate data against physicochemistry were run to look for relationships among the stream responses. For the regression analyses, the sample size of data points was 12 making 0.50 the minimum acceptable limit for r^2 with statistical power of 0.80. Although regressions with $r^2<0.50$ can be significant ($p<0.05$) with N=12, these relationships have little predictive power making conclusions subject.

Invertebrate assemblage data were also used to create multivariate ordinations (McCune 1997). Ordination axis values were then correlated with the data matrix to determine which taxa were important in generating separation among sites. The axis values for the sites were also correlated with land use and physicochemistry.

Results

Quantification of Watershed Urbanization

Urbanization in watersheds of the study streams ranged in all categories (Table 2). Percent cleared land in 1970 ranged from a low of 2.5% in Soco to 64.4% in Craw. The cleared land in 1990 was also the lowest in Soco (3.4%), but the highest value was found in Shel (60.1%). Building density in 1970 ranged from 0.02 buildings/hectare in John to 0.85 bld/ha in Swee. In 1990, the building density increased in all watersheds to range from 0.06 bld/ha in Soco to 1.23 bld/ha in Swee. Road density in 1970 ranged from 0.008 km of road/ha in two watersheds (John and Rich) to 0.06 km/ha in Swee. Road density increased in every watershed from 1970 to 1990 except Soco where there was no change over 20 years. Soco had the lowest road density in 1990 (0.012 km/ha), and the highest road density in 1990 was in Shel.

Urbanization measured immediately upstream in the riparian areas of the study sites also ranged widely (Table 2). Five streams (Beav, Cull, Haw, John, Soco) had no industrial development in the 200-m wide, 2-km upstream area, but Swee had over 50% industry in this area of its watershed. The percent of impervious surfaces ranged from 18.1% in Beav to 57.5% in Swee.

The number of urbanization variables used in regression analyses had to be reduced from the eight in Table 2. Pearson correlation revealed many strong relationships among the land use variables (Table 3). Historical (pre-1970) and current (post-1990) land use were strongly correlated ($p<0.0001$) indicating that the same variables measured at different times contain redundant information. For example, cleared land in 1970 and 1990 were strong positive correlates ($r=0.957$, $p<0.0001$)

showing that sites with high percent of cleared land in 1970 had high cleared land in 1990. The same relationship is true for building density ($p<0.0001$), and the correlation of 1970 building density with that in 1990 was strong ($r=0.942$). Road density in 1970 was not strongly correlated with road density in 1990 ($r=0.668$); however, road density in 1990 was strongly correlated with cleared land and building density in 1990 ($r=0.957$ and 0.929, respectively; $p<0.0001$). Road density was correlated with other urbanization variables which led me to use percent cleared land and building density to represent the current degree of urbanization in the study watersheds.

Table 2: Urbanization in the watersheds of 12 study streams in western North Carolina. Historic building density is pre-1970 and current building density is post-1980. Percent industry and percent impervious surface are measured within a 200-m wide, 2 km upstream section of the watershed.

Year	Metric	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
1970	**% Cleared**	12.5	64.4	13.7	42.9	7.2	12.3	16.0	9.5	58.6	2.5	20.5	55.4
	Building Density (no./ha)	0.28	0.44	0.03	0.62	0.02	0.30	0.10	0.11	0.53	0.04	0.22	0.85
	Road Density (km/ha)	0.026	0.056	0.010	0.042	0.008	0.015	0.008	0.014	0.014	0.012	0.021	0.060
1990	**% Cleared**	12.3	47.5	6.5	29.6	9.8	11.4	19.4	7.9	60.1	3.4	17.5	58.2
	Building Density (no./ha)	0.51	1.16	0.13	1.23	0.11	0.41	0.29	0.19	1.12	0.06	0.4	1.23
	Road Density (km/ha)	0.040	0.071	0.020	0.054	0.017	0.017	0.025	0.019	0.087	0.012	0.030	0.069
	% Industry	0.0	4.7	0.0	0.0	0.0	9.1	6.1	7.8	1.4	0.0	28.0	50.5
	% Impervious Surface	18.1	46.7	33.0	33.9	23.8	28.2	43.7	48.5	49.5	23.8	64.3	57.5

Table 3: Pearson correlation matrix of land use data. Values are correlation coefficients (r) with significance values indicated (**p<0.0001, *p<0.001, values with no * p>0.001).

	70 Cleared	**70 Bld. Dens.**	**70 Rd. Dens.**	**90 Cleared**	**90 Bld. Dens.**	**90 Rd. Dens.**	**Industry**	**Impervious**
70 Cleared	--							
70 Bld. Dens.	0.839 *	--						
70 Rd. Dens.	0.757	0.817	--					
90 Cleared	0.957 **	0.851 *	0.667	--				
90 Bld. Dens.	0.944 **	0.942 **	0.814	0.900 **	--			
90 Rd. Dens.	0.956 **	0.834 *	0.668	0.957 **	0.929 **	--		
Industry	0.321	0.544	0.522	0.429	0.326	0.256	--	
Impervious	0.528	0.410	0.347	0.561	0.399	0.444	0.681	--

Chemical Characteristics of Study Sites

Temperature and general water chemistry are summarized in Table 4. Temperature fluctuated seasonally from a low of 6.5°C (Haw in January) to a high of 24°C (Beav and Craw in July), but mean annual temperatures were similar in the 12 streams with a range of only 2.5°C (12.3°C in King to 14.8°C in Scot). The measured pH values were also consistent among the sites, all close to neutral. Dissolved oxygen values varied slightly among sites, but oxygen concentrations were at or above saturation for respective water temperatures on all sampling dates. Alkalinity, hardness, and conductivity varied considerably both seasonally and among site means.

Specific dissolved ions at the study sites also showed a wide range of values (Table 5). The highest annual mean concentration of nitrogen as nitrate and ammonium were found in Swee (3.15 ppm NO_3-N, 0.143 ppm NH_4-N), and the lowest values of nitrogen were found in King (0.08 ppm NO_3-N, 0.003 ppm NH_4-N). Ortho-phosphate ranged from 0.001 ppm (detection limit) in Craw and Cull to 0.035 ppm in Beav and Swan, but seasonal values ranged greatly. Swee had the highest concentrations of every other measured chemical (SO_4, Cl^-, Ca, Mg, Na, and K). The lowest annual mean concentrations of SO_4, Ca, Na, and K were found in King, but Cull had the lowest Cl, and Soco was lowest in Mg. Seasonal variability was also found in these chemicals, but most ranges were fairly small.

Correlations using chemical data were used to eliminate variables giving redundant information about stream chemical conditions (Table 6). Dissolved oxygen was not highly correlated with any other chemical ($p>0.001$) making it non-redundant and thus useful in future analyses. Alkalinity was highly correlated with a number of water chemistry variables. Calcium and magnesium were particularly strong correlates with alkalinity ($r = 0.965$ and 0.990, respectively; $p<0.0001$). Other measurements of dissolved ions (such as conductivity and chloride) were also highly correlated with alkalinity ($r = 0.975$ and 0.899, respectively; $p<0.0001$). Alkalinity was used in regression analyses because it was strongly correlated with a large number of chemicals. Nutrients in the water were highly variable (Table 5); however, a significant correlation was found between nitrate and ammonium (Table 6, $p<0.0001$). Ammonium was selected for regression analyses due to lack of relationships with other variables and its importance as a nitrogen source in stream processes. The list of chemical variables for analysis was reduced to dissolved oxygen, alkalinity, and ammonium.

Table 4: Physical and chemical characteristics of 12 streams in western North Carolina. Values are means with ranges of four samples (October 1996, January 1997, March 1997, July 1997).

	Beav	**Craw**	**Cull**	**Haw**	**John**	**King**	**Rich**	**Scot**	**Shel**	**Soco**	**Swan**	**Swee**
Temperature (°C)	14.2 (7-24)	14.1 (10.4-24)	12.9 (9.6-21)	14.6 (6.5-21.5)	12.7 (9-17)	12.3 (7-18)	13 (8-18.5)	14.8 (9-21)	14.2 (9-21)	13.9 (9-20)	13.8 (10-21)	14.2 (11-22.5)
pH	7.1 (7-7.3)	6.9 (6.8-7)	6.9 (6.9-7)	7.1 (7-7.1)	6.7 (6.5-6.7)	6.9 (6.7-7)	7.1 (7-7.3)	7.1 (6.9-7.3)	7.3 (7.1-7.5)	6.9 (6.7-7)	7.1 (6.9-7.5)	7.1 (6.9-7.2)
D. O. (mg/l)	9.4 (8.5-10.6)	9.3 (8.6-9.8)	9.8 (9-10.8)	9.3 (8.3-10.1)	10.7 (10-12.2)	10.1 (9.2-10.8)	10.2 (9.4-11.5)	10.9 (9.8-13.2)	9.3 (9.2-9.5)	10.3 (10-10.6)	9.8 (8.8-10)	9.3 (8.3-10)
Alkalinity (mg/l)	26.5 (10.2-34.2)	20.5 (6.9-27.4)	15.4 (6.9-20.5)	27.4 (17.1-41.1)	9.4 (6.9-13.7)	10.3 (6.9-13.7)	16.3 (10.3-20.5)	14.6 (10.3-20.5)	29.1 (13.7-41.1)	8.6 (6.9-13.7)	18.8 (6.9-27.4)	34.2 (13.7-61.6)
Hardness (mg/l)	44.5 (34.2-68.5)	34.2 (17.1-51.4)	30.0 (17.1-51.4)	59.1 (34.2-102.7)	25.7 (17.1-51.4)	23.5 (8.6-51.4)	27.8 (17.1-51.4)	25.7 (17.1-34.2)	85.6 (51.4-102.7)	21.4 (17.1-34.2)	25.7 (17.1-51.4)	72.8 (34.2-119.8)
Conductivity (μmho)	67.2 (50-79)	45.0 (40-52)	30.8 (25-38)	73.0 (55-84)	26.3 (23-30)	18.0 (15-20)	38.3 (30-45)	31.8 (25-40)	87.1 (78-92)	25.7 (20.1-29)	50.6 (38-70)	95.0 (88-102)

Table 5: Water chemistry of 12 streams in western North Carolina. Values are means with ranges of four samples (October 1996, January 1997, March 1997, July 1997). Units for values are ppm.

	Beav	**Craw**	**Cull**	**Haw**	**John**	**King**	**Rich**	**Scot**	**Shel**	**Soco**	**Swan**	**Swee**
NO_3-N	0.43 (0.33-0.51)	0.40 (0.35-0.45)	0.11 (0.07-0.14)	0.48 (0.37-0.58)	0.26 (0.18-0.31)	0.08 (0.04-0.09)	0.39 (0.36-0.43)	0.16 (0.09-0.2)	0.89 (0.58-1.08)	0.10 (0.04-0.14)	0.26 (0.21-0.32)	3.15 (0.66-10.45)
NH_4-N	0.011 (0.002-0.022)	0.06 (0.038-0.089)	0.010 (0.002-0.025)	0.025 (0.004-0.05)	0.003 (0.001-0.006)	0.003 (0.001-0.006)	0.007 (0.002-0.014)	0.006 (0.002-0.009)	0.015 (0.003-0.036)	0.006 (0.002-0.008)	0.017 (0.004-0.038)	0.143 (0.004-0.302)
O-PO_4	0.035 (0.001-0.105)	0.001 (0.001-0.001)	0.001 (0.001-0.003)	0.014 (0.001-0.022)	0.009 (0.005-0.011)	0.006 (0.001-0.012)	0.012 (0.001-0.022)	0.007 (0.001-0.013)	0.011 (0.001-0.026)	0.011 (0.001-0.019)	0.035 (0.001-0.126)	0.002 (0.001-0.004)
SO_4	5.40 (4.04-6.76)	1.55 (1.34-1.68)	1.41 (1.08-1.65)	4.67 (3.64-5.77)	1.42 (1.29-1.54)	0.90 (0.82-0.98)	3.59 (2.84-4.76)	1.56 (1.41-1.63)	3.15 (2.17-3.95)	1.39 (1.06-1.61)	3.69 (3.23-4.31)	6.12 (5.45-6.66)
Cl	4.23 (3.62-4.64)	2.24 (2.01-2.52)	1.22 (1.07-1.46)	6.19 (4.94-7.65)	1.85 (1.53-2.46)	1.37 (0.95-2.51)	1.72 (1.51-2.02)	1.78 (1.43-2.56)	4.37 (3.77-4.78)	1.72 (1.43-2.13)	3.28 (2.44-4.51)	7.58 (6.23-9.54)
Ca	5.13 (4.35-6.66)	3.28 (2.85-4.06)	2.77 (2.27-3.34)	5.97 (5.39-6.97)	1.64 (1.36-2.14)	1.23 (1.08-1.54)	3.15 (2.56-4.2)	2.50 (2.12-3.15)	7.70 (7.36-8.18)	1.34 (1.08-1.69)	4.11 (2.69-5.61)	9.68 (7.4-14.73)
Mg	2.29 (2.05-2.76)	1.75 (1.61-2.02)	0.85 (0.77-1.01)	2.74 (2.46-2.94)	0.44 (0.4-0.48)	0.45 (0.42-0.49)	1.08 (0.94-1.32)	1.03 (0.91-1.2)	3.00 (2.77-3.2)	0.35 (0.32-0.41)	1.41 (1.14-2.03)	3.81 (2.53-7.15)
Na	4.37 (3.98-4.69)	2.40 (2.17-2.7)	1.72 (1.58-1.94)	4.08 (3.76-4.38)	1.79 (1.62-2.07)	1.18 (1.06-1.26)	2.05 (1.78-2.53)	1.78 (1.61-2.03)	4.07 (3.77-4.32)	1.81 (1.55-2.15)	2.68 (2.19-3.63)	4.92 (3.64-6.48)
K	1.94 (1.63-2.26)	1.03 (0.91-1.25)	0.82 (0.71-0.98)	1.87 (1.68-2.03)	0.63 (0.55-0.75)	0.51 (0.45-0.56)	0.88 (0.73-1.12)	0.84 (0.71-1.1)	1.51 (1.42-1.61)	0.70 (0.59-0.89)	1.18 (1.0-1.67)	1.97 (1.47-2.33)

Table 6: Pearson correlation matrix of chemical data. Values are correlation coefficients (r) with significance values indicated (**p<0.0001, *p<0.001, values with no * p>0.001).

	D.O.	**Alk.**	**Hard.**	**Cond.**	**NO_3-N**	**NH_4-N**	**O-PO_4**	**SO_4**	**Cl**	**Ca**	**Mg**	**Na**	**K**
D.O.	--												
Alk.	-0.813	--											
Hard.	-0.703	0.886 *	--										
Cond.	-0.764	0.975 **	0.927 **	--									
NO_3-N	-0.456	0.723	0.682	0.740	--								
NH_4-N	-0.514	0.654	0.521	0.622	0.921 **	--							
O-PO_4	-0.133	0.149	-0.057	0.187	-0.216	-0.310	--						
SO_4	-0.605	0.844 *	0.632	0.842 *	0.668	0.543	0.450	--					
Cl	-0.675	0.899 **	0.818	0.924 **	0.789	0.700	0.161	0.870 *	--				
Ca	-0.725	0.965 **	0.923 **	0.983 **	0.826 *	0.701	0.081	0.827 *	0.919 **	--			
Mg	-0.781	0.990 **	0.915 **	0.983 **	0.776	0.700	0.079	0.821	0.929 **	0.979 **	--		
Na	-0.751	0.951 **	0.858 *	0.971 **	0.699	0.586	0.300	0.899 **	0.937 **	0.933 **	0.951 **	--	
K	-0.757	0.942 **	0.783	0.930 **	0.621	0.541	0.355	0.917 **	0.920 **	0.886 *	0.925 **	0.980 **	--

Physical Characteristics of Study Sites

The physical and habitat characteristics varied in all categories (Table 7). Physical measurement of stream channel stability was lowest in John (70) and highest in Shel. The substrate index was highest in John and lowest in Shel indicating the relationship of the Pfankuch index to substrate particle size distribution (Table 8, $r=-0.827$, $p<0.001$). Total suspended solids varied more among seasons at each site than it did between sites, and TSS was not correlated with any other physical stream trait (Table 8). Inorganic sediment was very low in most streams (for example 7.4 and 7.9 g/m^2 in John and Soco, respectively) when compared to Craw (124.3 g/m^2); however, the amount of sediment on the stream bottom was not correlated with other physical variables. Benthic organic matter was highest in John with over 30 g $AFDM/m^2$ and lowest in Craw with only 3.91 g $AFDM/m^2$. These two sites showed the opposite extremes for inorganic sediment and organic matter, but the relationship of all sites with these two physical measurements was not significant. From the significant correlations, I chose the substrate size index, inorganic sediment, and benthic organic matter to represent the physical aspects of in-stream habitat for regressions with urbanization and macroinvertebrate data.

Table 7: Physical habitat characteristics for 12 study streams in western North Carolina. Values are means with ranges of four samples (October 1996, January 1997, March 1997, July 1997).

	Beav	**Craw**	**Cull**	**Haw**	**John**	**King**	**Rich**	**Scot**	**Shel**	**Soco**	**Swan**	**Swee**
Stability Index[a]	99	121	96	107	70	111	101	106	130	87	110	113
Substrate Index[b]	4.98	5.19	5.02	4.93	5.97	5.10	5.31	5.25	4.39	5.84	5.27	5.02
TSS (mg/l)	5.68 (0.93-9.95)	7.25 (3.84-11.14)	9.17 (3.32-14.17)	5.68 (1.61-11.15)	7.00 (2.02-12.94)	3.07 (0.91-5.26)	10.48 (3.19-18.15)	10.24 (4.46-15.49)	4.95 (1.99-10.48)	6.57 (1.92-11.68)	11.29 (1.52-21.17)	6.22 (2.29-8.99)
IES (g/m^2)	32.3 (11.0-45.2)	124.3 (72.5-181.7)	14.1 (1.7-22.6)	53.1 (45.9-63.3)	7.4 (2.1-15.1)	14.7 (10.1-23.7)	14.0 (9.1-21.3)	26.8 (14.7-33.7)	39.6 (25.9-62.2)	13.5 (2.3-30.8)	7.9 (1.9-14.3)	40.3 (30.6-52.2)
BOM (g AFDM/m^2)	7.90	3.91	13.50	10.92	30.62	9.22	18.37	25.73	5.62	25.25	7.46	7.62

[a]Pfankuch 1975.
[b]Jowett and Richardson 1990.

Table 8: Pearson correlation matrix of in-stream physical habitat characteristics. Values are correlation coefficients (r) with significance values indicated (**p<0.001, *p<0.01, values with no *p<0.01).

	Stability	**Substrate**	**TSS**	**IES**	**BOM**
Stability	--				
Substrate	-0.827**	--			
TSS	-0.163	0.270	--		
IES	0.533	-0.299	-0.195	--	
BOM	-0.804*	0.771*	0.285	-0.506	--

Macroinvertebrate Assemblage of Study Sites

Table 9 shows the macroinvertebrate metric values calculated for each stream. The lowest density (890 /m^2) of benthic macroinvertebrates was found in Rich while the highest was found in Swee (4726 /m^2). Species richness in the streams ranged from 40 in Craw to 118 in Soco, and diversity (D_{Mg}) also had a wide range (4.46 to 14.24). Swee had the lowest values of Simpson's evenness (2.01), EPT taxa (12), and MAIS (7) and had the highest values of NCBI (8.42) and the percent of five dominant taxa (98.1%). Only Craw was lower than Swee in the percent of EPT in the macroinvertebrate assemblage (1.1% vs. 1.7%), but this range is small considering the highest value of 74.1% EPT found in John. John had the extreme high values for EPT taxa (64 shared with Soco) and MAIS (17 shared with Scot) and the lowest value of the NCBI. Soco had the highest evenness score (22.3) and the lowest percent of the five most dominant taxa.

Although the data show wide ranges for all measured macroinvertebrate metrics, much of the information is redundant among the different metrics. Macroinvertebrate metrics calculated for each stream can be broken into four groups: density, diversity, evenness or distribution, and tolerance. I correlated the metrics within each of the four groups to reduce the number of variables while preserving the most information about the macroinvertebrate assemblage (Table 10). The only measure dealing directly with abundance of organisms is invertebrate density, and it was not strongly related to any other metric (Table 10). Diversity measurements were strongly correlated ($r=0.995$, $p<0.0001$) because species number (richness) drives D_{Mg}. Richness was chosen to represent diversity of macroinvertebrates. Simpson's evenness index and % 5 dominant taxa use the distribution of organisms among the represented taxa and thus were highly correlated ($r=-0.945$, $p<0.0001$). In this case, Simpson's index was chosen because it includes relative abundance of all taxa rather than only the few most common. The NCBI, EPT taxa, and % EPT all contain information about tolerance, and these were highly correlated with each other (see Table 10 for r-values, $p<0.0001$). The NCBI was chosen because it was developed using tolerance values for specific taxa from North Carolina. The NCBI also contains the most taxonomic information about the entire macroinvertebrate assemblage, not just that of a few orders considered to be generally sensitive to pollution. MAIS scores for the streams were very highly correlated with diversity, evenness, and tolerance measurements ($p<0.0001$). Multimetric approaches, like the MAIS, are popular in biomonitoring as many only require family-level identification and are thus less labor intensive, yet they retain their sensitivity to detect impacted systems (Resh et al. 1995, Karr and Chu 1997). The MAIS, although a useful multimetric approach for studying impacted systems, was not used in further analyses based on lack of taxonomic resolution.

Table 9: Macroinvertebrate diversity and tolerance metrics calculated from 10 quantitative kick-net samples (5 in October, 5 in March) of the 12 study streams in western North Carolina.

	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
Density ($no./m^2$)	1611	1724	1807	2189	1293	1699	890	1167	2130	1135	3702	4726
Taxa Richness	93	40	105	69	112	87	74	97	47	118	65	44
D_{Mg}[a]	10.74	4.52	11.98	7.66	13.30	10.10	9.15	11.61	5.20	14.24	6.81	4.46
Simpson[b]	6.00	2.61	11.53	3.16	17.88	5.93	5.69	18.20	2.86	22.3	3.49	2.01
NCBI[c]	5.29	8.30	4.07	7.16	2.55	5.2	6.23	3.61	8.05	3.80	6.64	8.42
EPT Taxa	43	12	50	28	64	46	29	49	16	64	25	10
MAIS[d]	11	7	16	10	17	12	13	17	8	16	9	7
% EPT	36.1	1.1	41.0	18.1	74.1	35.9	28.8	68.1	3.6	59.4	12.3	1.7
% 5 Dominant	68.2	96.3	57.4	87.4	47.2	75.3	66.4	42.3	94.8	38.1	84.8	98.1

[a]Margalef's diversity, Clifford and Stephenson 1975.
[b]Simpson's Evenness Index, Simpson 1949.
[c]North Carolina Biotic Index, Lenat 1993.
[d]Multimetric Aggregated Index for Streams, Smith and Voshell 1997.

Table 10: Pearson correlation matrix of invertebrate data. Values are correlation coefficients (r) with significance values indicated (**p<0.0001, *p<0.001, values with no * p>0.001).

	Density	**Richness**	**D_{Mg}**	**Simpson**	**NCBI**	**EPT Taxa**	**MAIS**	**% EPT**	**% 5 Domi.**
Density	--								
Richness	-0.583	--							
D_{Mg}	-0.644	0.995 **	--						
Simpson	-0.549	0.859 *	0.876 *	--					
NCBI	0.588	-0.965 **	-0.964 **	-0.882 *	--				
EPT Taxa	-0.607	0.987 **	0.986 **	0.879 *	-0.972 **	--			
MAIS	-0.649	0.928 **	0.941 **	0.899 **	-0.958 **	0.918 **	--		
% EPT	-0.626	0.929 **	0.942 **	0.917 **	-0.975 **	0.946 **	0.955 **	--	
% 5 Domi.	0.650	-0.937 **	-0.956 **	-0.945 **	0.947 **	-0.926 **	-0.967 **	-0.959 **	--

Macroinvertebrate Response to Urbanization

Regressions of invertebrate metrics against land use variables from 1970 and 1990 were compared to show the redundancy of the predictive relationships (Fig. 2, Table 11). Invertebrate metrics related more strongly to the percent of cleared land in 1970 than to the percent cleared in 1990. However, building density and road density in 1990 were better predictors of macroinvertebrate metrics than building density and road density in 1970 (Table 11). The percent of cleared land represented both agricultural and urban areas, so cleared land might not accurately describe historical urbanization in a watershed. Therefore, the regressions of 1970 and 1990 building and road densities with macroinvertebrate metrics showed the redundancy of historical land use measurements in this case. Based on this analysis and the correlation of land use variables (Table 3), the land use variables used in further analyses were reduced to the 1990's measurements of percent cleared land, building density, percent industry, and percent impervious surface.

The degree of watershed disturbance (indicated by percent cleared land and building density) had a significant relationship with stream biodiversity (Figs. 3,4). Invertebrate density was not related to watershed urbanization (Figs. 3a, 4a). As the percent cleared land and building density increased, taxonomic richness (Figs. 3b, 4b; $p<0.001$) and Simpson's index (Figs. 3c, 4c; $p<0.001$) decreased. High NCBI values were found in streams with high degree of urbanization (Figs. 3d, 4d; $p<0.001$), and NCBI corresponded to high abundance of pollution-tolerant taxa in the benthic macroinvertebrate assemblage.

Urbanization in the 200-m wide, 2-km long areas upstream of sampling reaches had significant trends with some invertebrate metrics. Invertebrate density was significantly related to the percent of industry (Fig. 5a, $p<0.001$), but this relationship was driven by two extreme sites. Neither invertebrate diversity nor the NCBI was significantly related to percent industry (Figs 5b-d). From these relationships, where percent industry in watersheds was high, invertebrate density was also high but without similarly high diversity. Invertebrate density was also related to the percent impervious surface in this upstream area (Fig. 6a, $p<0.05$), but the relationship was weak ($r^2<0.50$).

High impervious surface area in the study watersheds was related to low invertebrate diversity (richness, Fig. 6b, $p<0.01$ and evenness, Fig. 6c, $p<0.05$) and high NCBI values (Fig. 6d, $p<0.05$), but the power to predict Simpson's evenness and the NCBI from impervious surface area was not very strong ($r^2<0.50$).

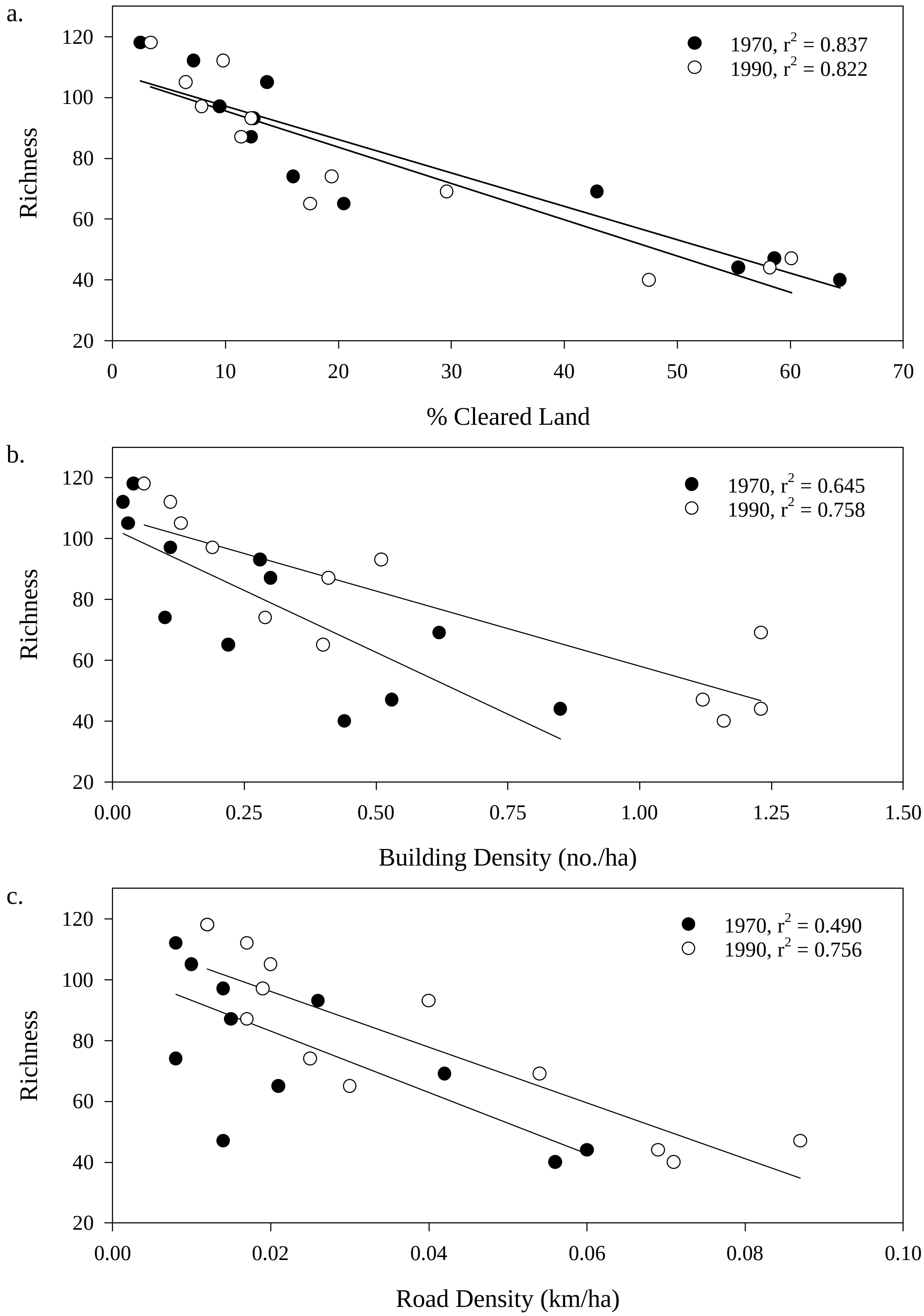

Figure 2a-c: Linear regressions of taxa richness with pre-1970 and post-1990 land use.

Table 11: Linear regressions relating watershed land use (historic and current) with macroinvertebrate metrics. Values are r^2 with significance indications (*p<0.05, **p<0.01, ***p<0.001).

	70 % Cleared	**90 % Cleared**	**70 Bld. Dens.**	**90 Bld. Dens.**	**70 Rd. Dens.**	**90 Rd. Dens.**
Density	0.248	0.304	0.479 *	0.279	0.362 *	0.215
Richness	0.837 ***	0.822 ***	0.645 **	0.758 ***	0.490 *	0.756 ***
Simpson	0.513 **	0.476 *	0.530 **	0.586 **	0.333 *	0.501 **
NCBI	0.803 ***	0.776 ***	0.706 ***	0.800 ***	0.521 **	0.755 ***

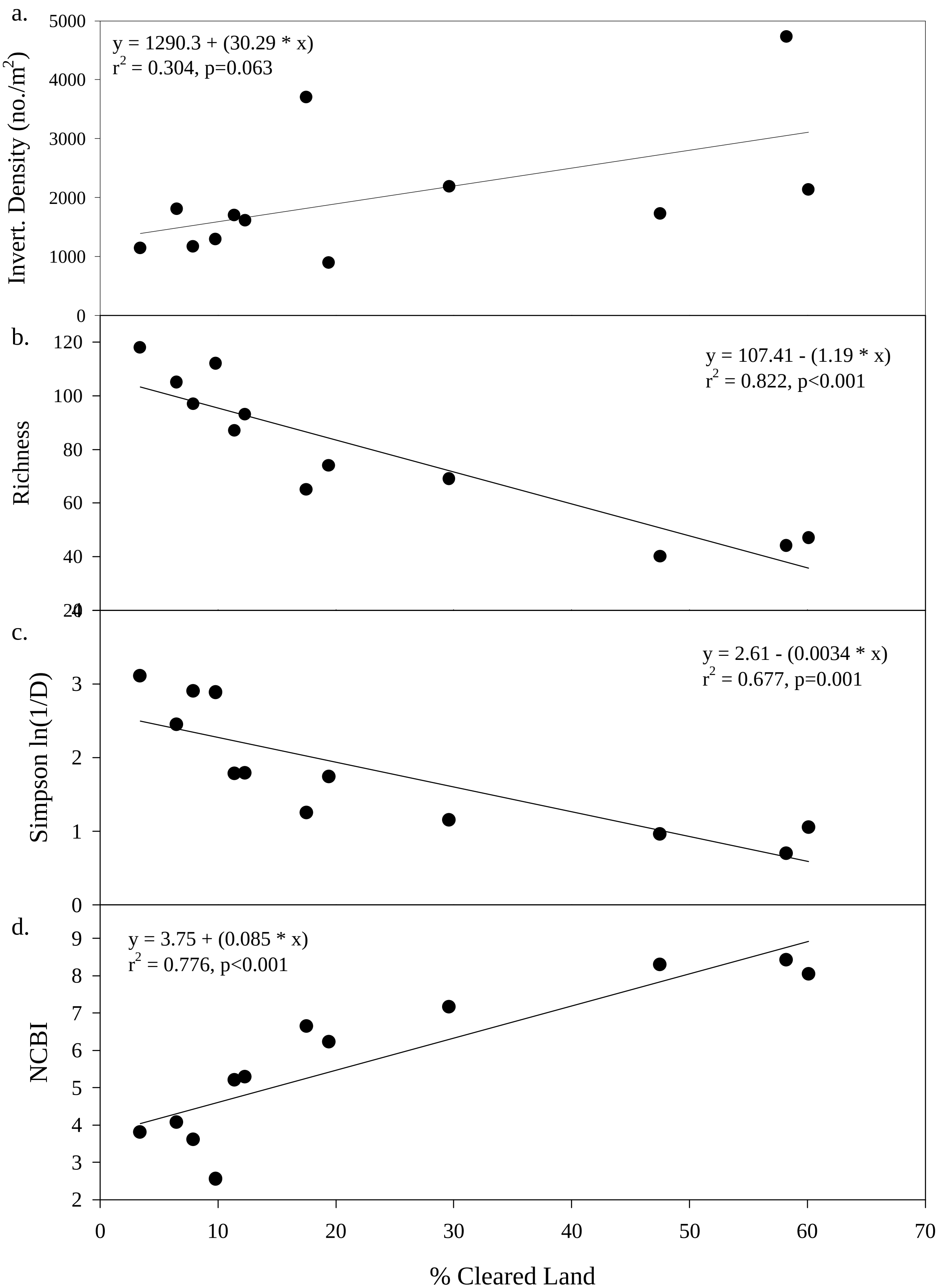

Figure 3a-d: Macroinvertebrate metrics as a function of % cleared land in the study watersheds.

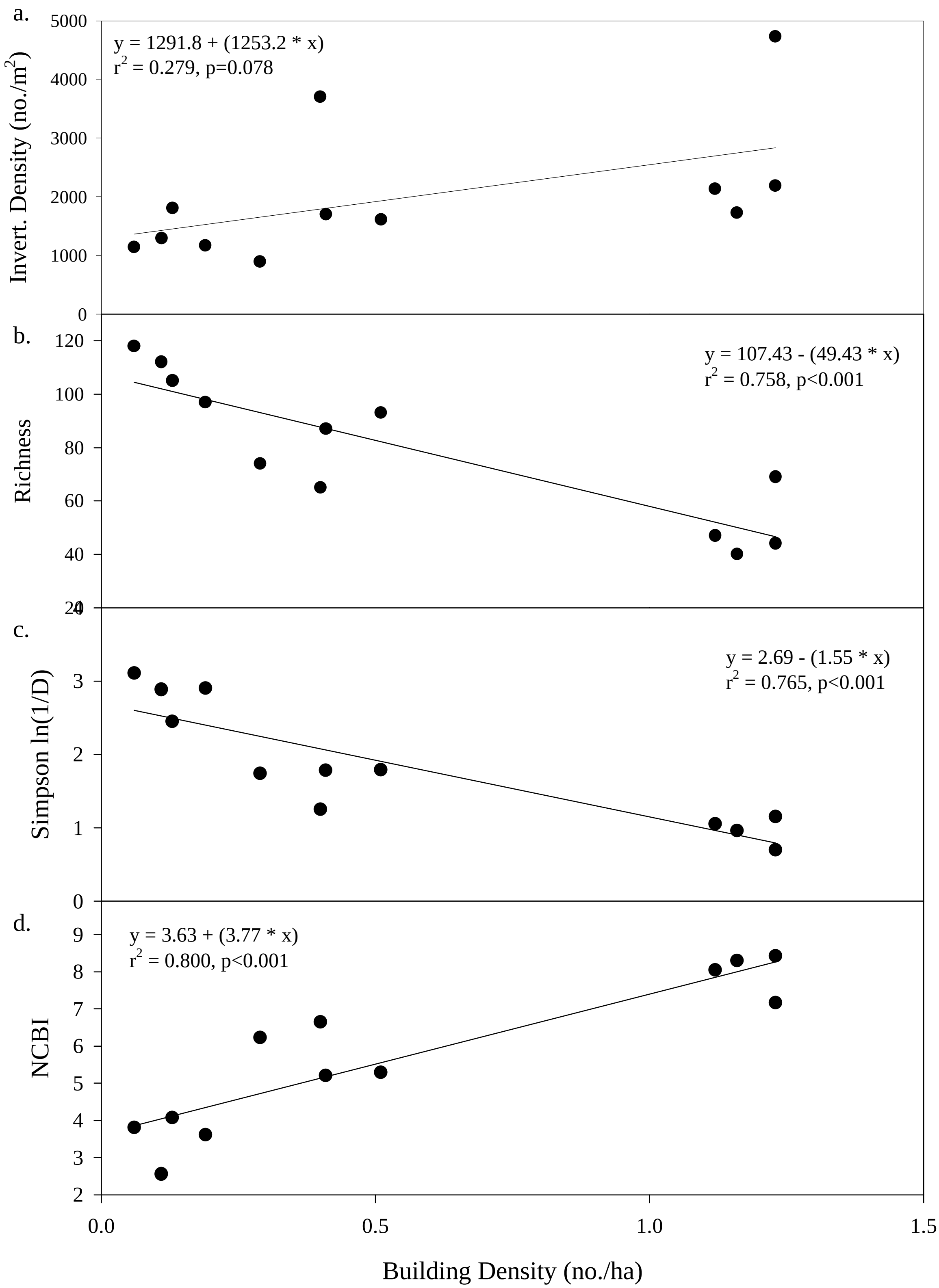

Figure 4a-d: Macroinvertebrate metrics as a function of the building density in the study watersheds.

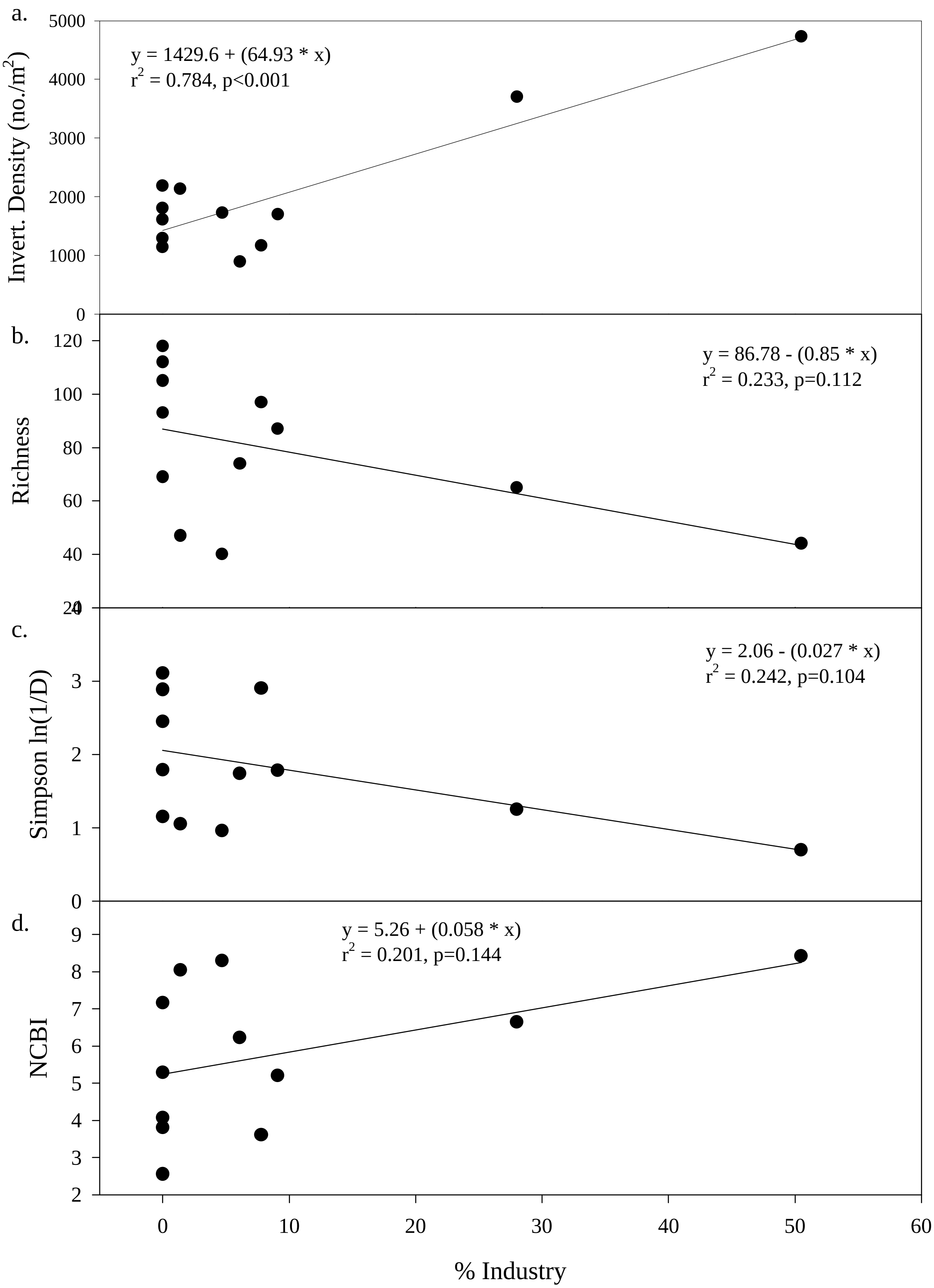

Figure 5a-d: Macroinvertebrate metrics as a function of of the amount of industrial development in a 200m wide, 2km upstream area of the study sites.

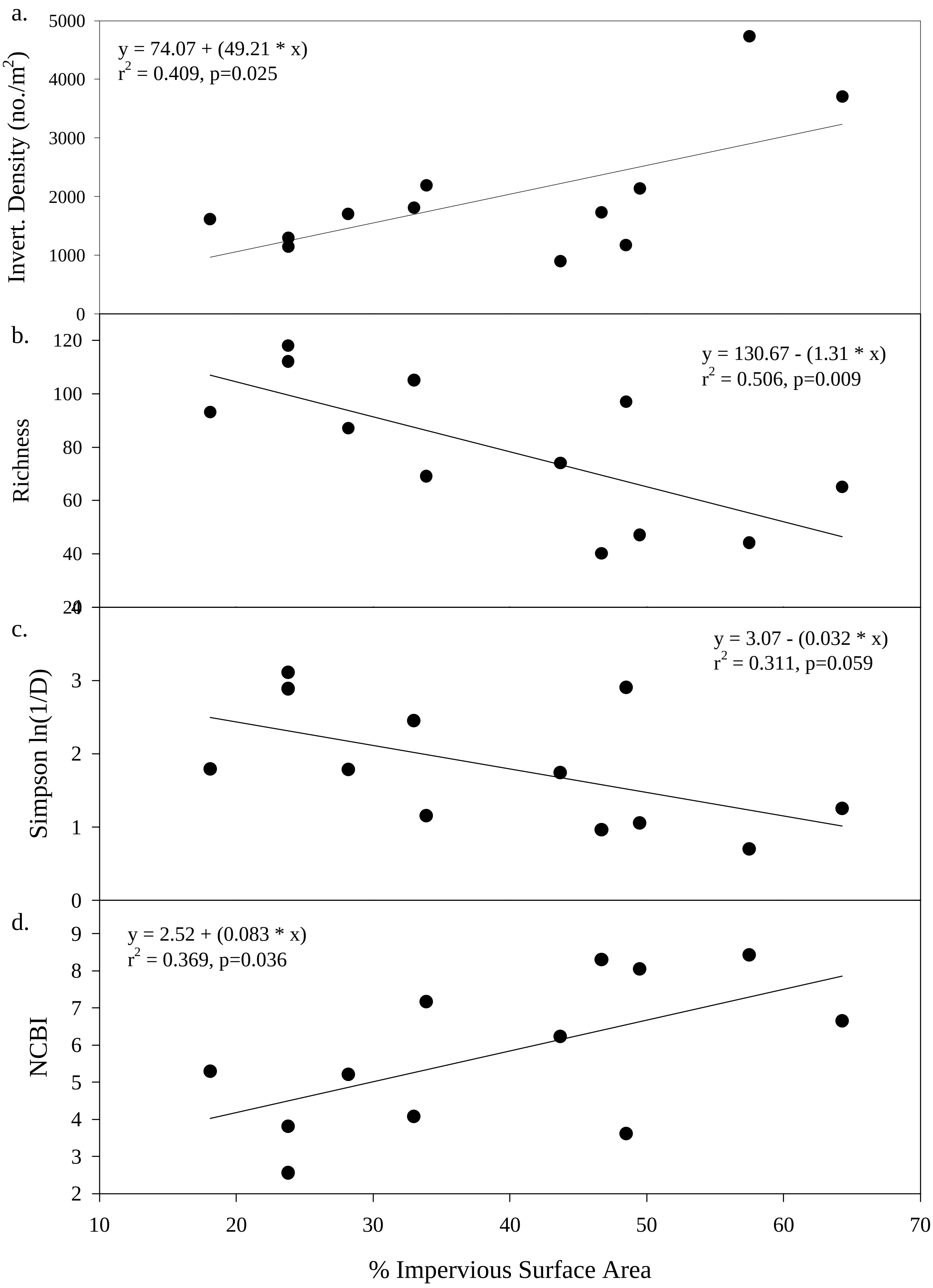

Figure 6a-d: Macroinvertebrate metrics as a function of the % impervious surfaces in a 200m wide, 2km upstream area of the study sites.

Chemical and Physical Response to Urbanization

Water chemistry and stream physical properties were related to the degree of watershed urbanization (Figs. 7,8). Dissolved oxygen, alkalinity, and ammonium concentration were significantly related to the percent cleared land (Fig. 7a-c, $p<0.05$), but the relationship of dissolved oxygen cleared land was not very explanatory ($r^2<0.50$). Water chemistry was also related to building density (Fig. 8a-c, $p<0.01$). Substrate composition was related to both percent cleared land and building density in the watershed (Figs. 7d, 8d; $p<0.05$). High percent cleared land predicted greater amount of sediment (Fig. 7e, $p<0.05$) and low amounts of organic matter (Fig. 7f, $p<0.05$) on the stream bottom, but these relationships explained only a small percent of the variance. However, inorganic sediment and benthic organic matter were strongly related to building density (Figs. 8e,f; $r^2=0.508$ and 0.511, respectively; $p<0.01$).

The urbanization immediately upstream of the sampling reach had variable relationships with water chemistry and stream physical traits. The ammonium concentration was significantly related to percent industry (Fig. 9c, $p<0.05$), but this relationship is not highly predictive ($r^2<0.50$). Industrial urbanization was not related to any other chemical or physical variable (Fig. 9a,b,d-f). Impervious surfaces in the riparian area upstream of a sampling site were not significantly related to in-stream conditions (Fig. 10), but this result may be due to the small spatial scale or technique used for quantifying impervious surface area.

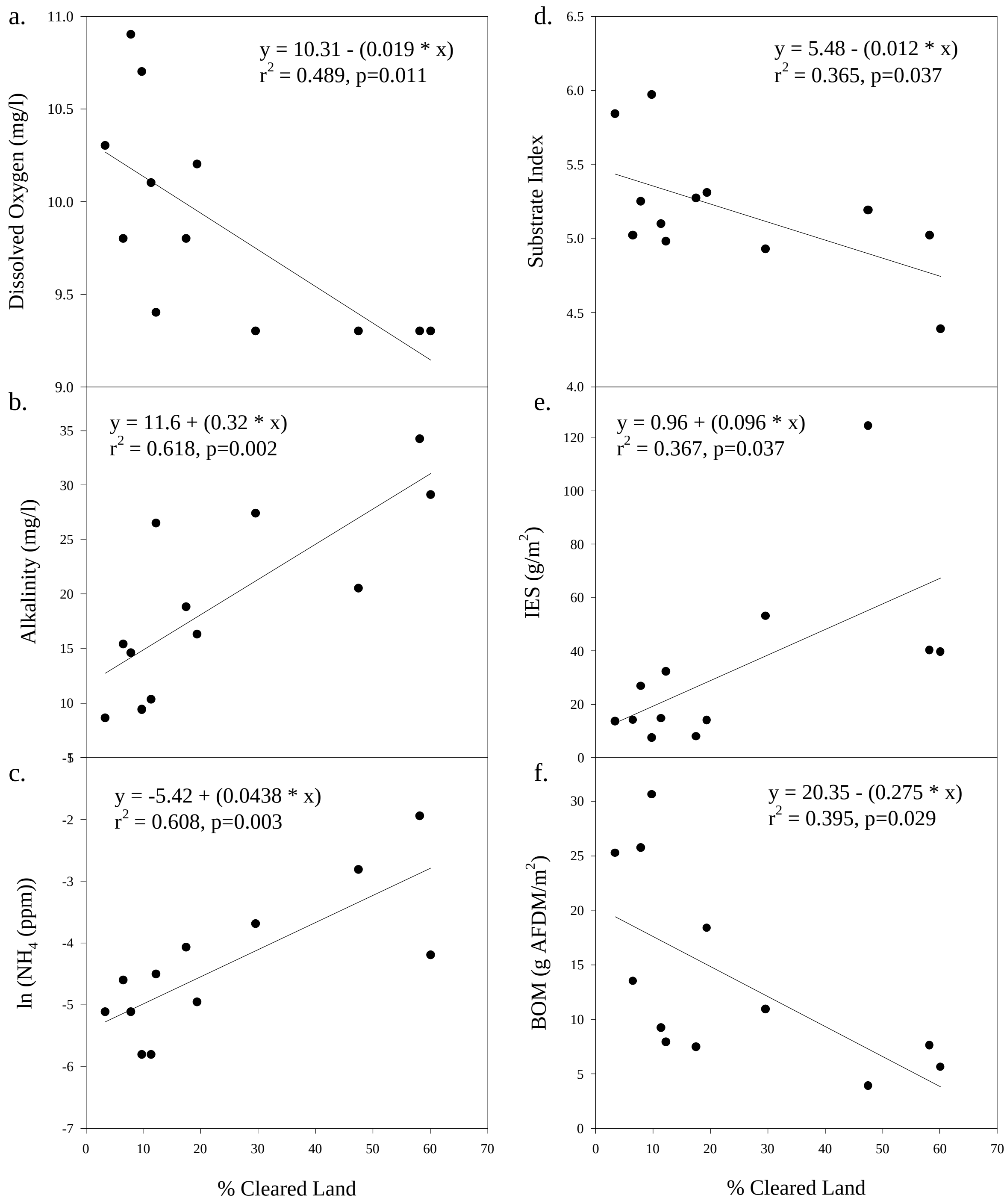

Figure 7a-f: Change in physical and chemical characteristics of streams as a function of the % of cleared land in study watersheds.

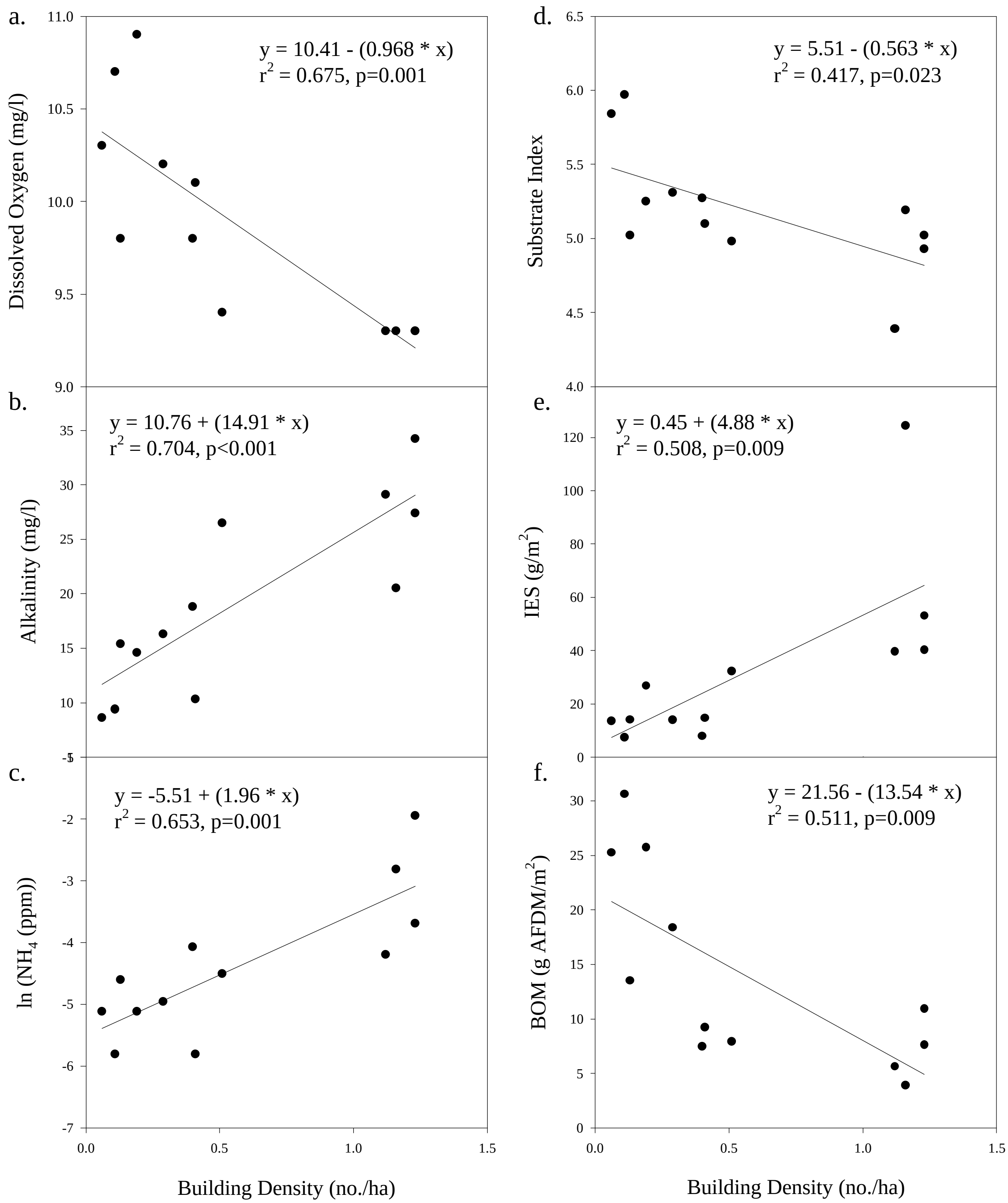

Figure 8a-f: Change in physical and chemical characteristics of streams as a function of the building density in study watersheds.

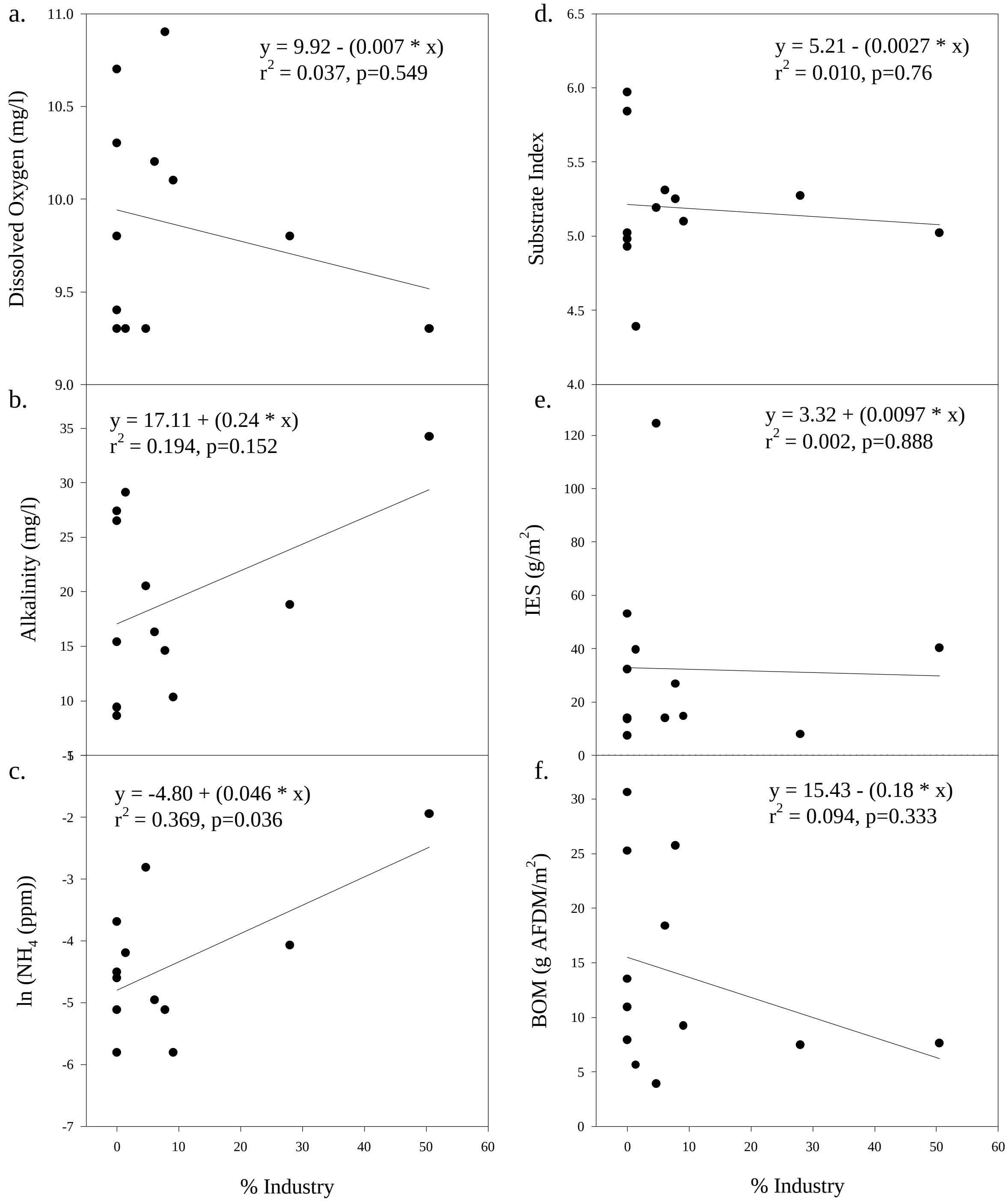

Figure 9a-f: Change in physical and chemical characteristics of streams as a function of the amount of industrial development in a 200m wide, 2km upstream area of the study sites.

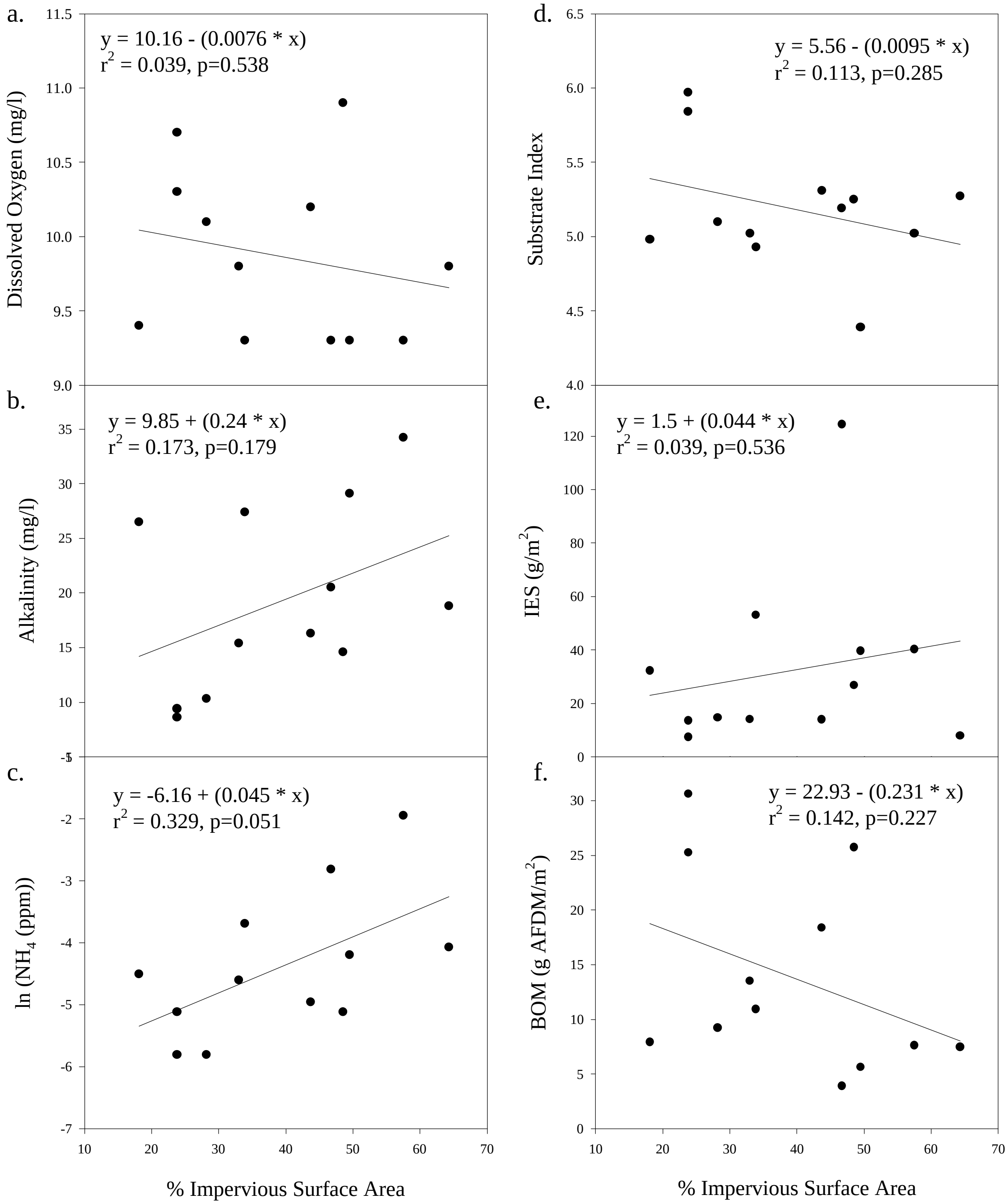

Figure 10a-f: Change in physical and chemical characteristics of streams as a function of the % impervious surfaces in a 200m wide, 2km upstream area of the study sites.

Macroinvertebrate Response to Physicochemistry

The chemical composition of the study streams had significant relationships with benthic macroinvertebrate abundance and assemblage structure. Although not related to density, dissolved oxygen was significantly related to invertebrate richness (Fig. 11b, $p<0.05$), Simpson's index (Fig. 11c, $p<0.001$), and the NCBI (Fig. 11d, $p<0.001$). High dissolved oxygen was related to higher values of richness and evenness but lower values of NCBI indicating high abundance of pollution-sensitive taxa. Richness, evenness, and NCBI were strongly related to alkalinity (Figs. 12b-d, $p<0.01$). Invertebrate density was significantly related to alkalinity (Fig. 12a, $p<0.05$) and ammonium (Fig. 13a, $p<0.01$); however, alkalinity did not explain much of the variance in density. Ammonium was significantly related to richness (Fig. 13b, $p<0.01$), Simpson's evenness (Fig. 13c, $p<0.01$), and NCBI (Fig. 13d, $p<0.01$).

Physical characteristics of these streams were also significantly related to the macroinvertebrate metrics. Invertebrate density was not significantly related to in-stream physical properties (Figs. 14a, 15a, 16a), but diversity and tolerance in the assemblage were related to physical properties. Diversity, evenness, and NCBI were significantly related to substrate size-class distribution (Fig. 14 b-d), but none of these regressions explained a significant portion of the variance. Richness and NCBI were also significantly related to inorganic sediment on the stream bottom ($p<0.05$ for both), but inorganic sediment did not explain greater than 50% of the variance in any macroinvertebrate metric. The strongest in-stream predictor of invertebrate diversity and assemblage structure was benthic organic matter (BOM). High amounts of BOM in the streams were related to high diversity (richness and Simpson's index, $p<0.01$ and $p<0.001$, respectively), and low NCBI scores ($p<0.001$).

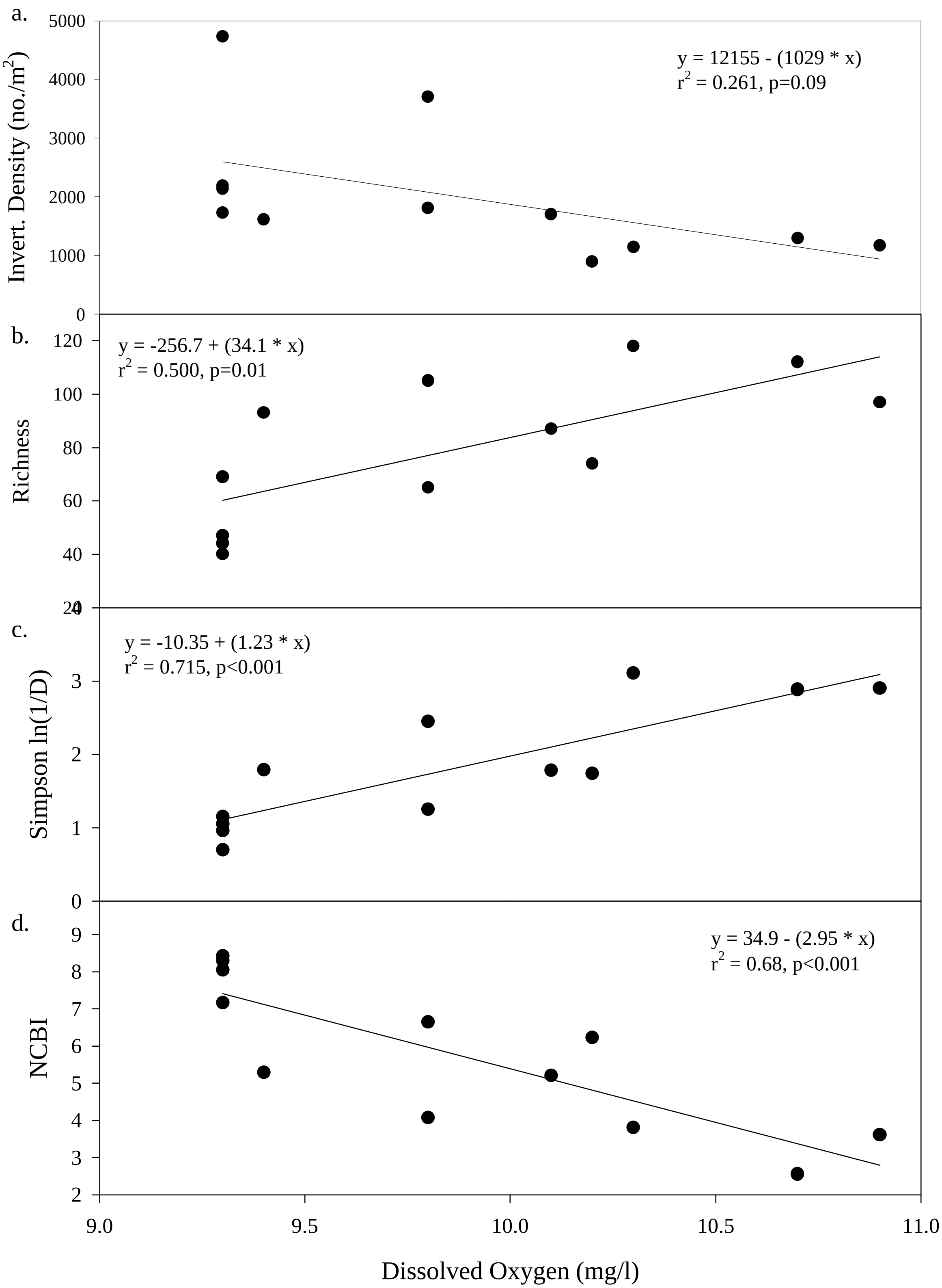

Figure 11a-d: Macroinvertebrate metrics as a function of dissolved oxygen.

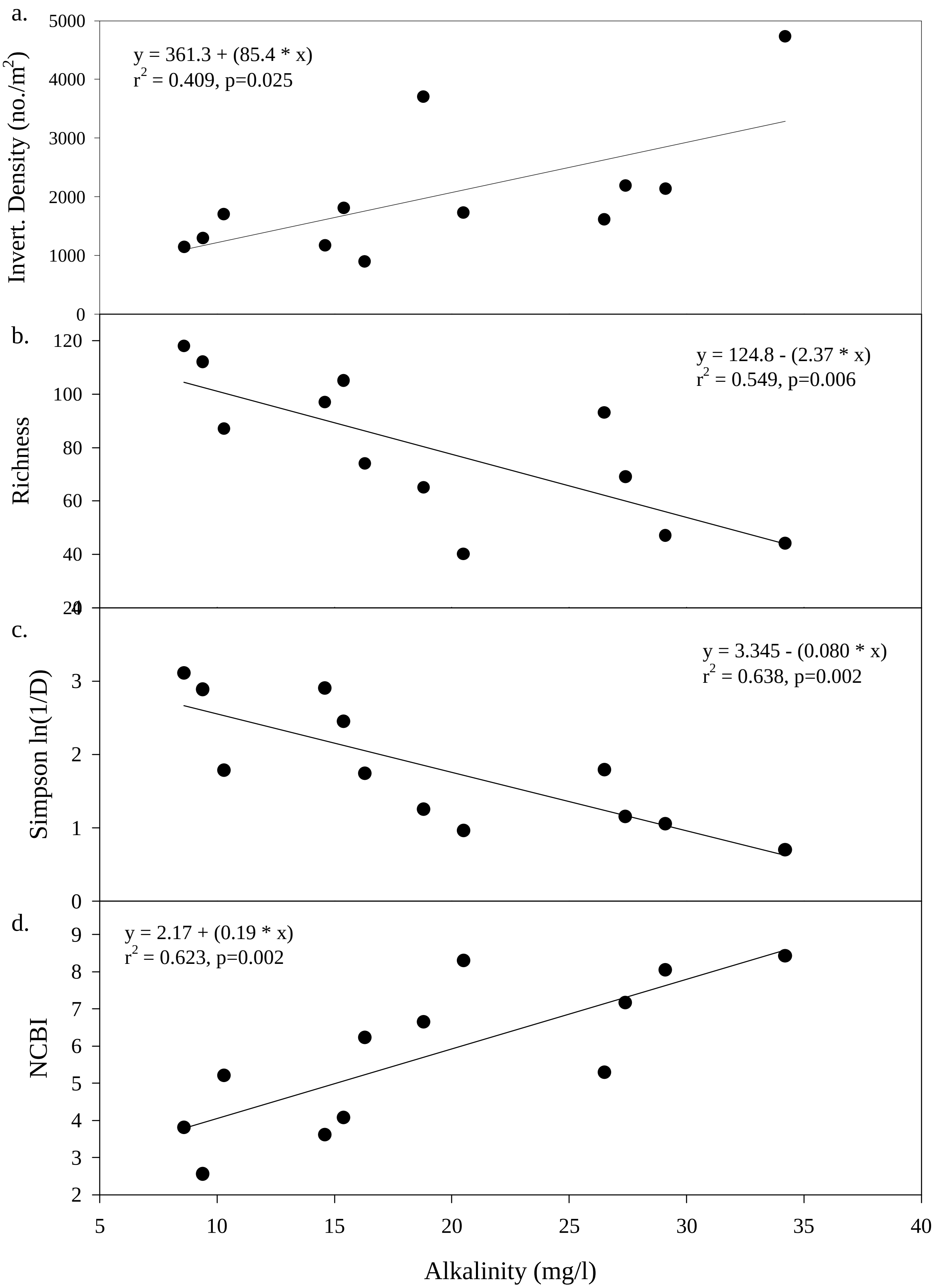

Figure 12a-d: Macroinvertebrate metrics as a function of alkalinity.

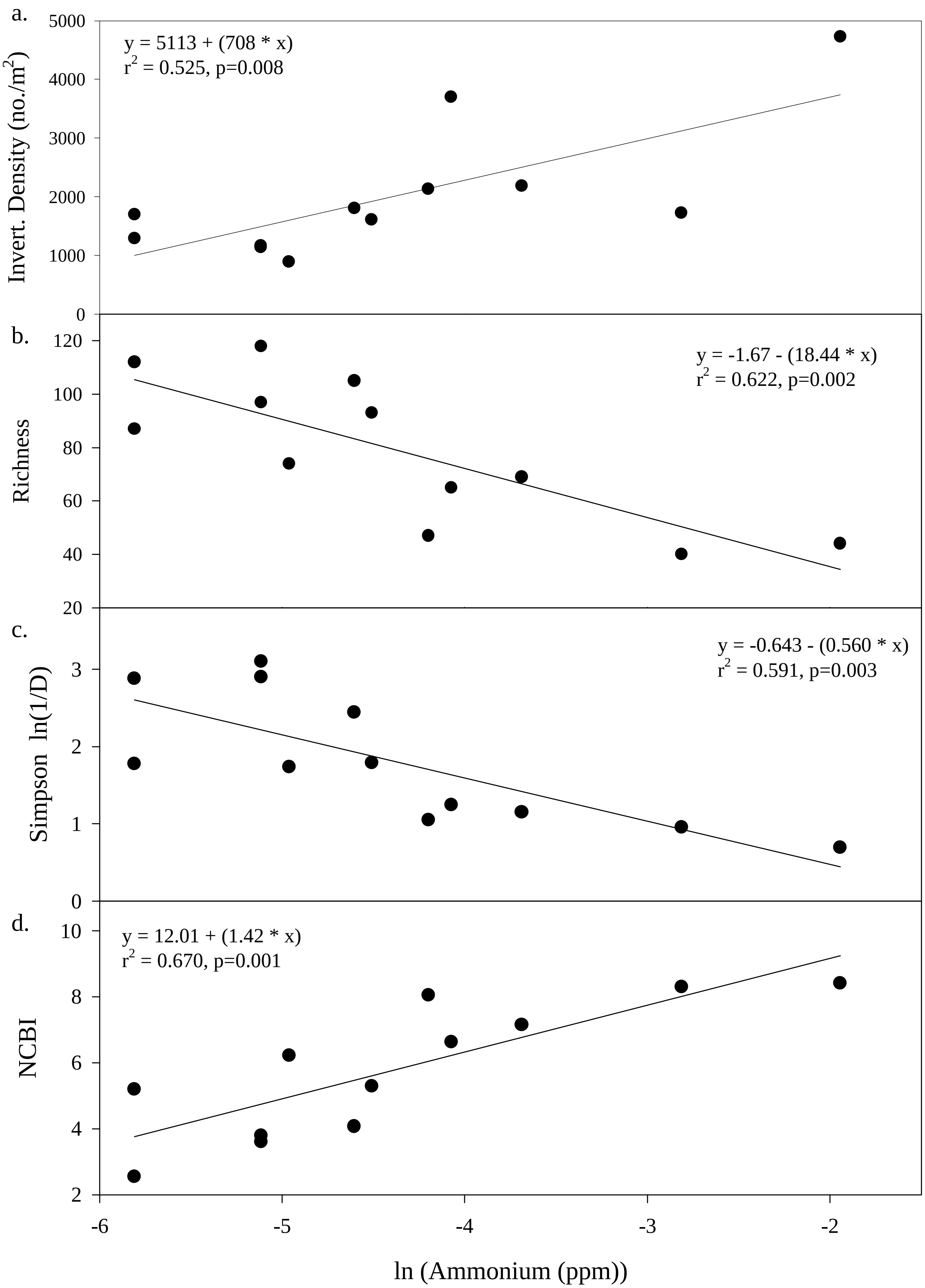

Figure 13a-d: Macroinvertebrate metrics as a function of ammonium.

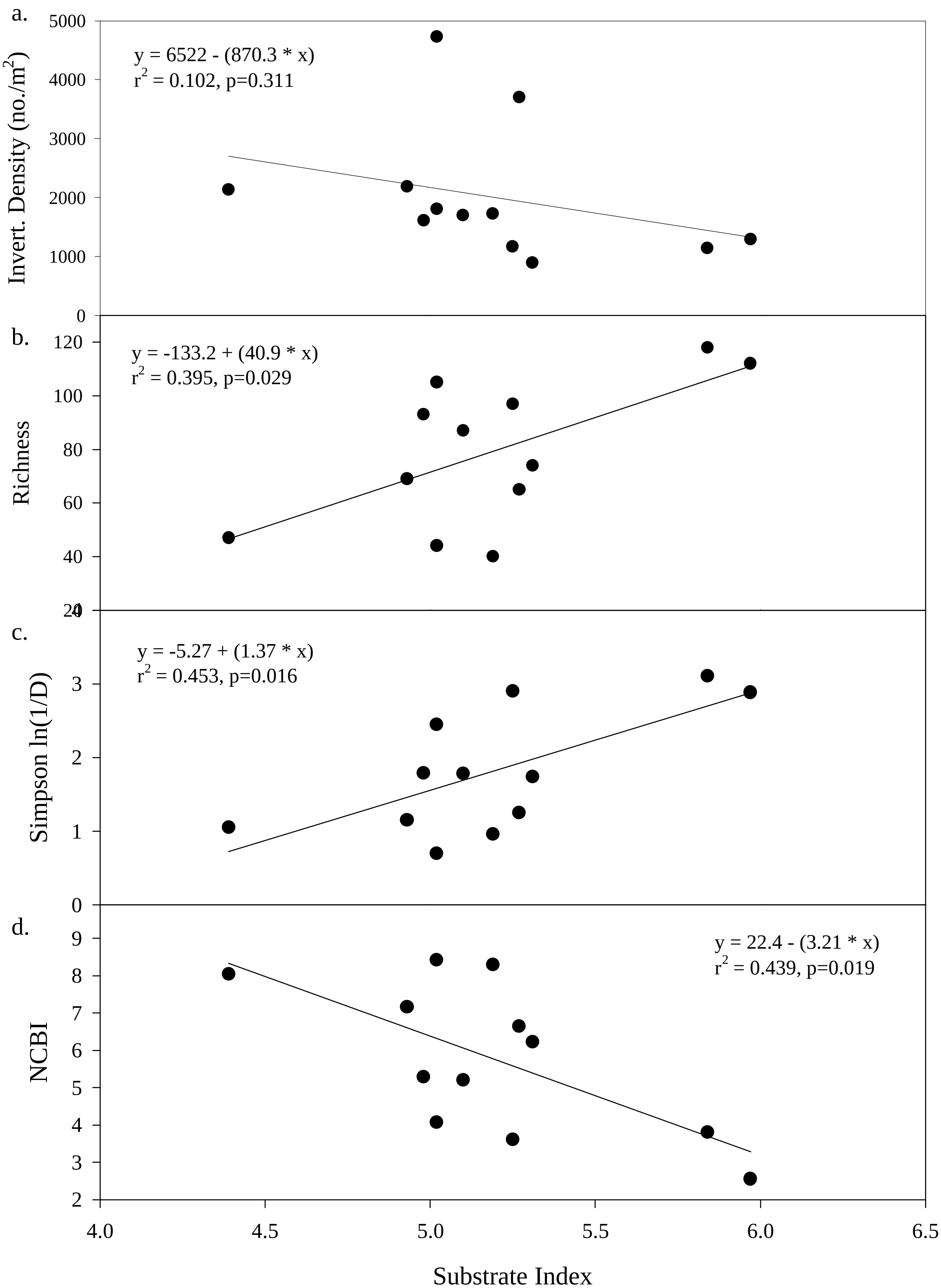

Figure 14a-d: Macroinvertebrate metrics as a function of substrate index.

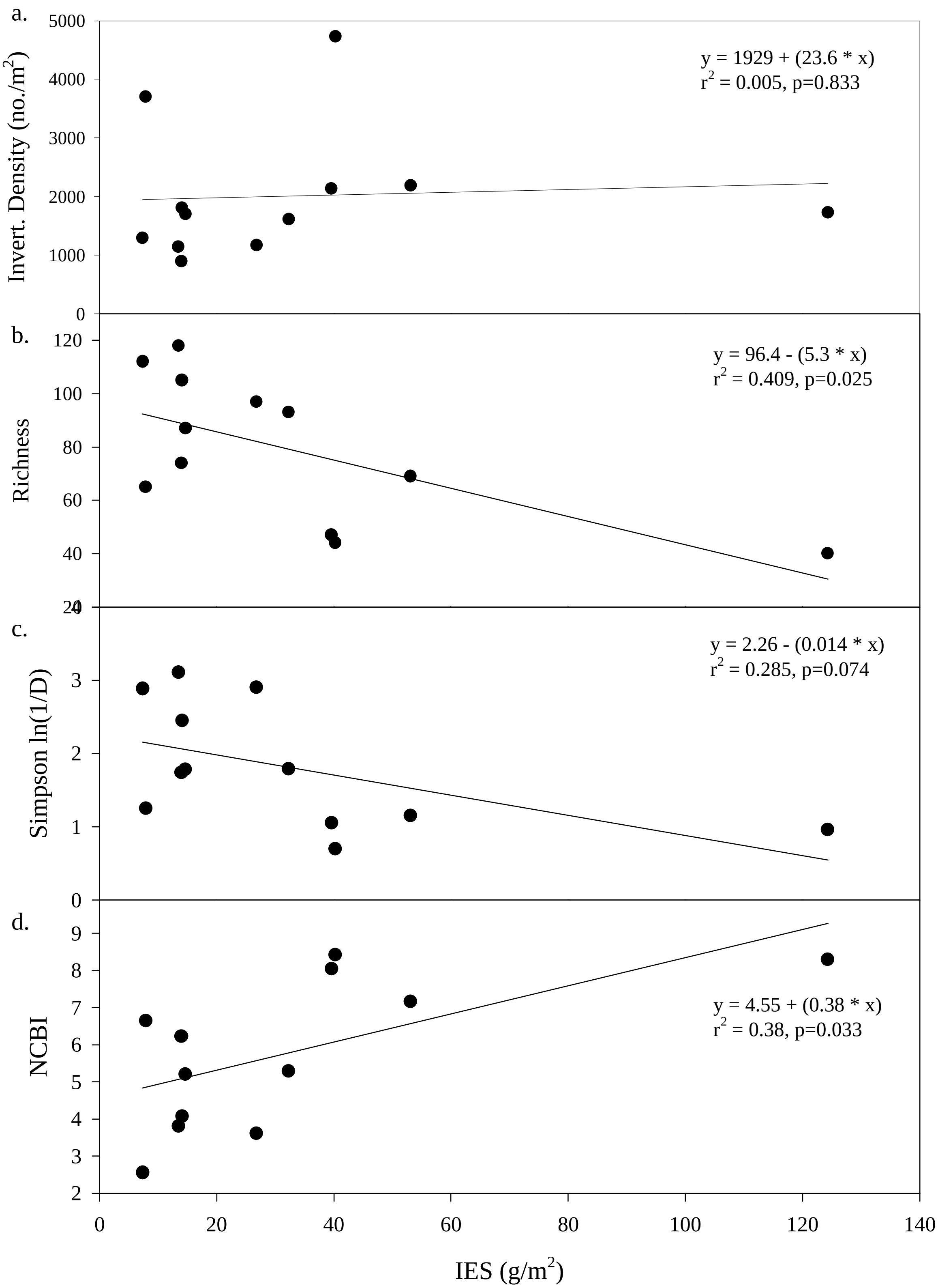

Figure 15a-d: Macroinvertebrate metrics as a function of inorganic epilithic sediment.

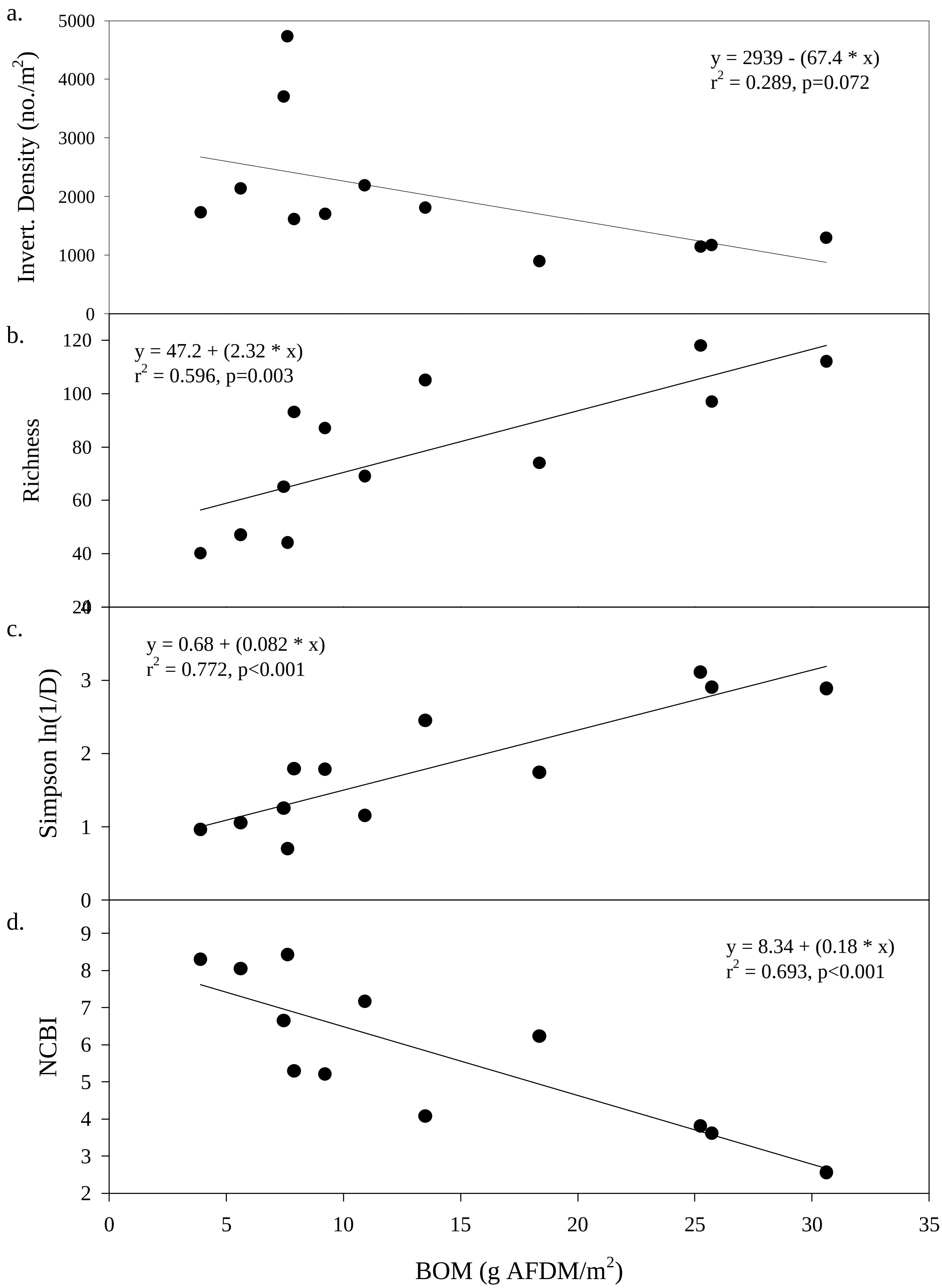

Figure 16a-d: Macroinvertebrate metrics as a function of benthic organic matter.

Ordination of Sites by Species Composition

Correspondence analysis (reciprocal averaging) results gave an ordination plot of the sites in species' space (Fig. 17). The coordinate system was created using presence-absence data from all samples, and the sites were plotted on these coordinates. Eigenvalue (λ) analysis showed the variability in the total data set explained by each axis in the ordination. The two primary axes generated from this data explained 72.3% of the variability among the sites (Axis 1 explained 43.4%, Axis 2 explained 28.9%).

Cross-correlating the ordination plot with the presence-absence data matrix revealed the taxa important in determining the spatial distribution of sites on the ordination plot. Axis 1 was negatively correlated with a suite of taxa (Table 12a), which indicated that sites with high axis 1 values were missing many or all of these taxa. Of the 23 negatively correlated taxa in Table 12a, 19 were Ephemeroptera, Plecoptera, or Trichoptera (EPT) taxa. These groups are considered to be sensitive to pollution, and the strong dependence of axis 1 with EPT taxa indicated a sensitivity gradient along this axis. The average tolerance value of all 23 taxa was significantly lower than the average tolerance value of the remainder of the taxa collected (Table 13, ANOVA on Ranks, $p<0.05$). The only significant positive correlate with axis 1 was the order Collembola.

The taxa primarily responsible for generating axis 2 are listed in Table 12b. Taxonomic data were more strongly related to axis 1 than to axis 2 (Table 12), and axis 2 did not represent any sensitive taxa. The average tolerance value of taxa positively correlated with axis 2 was not significantly different from the tolerance value of the remainder of the taxa. Most of the taxa correlated with axis 2 were rarely collected in my samples, and, as a result, this axis did not represent any biologically meaningful separation of the study sites.

Since the ordination plot represented all of the invertebrate data without biased selection of metrics, correlations of land use and physicochemical data with axes values were useful for attributing specific assemblage properties to specific environmental factors. The historical land use variables were revisited to see if they were related to the invertebrate assemblage. Although 1970 land use data were highly correlated with axis 1 values (Table 14a), the analogous 1990 data were more correlated with the ordination in all cases. The degree of watershed urbanization (percent cleared land, building density, and road density) was positively related with axis 1 of the ordination ($p<0.01$). The percent impervious surface area was also positively correlated with this axis ($p<0.05$) indicating that the sensitive taxa (from Table 12a especially) were absent from sites with large amounts of impervious surfaces.

Similar trends could be seen through the relationships of the ordination plots with in-stream characteristics. Dissolved oxygen, the substrate index, and BOM were strong negative correlates with axis 1 (Table 14b). These negative relationships indicate that sites with low dissolved oxygen, small substrate, and little BOM were missing several or all of the sensitive taxa from Table 12. Alkalinity was positively correlated with axis 1 meaning a negative relationship with sensitive taxa.

Axis 2 from the ordination plot was not significantly correlated with any land use, chemical, or physical variable implying that axis 1, along with its 43.4% of the variability and sensitive determining taxa, was a good measure of impact in these systems.

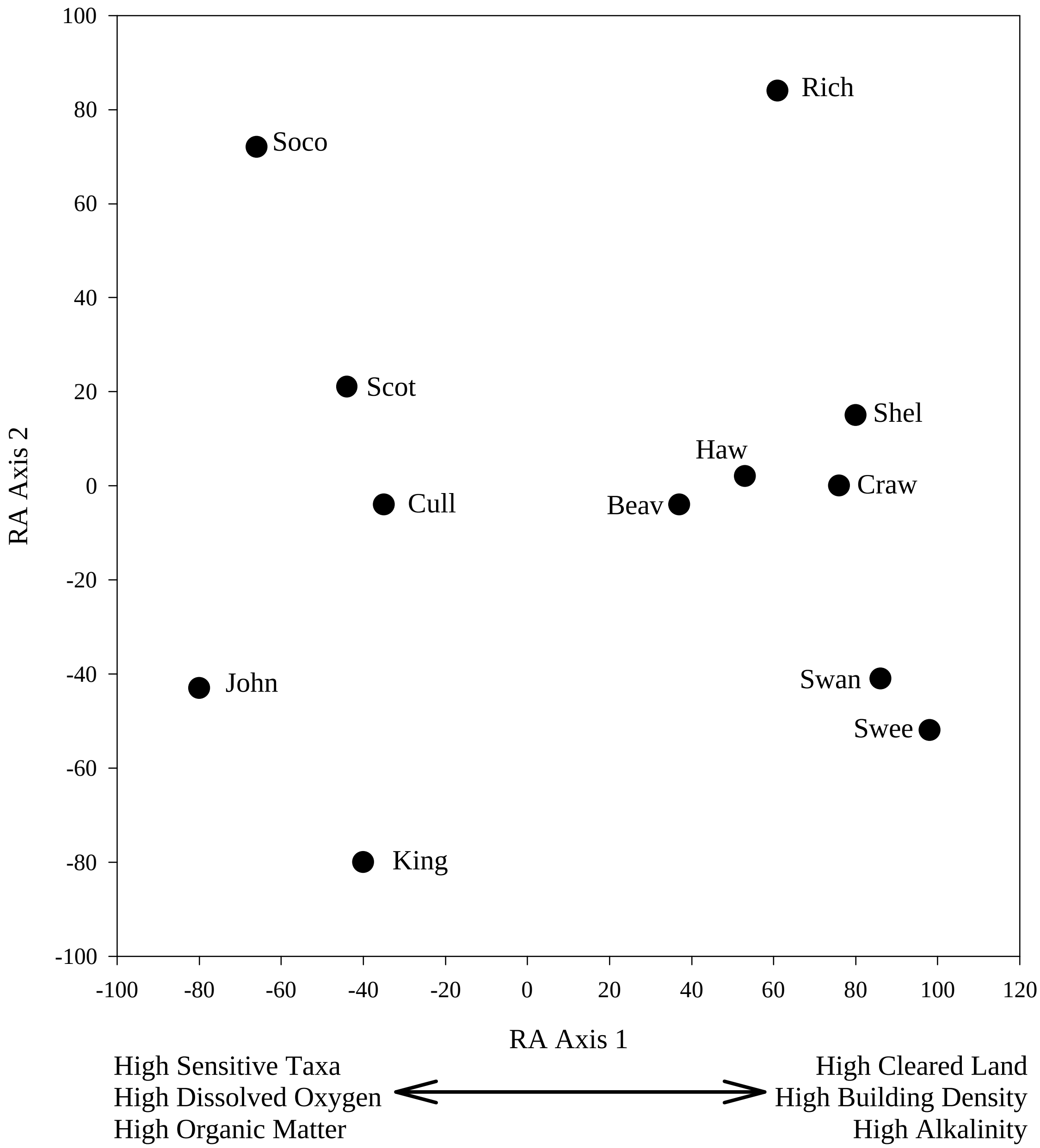

Figure 17: Correspondence analysis (reciprocal averaging) of invertebrate presence-absence data matrix. λ_1 = 0.285 (43.4%), λ_2 = 0.190 (28.9%). Variables listed on the left are negatively correlated with axis 1, and variables listed on the right are positively correlated with axis 1 (also see Tables 12 and 14).

Table 12: Pearson correlations (r, where $p<0.01$) of macroinvertebrate presence-absence data matrix with correspondence analysis axes values (a. RA Axis 1, b. RA Axis 2). Taxa presented in rank order of r (see Appendix 2 for complete taxonomic information).

a.

Taxon	**r**
Drunella lata	-0.956
Cinygmula subaequalis	-0.956
Haploperla brevis	-0.956
Parachironomus sp.	-0.956
Dicranota sp.	-0.895
Ephemerella argo	-0.895
Polycentropus sp.	-0.895
Leuctra sp.	-0.854
Rhithrogena spp.	-0.850
Sweltsa sp.	-0.850
Promoresia tardella	-0.838
Cultus decisus	-0.838
Goera calcarata	-0.838
Rhyacophila spp.	-0.838
Tallaperla sp.	-0.825
Epeorus pleuralis	-0.818
Collembola	0.766
Isoperla bilineata	-0.764
Yugus bulbosus	-0.764
Pteronarcys sp.	-0.753
Eukiefferiella brevicalcar	-0.753
Acroneuria abnormis	-0.728
Brachycentrus sp.	-0.725
Ephemerella rotunda	-0.721

b.

Taxon	**r**
Atherix lantha	0.782
Sympotthastia sp.	0.782
Noctuidae	0.771
Baetis pluto	-0.751
Cryptochironomus sp.	0.744

Table 13: Comparison of average tolerance values for taxa in the correspondence analysis ordination plot with average tolerance values (TV) for all remaining taxa. Comparison made using Kruskal-Wallis One-Way ANOVA on ranks and Dunn's Multiple Comparison Technique vs. average tolerance of remaining taxa as the control group.

	Median TV	**N**	**Diff. Of Ranks**	**Q Statistic**	**$p<0.05$**
Taxa Negatively Correlated with Axis 1	1.4	23	57.82	4.546	Yes
Taxa Positively Correlated with Axis 2	3.9	4	0.162	0.006	No
All Remaining Taxa	4.3	171	Control	Control	Control

Table 14: Pearson correlations (r) of land use (historical and current, a) and environmental variables (b) with correspondence analysis axis 1 values (*p<0.05, **p<0.01, ***p<0.001; axis 2 had no significant correlates).

a.

Land Use	r
70 % Cleared	0.760**
90 % Cleared	0.768**
70 Bld. Dens.	0.714**
90 Bld. Dens.	0.763**
70 Rd. Dens.	0.617*
90 Rd. Dens.	0.779**
% Industry	0.490
% Impervious	0.662*

b.

Env. Variable	r
Dissolved Oxygen	-0.775**
Alkalinity	0.819**
Ammonium	0.555
Substrate Index	-0.619*
IES	0.467
BOM	-0.779**

Discussion

The changing landscape of western North Carolina can be seen by comparing historical with current land use. In my study watersheds, 7 out of 12 sites have actually decreased in the percent of cleared land over the past 30 years, but all have increased in building and road density during this time (Table 2). The increase in forest cover coupled with increases in building and road density indicated a shift in land use from agricultural land to suburban development (SAMABC 1996). In this study, sites with the highest current building densities (Craw, Haw, Shel, Swee) had the highest building densities in 1970 indicating that these systems have been developing over the past 30 years. Given the differences in land use history between my study sites and the strong relationships of current urbanization with earlier development (Table 7), the impacts due to urbanization were difficult to tease apart. However, contrary to Harding and Benfield's (in press) findings with agricultural land use history, current urbanization variables were better predictors of macroinvertebrate metrics in my study than the same urbanization variables measured in 1970 (Fig. 2, Table 11, Table 14). For that reason, current land use in the watersheds was used as the independent variable to assess the impact on stream quality and macroinvertebrates.

Urbanization was significantly related to the macroinvertebrate assemblage found in my streams. Richness, evenness, and NCBI responded to increasing the degree of urbanization in the entire watershed, but density was not significantly predicted from these land use variables. As the percent cleared land and building density increased, diversity decreased while the proportion of pollution tolerant organisms in the macroinvertebrate assemblage (i.e., NCBI) increased. Sites with the highest current building density clustered closely on the regression plots (Fig. 4), and these sites have been urbanized longer than the other streams. Older urban areas in western North

Carolina experience different impacts of development as many storm drain pipes, sewer lines, and septic tanks age and leak chemicals and organic waste into neighboring streams (Duda et al. 1979, Hachmöller et al. 1991). These chemical and organic inputs influence the macroinvertebrate assemblage in streams by reducing pollution-sensitive organisms and replacing them with chironomids and oligochaetes, often in high abundance (Penrose et al. 1980, Lenat 1984). Streams under such impact have lower diversity and higher proportional abundance of pollution-tolerant organisms than streams not receiving sewage effluent (Jones and Clark 1987).

Although the duration and degree of urbanization in a watershed did impact stream biota, the type of urbanization present in a watershed can alter the benthic macroinvertebrate assemblage. The percent of industrial development in the area immediately upstream of my sampling reach was strongly related to invertebrate density in the stream (Fig. 5a), but industry was not significantly related to diversity. However, conclusions drawn from these relationships, although noteworthy, are suspect as the trends are driven by two sites. Of the study sites, only two had any appreciable amount of industry in their watersheds: Sweeten Creek and the Swannanoa River, both in Asheville, while five streams had zero industry in the area 2km upstream. Industry in western North Carolina is not very dense and tends to be centralized around older communities, such as Asheville (SAMABC 1996). The benthic samples taken from these two streams contained very high numbers and proportions of Chironomidae and Oligochaeta. The high densities in Swee and Swan dismiss the possibility of toxic chemical releases from nearby industries during my sampling period (Lenat and Crawford 1994), but they suggest enrichment of some kind, either from sewage outfall or industrial sources (Lenat 1984).

Impervious surface area was significantly related to density, richness, and NCBI; however, only richness could be explained substantially by the percent impervious surface area. Impervious surface area had been used as the best predictor of watershed urbanization impact on aquatic systems (Klein 1979, Pitt and Bozeman 1980, Pedersen and Perkins 1986, Steedman 1988), and many governmental agencies have been using the impervious surface area in watersheds as an indicator of potential urbanization impact

(Center for Watershed Protection 1994). While not dismissing the impacts due to impervious surface area completely, my results do not strongly support the assertion that impervious surface area alone is a good measure of urbanization impact. However, many many potential sources of influence from impervious surfaces further upstream or outside the 100m riparian zone were not measured in my study. Extrapolating impervious surface area measurement to the entire watershed from the small upstream area used in my study would severely overestimate the total amount of impervious surface area.

The chemical and physical characteristics of streams are determined by geology and vegetation in watersheds, and urbanization disrupts natural processes resulting in altered in-stream conditions (Benke et al. 1981). The relationships of water chemistry and physical stream structure to land use variables showed the dependency of the abiotic characteristics in my streams on urbanization in the watershed. With increased urbanization, dissolved oxygen dropped while alkalinity and ammonium increased suggesting enrichment of these systems (Townsend et al. 1983). In some cases, nutrient loading or sewage outflow can create high biological oxygen demand resulting in dramatic shortages of oxygen in the water, and dissolved oxygen seemed to decrease with increasing urbanization in my study (Figs. 7a and 8a). However, concentrations of oxygen were at or above saturation levels for the temperature and altitude of the study sites showing that human influence in the study watersheds was not creating hypoxic environments.

Undisturbed streams in the southern Appalachians tend to be slightly acidic and to have low concentrations of dissolved ions and nutrients (Simmons and Heath 1979), but human development of the landscape changes natural geologic processes resulting in increased dissolved ions in receiving water bodies (Allan et al. 1997). In my study streams, alkalinity and ammonium were both strongly related to the percent cleared land and the building density (Figs. 7b,c and 8b,c), but neither chemical variable was strongly related to industry or impervious surface area. Cleared land in the study watersheds can be attributed to many sources including agriculture, golf courses (e.g., Beav), college campuses (Cull, King), residential areas (Haw), and town centers (Craw). Removing vegetation for development requires dramatic upheaval of vegetation and soil potentially explaining higher alkalinity in streams with more cleared land and higher building density. Also, areas with large expanses of maintained and fertilized lawn (e.g., golf courses, residential areas) can contribute nutrients in runoff from storms thereby explaining higher ammonium with land clearing (Hachmöller et al. 1991, Morse et al. 1993). Agricultural areas in the study watersheds could also influence water chemistry and other in-stream conditions (Harding and Winterbourn 1995), but the amount of agricultural land in my study watersheds was negligible and far upstream of my sampling reach.

The physical structure of streams is dramatically altered by human activity in watersheds (Richards and Host 1993, Richards et al. 1997). Increasing the amount of cleared land and building density in my study resulted in significant increases in inorganic sediment in the streambed and a subsequent reduction of substrate heterogeneity (Figs. 7d-e, 8d-e). Benthic organic matter (BOM) was also related to watershed urbanization, but, contrary to my expectation, cleared land was not the best predictor of BOM standing stock. Reductions in BOM were predicted best by increases in building density. A large proportion of development in western North Carolina has occurred along stream corridors because the mountains are more difficult to access for construction than for logging (SAMAB 1996). Therefore, organic matter from the riparian zone, the primary allochthonous source of organic matter for streams (Osborne and Kovacic 1993), would be more affected by buildings than by the amount of cleared land over the entire watershed. My results showed this relationships, and BOM was a very strong predictor of macroinvertebrate metrics. Industry and impervious surface area were not related to substrate, sediment load, or BOM; however, physical characteristics of streams can be influenced by changes at a larger scale than that used in my study to measure industry and impervious surfaces (Allan et al. 1997, Johnson and Covich 1997).

Increasing degree of urbanization (shown by percent cleared and building density) had a significant impact on the chemical conditions of my streams, but are macroinvertebrate metrics similarly related to in-stream conditions? Dissolved oxygen in the streams was at or above saturation on all sampling dates in all sites, so the strong relationships in Fig. 11 did not represent ecologically significant trends. High alkalinity

(Fig. 12) and ammonium (Fig. 13) were related to low diversity and high NCBI score. The relationships suggest chemical nutrient enrichment in some of my streams where low dissolved oxygen with high alkalinity, and high ammonium all relate to low diversity (Townsend et al. 1983). In this study, the relationships of alkalinity and ammonium to macroinvertebrates show striking similarities. Streams with high ammonium concentrations had lower diversity but greater invertebrate density than streams with low ammonium indicating a possible chemical link of increasing urbanization with the biotic response in the stream (Lenat 1984).

In-stream conditions that affect macroinvertebrates are not limited to water chemistry, and several characteristics of the streams physical template of the study sites were altered by urbanization. The role of microhabitat is central to understanding the organization and diveristy of benthic communities as changes in the physical structure of the stream bottom result in different assemblages of organisms (Pennak and van Gerpen 1947, Allan 1975, Ward 1975, Minshall 1984). The reduction of average substrate particle size may help explain lower diversity and an increase in the relative abundance of pollution tolerant taxa in the study streams. Many others have shown reductions in diversity and sensitive taxa due to sedimentation and loss of substrate heterogeneity (e.g., Cordone and Kelly 1961, Chutter 1969, Cobb et al. 1992, Waters 1995), but my results are less clear on these relationships. Although several invertebrate metrics are significantly related to substrate size (Fig. 14b-d) and inorganic sediment (Fig. 14b,d), none of the regressions explains a satisfactory amount of the variance (less than 50% of variance). The regressions of substrate size index to predict macroinvertebrate response were unreliable because three sites appear to be driving the relationships (Fig. 14). Jonathan Creek and Soco Creek had the highest substrate size index measurements, and these two streams also had the highest diversity of macroinvertebrates. John and Soco both had substrate dominated by large cobble rock with little sediment (IES, Table 7). The site with the lowest substrate size index (i.e., substrate dominated by smaller rocks) was Shelton Branch. The remaining sites form a cloud of points with seemingly little relationship other than the one caused by John, Soco, and Shel.

Inorganic sediment was significantly related to macroinvertebrate metrics, but the regressions are dependent on one site for direction. In this case, Crawford Branch had a thick sediment mat over much of the substrate resulting in the extremely high IES values (>2 times the next lowest, Table 7). Many studies have found contradictory effects of increasing sediment load on macroinvertebrate assemblages (Williams and Mundie 1978, Williams 1980, Lenat et al. 1981, Erman and Erman 1984). Studies where the sedimentation was severe enough to cause a complete shift in substrate characteristics (i.e. gravel/cobble to a homogeneous sediment layer) showed the most dramatic change in the invertebrate assemblage, yet even these results were not consistent. Lenat et al. (1979) found increases in total abundance with the large amount of deposited sediment due to oligochaete worms and burrowing chironomid larvae, but Hogg and Norris (1991) showed reductions in both diversity and abundance in areas with large sediment deposits suggesting toxicity in stream sediment. Ssediments in urban streams can sustain high concentrations of toxic metals (Wilber and Hunter 1977, Pitt and Bozeman 1980, Pratt et al. 1981) or retain high nutrient concentrations (Lemly 1982) suggesting additional factors potentially affecting macroinvertebrates in my streams. Chemical adsorption to sediment was not measured in this study, but chemical-sediment relationships could possibly explain the inconclusive responses of macroinvertebrates to substrate alteration and inorganic sediment. Macroinvertebrate assemblages change with the type of physical and chemical condition presented, and the interaction of these factors further complicates our understanding of the mechanisms of land use impact on streams.

The importance of riparian vegetation to stream ecosystems in forested regions is well known (Cummins 1974, Sweeney 1992, Osborne and Kovacic 1993), and land use may severely impact this fundamental resource of organic matter for stream organisms (Webster et al. 1992, Harding and Winterbourn 1995). The amount of available benthic organic matter (BOM) was one of the abiotic variables most impacted by urbanization in my streams, and it also showed the strongest relationship with macroinvertebrate diversity, evenness, and sensitivity (Fig. 16, Table 14b). High BOM may facilitate biodiversity in streams by providing a limited food resource for many types of aquatic insect (Morse et al. 1993), and many leaf-shredding insect nymphs and larvae are sensitive to pollution (Lenat 1993). Other studies have shown the same response of macroinvertebrates to BOM and go further to state that the amount of allochthonous detritus in streams is a more important factor regulating benthic macroinvertebrates than physical changes in substrate (Egglishaw 1964, Murphy et al. 1981, Culp et al. 1986). Richards and Host (1994) noted the significant effect of organic matter on structuring macroinvertebrate assemblages but did not discount the possible interaction of BOM with other abiotic factors. However, eliminating organic matter inputs to a southern Appalachian stream while leaving the forest intact has severely altered the bioenergetics and production of a stream system at Coweeta Hydrologic Laboratory (Wallace et al. 1997). Wallace et al. (1997) showed the dependence of several invertebrate groups on the input of organic matter from terrestrial sources, and my results support the assertion that BOM is important in determining macroinvertebrate assemblages in streams.

Results from my correspondence analysis and subsequent correlations showed relationships of urbanization and physicochemistry to benthic macroinvertebrate assemblage in the study sites. Figure 17 is a visual representation of study sites along axes generated using presence-absence taxonomic information for my twelve streams. Some people argue that ordination plots and multivariate statistics are not biologically relevant (Fore et al. 1996), but one can apply biological knowledge to ordinations using correlation analysis (Jones and Clark 1987). The taxa important in determining the distribution of sites on the ordination plot were found by correlating the ordination axes values for each site with the presence-absence information used to generate the axes. This correlation produced a list of specific taxa from which I chose those taxa most strongly correlated to the ordination axes ($r>0.71$, $r<-0.71$; Table 12). In this case, the taxa negatively correlated with axis 1 had a significantly lower median tolerance value (from Lenat 1993) than both the taxa on axis 2 and all remaining taxa (Table 13, Dunn's Multiple Comparison Technique, $p<0.05$) indicating that axis 1 represents a tolerance gradient. Sites having sensitive organisms were found on the negative side of axis 1, and sites without these sensitive organisms (those in Table 12a) had positive axis 1 values. Taxa correlated with axis 2 did not have significantly different tolerance values than the remaining taxa, so separation on this axis was not indicative of pollution tolerance.

Assuming consistency in background conditions among the sites, Fig. 17 represented the actual differences between the communities found at each site that can then be attributed to land use or environmental changes (Marchant et al. 1995).

Knowing that the ordination contains biologically relevant information encouraged me to explore the relationships of the various urbanization and physicochemical variables with the correspondence analysis plot. Many of these correlations using the multivariate axis values showed similar trends to the regressions of macroinvertebrate metrics with urbanization and physicochemistry. Percent cleared land and building density were strong positive correlates with axis 1 (Table 14a) showing that sites without the sensitive taxa listed in Table 12a also had high amounts of urbanization. Physicochemical variables were also related to axis 1 (Table 14b). Dissolved oxygen and BOM were strong negative correlates indicating that sites with sensitive taxa had higher dissolved oxygen and BOM than sites without sensitive taxa. Alkalinity showed the opposite effect in that streams without sensitive taxa tended to have higher alkalinity. The substrate index was only weakly related to the ordination axis, and no significant relationship existed for ammonium or inorganic sediment. These results were similar to those shown when using metrics to quantify specific attributes about the macroinvertebrate assemblage.

Biological indices (e.g., NCBI, MAIS) can be useful for establishing biocriteria to limit development's impact on reveiving waters (Karr and Chu 1997). NCBI scores and diversity certainly performed well in this study for detecting human impact, and multimetric indices hold a great deal of potential in regional biomonitoring efforts. Categorizing streams based on biotic index scores can be very useful in hypothesis generation and placing acceptable limits on urbanization and other land use practices. For example, using Lenat's (1993) water quality class ratings for the mountain region of North Carolina (Table 3 of Lenat 1993; all of my sites are located in this ecoregion), one could calculate (using my regression equations) the maximum building density and/or percent of cleared land allowed yet preserving biotic integrity in a stream. Table 15 shows the ranges of NCBI scores for different stream health ranging from excellent to poor (from Lenat 1993) along with predicted land use variable values corresponding to degrees of impact. Based on the results from my study, in order to maintain an NCBI score in the "excellent" category, building density in the entire watershed must remain below 0.146/ha (0.06/acre or 1 bldg./16.67 acres) and the amount of cleared land must remain below 5 percent. "Poor" NCBI scores should be found in streams with watershed building densities of 0.91/ha (0.37/acre or 1 bldg./2.72 acres) and with 39 percent cleared land. These are just examples derived from the regressions in my study, but one could use these calculated endpoints as predictions for urbanization impact on macroinvertebrates in western North Carolina. From the proposed maximum and minimum values of different land use variables, one could examine the macroinvertebrate assemblage to test the validity of the predictions and find other factors potentially explaining deviations from expected results. Establishing maximum and minimum values for different biocriteria (e.g. NCBI) through rigorous investigation could be very useful for landscape and urban planners to set maximum development density values that would preserve the biological integrity of stream ecosystems. Setting acceptable disturbance limits could also be used to predict biological response to a variety of environmental variables influenced by large scale alterations and even global change (Cobb et al. 1992, Changnon and Demissie 1996).

Studying the impact of urbanization on stream ecosystems is important as human encroachment through urban sprawl increases throughout the world. Increased development in watersheds has a dramatic effect on stream biodiversity. Clearing forested land disrupts typical detritus based food webs in streams and alters the organic matter dynamics in impacted streams. The complexity of urbanization makes determining exact mechanisms for observed effects difficult, but several physical and chemical characteristics of streams are related to watershed urbanization. Changes in the physicochemistry of streams due to urbanization result in low diversity macroinvertebrate assemblages dominated by pollution-tolerant organisms. Generating acceptable limits of development in watersheds is necessary to protect our threatened aquatic resources, and understanding the pathways of land use impact on aquatic biota is central to this effort.

Table 15: Calculation of acceptable limits of land development in watersheds using regressions and NCBI scores for water quality classes in Mountain ecoregion of western North Carolina (from Table 3 of Lenat 1993).

Water Quality Class	NCBI Score Range	Limits of Building Density (no./ha)	Limits of % Cleared Land
Excellent	<4.18	<0.146	<5.06
Good	4.17-5.09	0.146-0.387	5.06-15.76
Good-Fair	5.10-5.91	0.387-0.605	15.76-25.41
Fair	5.92-7.05	0.605-0.907	25.41-38.82
Poor	>7.05	>0.907	>38.82

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Appendix 1: Taxonomic keys used to identify macroinvertebrates

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Appendix 2: Presence-absence of all macroinvertebrate taxa in the 12 study streams from all samples.

Taxon	**Beav**	**Craw**	**Cull**	**Haw**	**John**	**King**	**Rich**	**Scot**	**Shel**	**Soco**	**Swan**	**Swee**
ORDER EPHEMEROPTERA												
FAMILY AMELETIDAE												
Ameletus sp.					+					+		
FAMILY BAETIDAE												
Acentrella spp.	+	+	+	+	+	+	+	+	+	+	+	+
Baetis brunneicolor	+		+	+	+	+	+	+	+	+		
Baetis intercalaris	+		+	+	+	+	+	+	+	+	+	+
Baetis macdunnoughi						+						
Baetis pluto	+		+	+	+	+					+	+
Baetis tricaudatus	+			+	+	+				+		
Cloeon alamance	+						+					
FAMILY BAETISCIDAE												
Baetisca carolina	+		+									
Baetisca gibbera	+		+						+	+		
FAMILY EPHEMERELLIDAE												
Drunella cornutella				+	+							
Drunella lata			+		+	+		+		+		
Drunella tuberculata								+				
Drunella walkeri			+			+		+				
Drunella wayah										+		
Ephemerella argo	+		+		+	+		+		+		
Ephemerella crenula	+	+	+	+	+	+	+	+		+		
Ephemerella dorothea	+		+	+	+	+	+	+	+	+	+	
Ephemerella inconstans	+			+			+	+		+	+	
Ephemerella invaria	+						+					
Ephemerella rossi	+		+		+			+				
Ephemerella rotunda			+		+					+		

Taxon	**Beav**	**Craw**	**Cull**	**Haw**	**John**	**King**	**Rich**	**Scot**	**Shel**	**Soco**	**Swan**	**Swee**
Ephemerella subvaria		+	+				+	+		+		
Eurylophella spp.	+			+	+	+	+	+		+	+	
Serratella sp.	+	+	+		+		+	+		+		
FAMILY HEPTAGENIIDAE												
Cinygmula subaequalis			+		+	+		+		+		
Epeorus pleuralis	+		+	+	+	+		+		+		
Epeorus vitreus	+	+	+		+	+	+	+		+		
Rhithrogena spp.			+		+	+		+		+		
Stenacron carolina			+			+						
Stenacron interpunctatum	+											
Stenacron pallidum		+	+	+	+	+	+			+		
Stenonema carlsoni	+											
Stenonema exiguum			+									
Stenonema ithaca			+	+			+				+	
Stenonema mediopunctatum				+							+	
Stenonema modestum	+			+	+	+	+	+	+	+	+	
Stenonema pudicum	+	+	+	+	+	+	+	+	+	+	+	
Stenonema terminatum	+			+	+	+	+	+	+	+	+	+
Stenonema vicarium	+											
FAMILY ISONYCHIIDAE												
Isonychia bicolor				+	+			+		+		
FAMILY LEPTOPHLEBIIDAE												
Paraleptophlebia spp.	+			+	+	+	+	+		+		
FAMILY NEOEPHEMERIDAE												
Neoephemera purpurea										+		
ORDER ODONATA												
Suborder Anisoptera												
FAMILY AESHNIDAE												
Aeshna umbrosa	+											

Taxon	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
FAMILY CORDULEGASTRIDAE												
Cordulegaster maculata			+									
FAMILY GOMPHIDAE												
Gomphus sp.			+	+								
Lanthus sp.	+		+		+					+		
Ophiogomphus mainensis							+			+		
Suborder Zygoptera												
FAMILY CALOPTERYGIDAE	+											
ORDER PLECOPTERA												
FAMILY CAPNIIDAE												
Allocapnia sp.						+				+		
Paracapnia angulata					+							
FAMILY CHLOROPERLIDAE												
Haploperla brevis			+		+	+		+		+		
Sweltsa spp.					+	+		+		+		
FAMILY LEUCTRIDAE												
Leuctra sp.			+	+	+	+		+		+		
Paraleuctra sara	+		+			+						
FAMILY NEMOURIDAE												
Amphinemura delosa					+					+		
Prostoia similis						+						
FAMILY PELTOPERLIDAE												
Peltoperla sp.						+						
Tallaperla sp.			+		+	+				+		
FAMILY PERLIDAE												
Acroneuria abnormis	+		+		+	+		+		+	+	
Paragnetina immarginata			+		+	+	+	+		+	+	
FAMILY PERLODIDAE												
Cultus decisus			+		+			+		+		

Taxon	**Beav**	**Craw**	**Cull**	**Haw**	**John**	**King**	**Rich**	**Scot**	**Shel**	**Soco**	**Swan**	**Swee**
Isogenoides hansoni					+					+		
Isoperla bilineata	+				+	+		+		+		
Isoperla marlynia			+							+		
Isoperla orata						+						
Malirekus hastatus					+							
Yugus bulbosus			+		+	+		+				
FAMILY PTERONARCYIDAE												
Pteronarcys sp.	+		+		+			+		+		
ORDER MEGALOPTERA												
FAMILY CORYDALIDAE												
Corydalus cornutus											+	+
Nigronia serricornis	+							+		+		
ORDER COLEOPTERA												
FAMILY CHRYSOMELIDAE					+							
FAMILY CURCULIONIDAE										+		
FAMILY DYTISCIDAE												
Hydrovatus pustulatus										+		
FAMILY ELMIDAE												
Dubiraphia bivittata		+				+						
Microcylloepus pusillus			+	+								
Optioservus ovalis	+	+	+	+	+	+	+	+		+	+	
Oulimnius latiusculus	+	+	+	+	+	+	+	+	+	+	+	+
Promoresia elegans			+		+		+	+		+		
Promoresia tardella			+		+			+		+		
Stenelmis sp.	+	+	+	+				+	+		+	+
FAMILY HYDROPHILIDAE								+				+
FAMILY PSEPHENIDAE												
Ectopria sp.	+		+	+	+			+		+	+	+
Psephenus herricki	+	+	+	+	+	+	+	+	+	+	+	

Taxon	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
ORDER LEPIDOPTERA												
FAMILY NOCTUIDAE							+	+		+		
FAMILY PYRALIDAE					+			+		+	+	
ORDER TRICHOPTERA												
FAMILY BRACHYCENTRIDAE												
Brachycentrus sp.			+			+		+		+		
Micrasema sp.			+	+	+		+	+		+	+	
FAMILY GLOSSOSOMATIDAE												
Glossosoma sp.	+		+			+	+	+	+	+		
FAMILY GOERIDAE												
Goera calcarata			+		+			+		+		
Goerita semata	+											
FAMILY HYDROPSYCHIDAE												
Arctopsyche irrorata					+							
Cheumatopsyche sp.	+	+	+	+	+	+	+	+	+	+	+	+
Diplectrona modesta	+		+	+	+	+	+	+	+	+	+	+
Hydropsyche betteni	+	+		+	+				+	+	+	+
Hydropsyche bronta	+		+	+	+		+	+	+	+	+	
Hydropsyche demora											+	
Hydropsyche macleodi					+	+		+				
Hydropsyche morosa	+											
Hydropsyche slossonae					+					+		
Hydropsyche sparna	+		+		+		+	+		+	+	
Hydropsyche venularis	+	+	+	+	+	+	+	+	+	+	+	+
FAMILY HYDROPTILIDAE												
Leucotrichia pictipes	+						+		+		+	
Neotrichia sp.					+					+		+
FAMILY LEPIDOSTOMATIDAE												
Lepidostoma sp.						+						

Taxon	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
FAMILY LEPTOCERIDAE												
Oecetis cinerascens										+		
Setodes sp.										+		
FAMILY LIMNEPHILIDAE												
Hydatophylax argus					+							
Pycnopsyche sp.					+							
FAMILY PHILOPOTAMIDAE												
Dolophilodes sp.	+			+	+	+		+		+	+	+
FAMILY POLYCENTROPODIDAE												
Polycentropus sp.	+		+		+	+		+		+		
FAMILY PSYCHOMYIIDAE												
Lype diversa		+		+			+			+		
Psychomyia flavida			+							+		
Psychomyia nomada										+		
FAMILY RHYACOPHILIDAE												
Rhyacophila amicis					+					+		
Rhyacophila atrata			+		+	+		+		+		
Rhyacophila carolina			+		+			+		+		
Rhyacophila fuscula	+		+		+			+		+		
Rhyacophila minor								+		+		
ORDER DIPTERA												
FAMILY ATHERICIDAE												
Atherix lantha							+			+		
FAMILY BLEPHARICERIDAE												
Blephariccera sp.			+		+		+	+		+		
FAMILY CERATOPOGONIDAE												
Atrichopogon sp.	+					+						+
Dasyhelea sp.			+									
Palpomyia sp.			+			+						

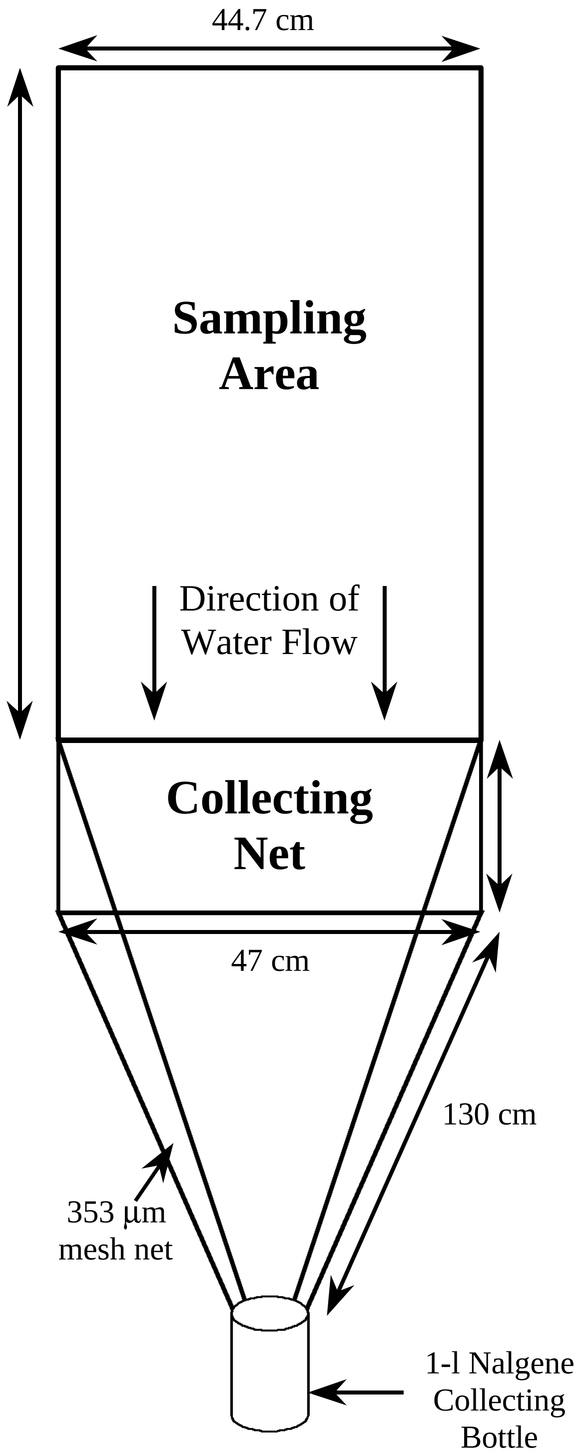
Taxon	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
Probezzia sp.	+		+		+					+	+	
Stilobezzia sp.		+	+						+	+	+	
FAMILY CHIRONOMIDAE												
SUBFAMILY CHIRONOMINAE												
Tribe Chironomini												
Cryptochironomus sp.			+	+			+	+	+	+		
Demicryptochironomus cuneatus	+		+			+				+		
Microtendipes pedellus	+		+									
Parachironomus sp.	+		+	+								+
Polypedilum aviceps	+			+	+	+				+		
Polypedilum convictum	+		+	+	+	+	+				+	+
Polypedilum laetum												+
Polypedilum scalaenum											+	
Polypedilum tritum				+								
Polypedilum sp. C							+					
Robackia demeijerei										+		
Saetheria tylus								+				
Stenochironomus sp.										+		
Tribe Tanytarsini												
Micropsectra sp.					+	+						
Rheotanytarsus sp.	+		+				+					
SUBFAMILY DIAMESINAE												
Diamesa sp.		+	+		+	+	+	+	+	+		+
Potthastia longimana		+	+	+	+						+	+
Sympotthastia sp.							+			+		
SUBFAMILY ORTHOCLADIINAE												
Brillia flavifrons		+		+	+	+	+		+	+		+
Brillia parva					+							
Cardiocladius obscurus											+	

Taxon	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
Corynoneura taris	+			+			+		+			
Cricotopus/Orthocladius Complex	+	+	+	+	+	+	+	+	+	+	+	+
Cricotopus bicinctus							+					
Cricotopus trifasciatus		+					+				+	+
Diplocladius cultriger			+									
Eukiefferiella brehmi	+			+	+			+				
Eukiefferiella brevicalcar	+		+		+			+		+		
Eukiefferiella claripennis	+	+	+	+			+			+		
Eukiefferiella devonica			+					+				
Eukiefferiella gracei											+	
Eukiefferiella pseudomontana							+	+				
Limnophyes sp.			+		+	+	+		+			
Nanocladius sp.							+					
Orthocladius annectens		+		+				+	+			+
Orthocladius obumbratus			+			+		+	+	+	+	+
Orthocladius oliveri		+			+	+	+	+			+	+
Parachaetocladius sp.			+		+	+		+		+		
Paracricotopus sp.					+							
Parametriocnemus lundbeckii	+							+		+	+	
Paratrichocladius sp.										+		
Rheocricotopus tuberculatus			+		+	+				+		+
Synorthocladius sp.							+					
Thienemanniella xena	+	+	+	+	+	+				+	+	+
Tvetenia sp.	+		+		+						+	
Zalutschia briani	+											
SUBFAMILY TANYPODINAE												
Alotanypus sp.					+							
Conchapelopia sp.	+	+	+	+	+	+	+	+	+	+	+	+
Monopelopia boliekae									+			

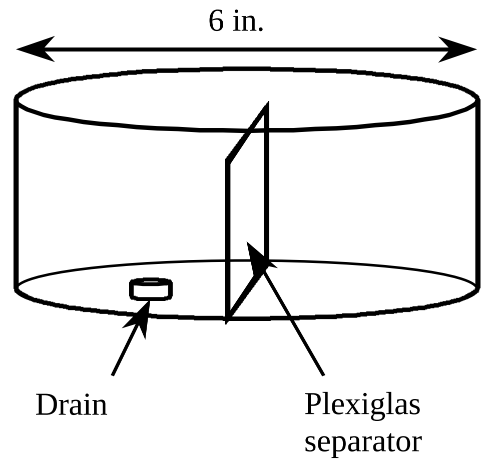
Taxon	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
Nilotanypus spp.	+					+					+	
FAMILY CULICIDAE												
Anopheles sp.										+		
FAMILY EMPIDIDAE												
Chelifera sp.			+	+	+	+		+	+	+		+
Clinocera sp.	+		+	+		+		+		+	+	
Hemerodromia sp.	+	+	+	+	+	+	+	+	+	+	+	+
FAMILY PSYCHODIDAE	+		+	+					+	+		
FAMILY SIMULIIDAE												
Prosimulium spp.	+	+	+	+	+	+	+	+	+	+	+	+
Simulium spp.	+		+	+	+	+	+	+		+	+	
FAMILY STRATIOMYIDAE												
Nemotelus sp.						+						
FAMILY TABANIDAE												
Chrysops sp.					+	+						
FAMILY TANYDERIDAE												
Protoplasa fitchii			+			+		+				
FAMILY TIPULIDAE												
Antocha sp.	+	+	+	+	+	+	+	+	+	+	+	+
Dicranota sp.	+		+		+	+		+		+		
Hexatoma sp.	+	+	+		+	+		+		+	+	
Molophilus sp.						+						
Tipula spp.	+		+	+	+	+	+	+	+	+	+	+

Non-Insect Taxon	Beav	Craw	Cull	Haw	John	King	Rich	Scot	Shel	Soco	Swan	Swee
PHYLUM PLATYHELMINTHES												
CLASS TURBELLARIA	+		+	+	+	+	+		+		+	
PHYLUM NEMATODA	+	+	+	+	+	+	+	+	+	+	+	+
PHYLUM ANNELIDA												
CLASS OLIGOCHAETA	+	+	+	+	+	+	+	+	+	+	+	+
PHYLUM ARTHROPODA												
Subphylum Chelicerata												
CLASS ARACHNIDA												
ORDER HYDRACARINA	+	+	+	+	+	+	+	+	+	+	+	+
Subphylum Crustacea												
CLASS COPEPODA	+	+		+		+	+		+			+
CLASS MALACOSTRACA												
ORDER AMPHIPODA												
Family Asellidae	+										+	+
ORDER ISOPODA												
Family Gammaridae				+			+	+				
ORDER DECAPODA												
Family Cambaridae	+	+		+	+		+		+	+		+
Subphylum Uniramia (incl. Insecta)												
CLASS ENTOGNATHA												
ORDER COLLEMBOLA	+	+		+			+		+			+
PHYLUM MOLLUSCA												
CLASS BIVALVIA	+		+	+	+		+	+		+	+	+
CLASS GASTROPODA												
SUBCLASS PROSOBRANCHIA												
Family Pleuroceridae	+		+	+			+	+	+		+	
SUBCLASS PULMONATA												
Family Ancylidae	+	+	+	+	+		+	+	+	+	+	

Stream Sampler



Sample Splitter



Curriculum Vitae

CURRICULUM VITAE
for
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EDUCATION

1987-91	Governor Mifflin High School, Shillington, Pennsylvania, USA
1991-95	Bucknell University, B. S. in Biology, Lewisburg, Pennsylvania, USA
1995-present	Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA

EMPLOYMENT

1991-95	Animal care technician, Biology Department Animal Facility, Bucknell University
1993-95	Research assistant, Biology Department, Bucknell University
1992-95	Teaching assistant, Biology Department, Bucknell University
1995-present	Teaching assistant, Department of Biology, Virginia Polytechnic Institute and State University
1996-present	Research assistant, Department of Biology, Virginia Polytechnic Institute and State University

Courses Taught:

Introductory Biology Lab - Bucknell University
Cellular and Molecular Biology Lab - Bucknell University
Plant and Animal Physiology Lab - Bucknell University
Population and Community Biology Lab - Bucknell University
General Biology Lab - Virginia Polytechnic Institute and State University
Principles of Biology Lab - Virginia Polytechnic Institute and State University
Field and Lab Ecology - Virginia Polytechnic Institute and State University
Aquatic Entomology – Virginia Polytechnic Institute and State University

RESEARCH

1993	Research assistant, DNA Sequencing, Dr. J. Tonzetich, Biology Department, Bucknell University
1993-94	Environmental research, Groundwater chemistry and bacteria of the Montandon Marsh, Northumberland Co., Pennsylvania, USA
1993-95	Research assistant, Water chemistry of streams in different physiographic regions of New Zealand, Dr. W. F. McDiffett, Biology Department, Bucknell University
1994-95	Environmental research, Treating the first flush: artificial wetland stormwater runoff treatment project, Bucknell University
1995-present	Biodiversity of stream benthic macroinvertebrate assemblages along an urban land use gradient, Master's research, Virginia Polytechnic Institute and State University
1996-present	Effects of leaf litter exclusion and wood removal on phosphorus and nitrogen retention in a first-order forest stream, Dr. J. R. Webster, Virginia Polytechnic Institute and State University

PROFESSIONAL ACTIVITIES

Memberships in Professional Associations:

American Institute of Biological Sciences
American Society of Limnology and Oceanography
Ecological Society of America
North American Benthological Society
Virginia Academy of Science

Professional Involvement:

Representative and liaison for the Human Resources Committee and Graduate Resources Committee of the North American Benthological Society, 1998-present
Coordinator for Prospective Biology Graduate Student Lunches, 1997-present
Biology Graduate Student Assembly Social Chair, 1996-1998
Faculty and Graduate Student Photograph Board Coordinator, 1996
Judge, Virginia Junior Academy of Science, 56th Annual Meeting, Blacksburg, Virginia, 20-23 May 1997

PUBLICATIONS

In Preparation:

Webster, J. R., J. L. Tank, J. B. Wallace, J. L. Meyer, S. L. Eggert, T. P. Ehrman, B. R. Ward, B. L. Bennett, P. F. Wagner, and M. E. McTammany. 1998. Effects of litter exclusion and wood removal on phosphorus and nitrogen retention in a forest stream (in prep).

CONFERENCES

Abstracts and Presentations:

M. E. McTammany, J. S. Harding, E. F. Benfield, P. V. Bolstad, and G. A. Edwards. The impact of urbanization type and degree on benthic macroinvertebrates and stream quality. Long-Term Ecological Research Meeting: Coweeta Hydrologic Laboratory; Athens, Georgia; 15-16 June 1998

M. E. McTammany, J. S. Harding, E. F. Benfield, P. V. Bolstad, and G. A. Edwards. The impact of different degrees and types of urbanization on benthic macroinvertebrates in southern Appalachian streams: potential mechanisms for land use impact. American Society of Limnology and Oceanography/Ecological Society of America Joint Meeting; St. Louis, Missouri; 7-12 June 1998

M. E. McTammany, J. S. Harding, E. F. Benfield, P. V. Bolstad, and G. A. Edwards. Mechanisms of macroinvertebrate response to urbanization: gradients of degree and type. North American Benthological Society, 46th Annual Meeting; Prince Edward Island, Canada; 2-5 June 1998

M. E. McTammany, J. S. Harding, and E. F. Benfield. 1997. Biodiversity in urbanized stream systems of the southern Appalachians. Long-Term Ecological Research Meeting: Coweeta Hydrologic Laboratory; Athens, Georgia; 16-17 June 1997

M. E. McTammany, J. S. Harding, and E. F. Benfield. 1997. Do stream invertebrate assemblages reflect variations in watershed urbanization? North American Benthological Society, 45th Annual Meeting; San Marcos, Texas; 27-30 May 1997

J. R. Webster, J. L. Tank, J. B. Wallace, J. L. Meyer, S. L. Eggert, T. P. Ehrman, B. R. Ward, B. L. Bennett, P. F. Wagner, and M. E. McTammany. Effects of leaf litter exclusion and wood removal on phosphorus and nitrogen retention in a first-order forest stream. North American Benthological Society, 45th Annual Meeting; San Marcos, Texas; 27-30 May 1997

M. E. McTammany, J. S. Harding, and E. F. Benfield. 1997. Biodiversity and differential urbanization in southern Appalachian stream ecosystems. Virginia Academy of Science, 75th Annual Meeting; Blacksburg, Virginia; 20-23 May 1997

Attended:

Long Term Ecological Research Meeting: Coweeta Hydrologic Laboratory; Athens, Georgia; 17-18 June 1996

North American Benthological Society, 44th Annual Meeting; Kalispell, Montana; 3-7 June 1996

GRANTS & FELLOWSHIPS

Travel Fund Project, Graduate Student Assembly, Virginia Polytechnic Institute and State University, Spring 1998

General Endowment Travel Award, North American Benthological Society, 1998

Graduate Research Development Project, Graduate Student Assembly, Virginia Polytechnic Institute and State University, Summer 1997

Travel Fund Project, Graduate Student Assembly, Virginia Polytechnic Institute and State University, Spring 1997

McKenna Environmental Research Fellowship, funded June-August 1993 and June-August 1994

HONOR SOCIETIES

Sigma Xi - General science society, inducted 1998, Virginia Polytechnic Institute and State University

Phi Kappa Phi - Graduate student honor society, inducted 1996, Virginia Polytechnic Institute and State University

Phi Sigma - Biological sciences honor society, inducted 1995, Bucknell University

Alpha Lambda Delta - First-year student honor society, inducted 1992, Bucknell University

REFERENCES

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Dr. J. R. Voshell, Jr., Department of Entomology, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

Dr. W. F. McDiffett, Department of Biology, Bucknell University, Lewisburg, PA 17837