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Southern two-lined salamanders in urbanizing watersheds

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Abstract Forested riparian buffers are an increasingly common method of mitigating the negative effects of impervious surface cover on water quality and wildlife habitat. We sampled larval southern two-lined salamanders (*Eurycea cirrigera*) in 43 streams, representing the range of impervious surface cover and forested riparian buffer width across Wake County, NC, USA. Larval abundance decreased with increasing impervious surface cover in the upstream catchment, but was not affected by buffer width. This is likely a result of an incomplete buffer system and culverts or other breaches along streams. Larval abundance increased with detritus cover in the stream to a threshold and then decreased as detritus continued to increase. As percent pebble substrate in the stream increased, especially in perennial streams, larval salamander abundance also increased. We suspect salamanders were unable to migrate with the water column during dry periods in intermittent streams with sedimented interstices below the surface, resulting in low abundances. A combination of increased peak flows and sedimentation, reduced base flow, and chemical changes likely reduces the abundance of salamanders in urban and suburban streams. We suggest creation of catchment-wide, unbreached buffers to maintain the integrity of stream habitats in urbanizing watersheds.

Keywords Eurycea cirrigera · Forested buffer · Impervious surface · North Carolina · Stream ecology · Urbanization · Water quality · Watershed management

Introduction

Urbanization is one of the major concerns of the twenty-first century, affecting transportation, urban planning, water resources, parks and recreation, commerce, taxation, emergency services, utilities, and people (Jensen and Cowen 1999). Much of urban development has moved away from city-center designs to a sprawling, dendritic pattern

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(Carlson and Arthur 2000). Commercial development has followed the major roadways while residential development follows a more dispersed pattern, converting agricultural and forestland along rural roads (Carlson and Arthur 2000). In the USA, the conversion of land to urban and suburban uses is driven by changing social conditions as well as human population growth. Even in regions with stable or decreasing populations, land still is being converted as society trends towards fewer people per house and more second and vacation home ownership (Burchell et al. 2002).

Urbanization causes many changes in the landscape, including increased impervious surface cover. Impervious surfaces, such as rooftops and roads, prevent water from penetrating into the soil. Increased impervious surface cover changes stream flow patterns through more rapid peaking of floods, greater peak discharge, reduced groundwater recharge, and reduced base-flow. This modifies channel dimensions (width and depth), bankfull discharge, and sediment supply (Paul and Meyer 2001; Wang et al. 2001; Jennings and Jarnagin 2002), and results in decreased substrate and bank stability, accelerated channel erosion, and habitat simplification (Booth et al. 2002). As runoff increases, chemical changes to waterways also occur, including increased suspended solids, increased concentrations of heavy metals, and a decrease in dissolved oxygen (Paul and Meyer 2001; Gray 2004).

Relatively small changes in impervious surface cover can cause major changes in aquatic biota. These changes often are detected before physical or chemical changes in the water (Wang et al. 2001; Wang et al. 2003). Aquatic macroinvertebrate responses are best studied, with increased impervious surface cover resulting in decreased abundance, rapid loss of sensitive species, and decreased diversity (Paul and Meyer 2001; Gray 2004). As little as 6% impervious surface cover can affect aquatic macroinvertebrates, while changes in water quality might not be detected until 45% impervious surface cover (Morse et al. 2003).

Forested riparian buffers often are used to mitigate the effects of impervious surface cover. Buffers are permanent areas of vegetation between pollutant sources and a receiving water body, managed separately from adjacent land (Viaud et al. 2004). Forested buffers can provide stream bank stability, maintain thermal and hydrologic regimes, and reduce pollution from sediment, nutrients, and pesticides (Muscott et al. 1993; Jones et al. 1999; Tomer et al. 2003; Viaud et al. 2004). Forested riparian buffers also can provide critical habitat for semi-aquatic species, including herptile breeding, foraging, and migration habitat (Semlitsch and Bodie 2003). Because of their benefits, governments at many jurisdictional levels have recommended or implemented forested riparian buffer standards (Tomer et al. 2003; Willson and Dorcas 2003). Forested riparian buffers typically are regulated by their width (Lee et al. 2004); however, the effectiveness of this approach is debated (Tomer et al. 2003).

Stream plethodontid salamanders are widespread, abundant, and have been suggested as an effective bioindicator of water quality (Rocco and Brooks 2000). Salamanders serve as an important predator in aquatic systems and a main prey species for many terrestrial animals, facilitating an essential energy flow from aquatic to terrestrial. The loss of salamander abundance and diversity in urban streams critically modifies trophic relationships, altering small stream ecology (Minton 1968; Orser and Shure 1972; Rocco and Brooks 2000; Willson and Dorcas 2003). Despite these qualities, salamanders are notably under-studied in urban environments. Two studies that investigated the effects of urbanization on stream salamanders revealed that urbanization and other land disturbance reduces stream salamander abundance and diversity (Orser and Shure 1972; Willson and Dorcas 2003). Our research builds on this previous work by examining a wider range of buffer width and impervious surface combinations at a greater number of sites, and using continuous measurements of impervious surface cover and forested riparian buffer width.

This study also adds another dimension to Greenways for Wildlife, an ongoing research program being conducted in Wake County, NC. Greenways often are constructed as a means of mitigating some of the negative effects of development, with hundreds of projects completed or underway in North America (Searns 1995; Jongman and Pungetti 2004; Bryant 2006). Although often stated as a benefit of greenways in urban and suburban settings, the contribution of greenways to wildlife conservation is unclear (Schiller and Horn 1997; Sinclair et al. 2005). If urban and landscape planners are to successfully incorporate the needs of wildlife into greenway planning, design, and management, they must know which characteristics and environmental factors contribute to a greenway's wildlife habitat value. Ecologists and conservation biologists can play an important role in this endeavor by conducting research on wildlife–greenway relationships and disseminating their findings among land use planners (Miller and Hobbs 2002; Broberg 2003; Jongman and Pungetti 2004). The goal of the Greenways for Wildlife program is to provide information to greenway and urban planners as they incorporate the requirements of native plants and wildlife into their designs (Sinclair et al. 2005; Hess and Moorman 2006; Mason et al. in press).

Objectives

Our study was designed to investigate the effects of impervious surface cover and forested riparian buffer width on abundance of stream salamanders. Physical and chemical stream properties were measured to account for local habitat effects. We sampled salamanders in 43 streams, representing the range of impervious surface cover and forested riparian buffer width combinations across Wake County, NC, USA in 2004. Our goals were to determine in more detail than previous studies the point at which increasing levels of impervious surface cover affect salamanders; to determine if adjacent forested buffers mitigate the effects of impervious surfaces distributed throughout the watershed; and to provide management recommendations for greenway and city planners.

Materials and methods

Study area

Wake County is located in central North Carolina and is home to the state capital, Raleigh. With an area of 2,225 km^2, Wake County is experiencing rapid population growth. The population reached 750,000 people in the year 2005 and is expected to exceed one million people by 2016 (Wake County 2006). The number of houses in Wake County is projected to increase 37.5% between 2000 and 2025 (Burchell et al. 2002). In the face of continued population growth and development pressures, Wake County and several municipalities within the county have increased efforts to protect open space (Wake County 2006). These efforts include the protection of greenways, largely along streams and in conjunction with the establishment of sewer line easements.

Wake County is in the Piedmont region of North Carolina with a primary underlying geology of Triassic and Raleigh metamorphic belt. It is part of the Neuse and Cape Fear River basins that drain southeast to the Atlantic Ocean (Wake County 2006). The monthly average temperature ranges from 4.2 to 26.0°C with a mean annual rainfall of 115 cm

(NOAA et al. 2000). The county exhibits a range of urban to rural land uses, including industrial, commercial, residential, agriculture, grass, coniferous forest, deciduous forest, mixed forest, and open water land cover types (Wake County 2006).

Site selection and sample design

We sampled streams associated with greenways in Wake County. Working along the greenways provided a consistent linear feature, facilitated access, and ensured some degree of protection against forest buffer modifications during sampling. We used a geographic information system to select potential sites from all the greenways in Wake County associated with stream corridors. We measured the upstream catchment area of each potential site using the United States Geological Survey (USGS) 10-m digital elevation model (DEM), ArcGIS 8.3, and the ArcGIS extension ArcHydro. We identified all sites with (1) a flowing stream; (2) a catchment between 0.65 and 1.95 km^2 to control for stream size; and (3) a forested buffer of constant width for a 50-m reach along which there were no culverts, dams, or other direct human disturbance. Thirty-nine sites met these criteria and provided a wide range of impervious surface cover and riparian buffer width combinations (Fig. 1). We also included four reference sites within William B. Umstead State Park, in a 22-km^2 protected area in Wake County. Though historically disturbed for agriculture, these sites served as a reference for salamander abundance in streams with almost completely forested catchments. Impervious surface in the reference sites was less than 6% and limited to park roads and low-density residential development at the extreme upstream portions of the catchments.

Each of the 43 sites was sampled three times—once in April, May, and November. We sampled three sites per day and used Latin squares to randomize sampling order by day and time to avoid, for example, always sampling streams with wide buffers in the morning.

Salamander sampling

The initial design of our study included sampling five historically common stream salamander species: northern dusky salamander (*Desmognathus fuscus*), southern two-lined salamander (*Eurycea cirrigera*), three-lined salamander (*Eurycea guttolineata*), mud salamander (*Pseudotriton montanus*), and red salamander (*Pseudotriton ruber*). Mud and red salamanders were not observed during preliminary sampling, and northern dusky and three-lined salamanders were very rare. Southern two-lined salamanders (*E. cirrigera*),

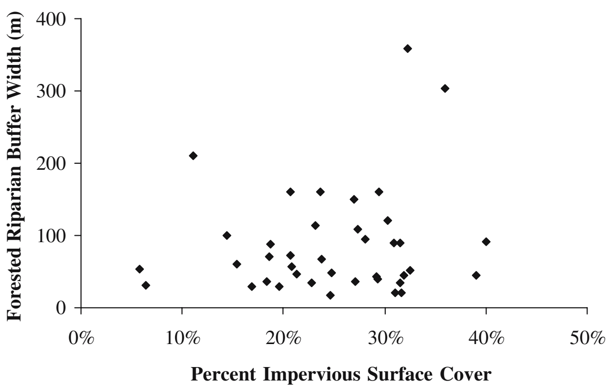


Fig. 1 Distribution of percent impervious surface cover and forested riparian buffer width for 39 non-reference sites sampled in Wake County, NC, USA (2004)

however, were found in varying abundances and became the focus of our study. We further narrowed our focus to larval *E. cirrigera,* which hatch in the spring and remain in the stream for two full years before metamorphosing into adults during the summer of their second year. The larval life stage is obligate-aquatic and most affected by stream changes, whereas adults can seek refuge in terrestrial environments. Because up to three age classes of larvae can be present in a stream at one time, they are abundant at all times of year, allowing easier, consistent sampling.

To sample *E. cirrigera* larvae, we established a 50-m reach at each stream site (Jones et al. 1999). This length provided a good sample of the habitat variability in these small streams. Within each reach, we sub-sampled three 10-m segments: 0–10, 20–30, and 40–50. We searched for salamanders in each 10-m segment from downstream to upstream, removing all surface substrate including rocks, debris, and detritus. Salamanders were captured using a bait net or dip net and placed in a bucket. At the end of the segment, we recorded the age class and length of all individuals before releasing them at the downstream end of the segment. Substrate was replaced to its original condition, and the process was repeated for the second and third segments within a reach.

Habitat sampling

We collected physical, chemical, and biological habitat data at each site to account for the influence of local habitat on salamander abundance. During salamander sampling, we measured date, time, air temperature, and general weather (clear, partly cloudy, partly sunny, or overcast). At each of the three segments within a site, we recorded water temperature, pH, and conductivity using a Hanna combination tester.

We collected additional habitat data for each 10-m segment at all sites in June. Stream width and maximum depth, typically at thalweg, were averaged from three measurements at downstream, mid-section, and upstream locations. We estimated canopy cover using a spherical densiometer at the downstream and upstream points of the segment. The percent of the 10-m segment that was riffle, run, or pool was estimated visually. We visually estimated percent substrate in the classes silt (<0.062 mm), sand (0.062–2 mm), pebble (2.1–45 mm), cobble (46–256 mm), boulder (257–4,096 mm), and bedrock to the nearest 5% (USDA 2006). Detritus, woody debris, and litter were estimated visually as 0, 1, 5%, or the nearest 5% of substrate covered, as were the percent of the stream bank that was undercut and the percent of the bank that had exposed roots. We surveyed the channel profile and calculated a bank-to-height ratio (top of low bank: bankfull) to determine degree of incision.

Impervious surface cover

We measured impervious surface cover in each catchment using USGS 2003 high-resolution, true color, digital orthoimagery of the Raleigh–Durham area. Feature Analyst, Visual Learning Systems' extension, was used within ArcGIS to map impervious surface cover in the imagery (Miller 2005). With training, Feature Analyst can identify classes with similar combinations of color, texture, shape, and pattern. We trained Feature Analyst to identify impervious surfaces using three randomly selected images and applied this training to the 111 images covering our study sites. We used the area of impervious surface within the upstream catchment to calculate the percent impervious surface cover value for each site.

We conducted an accuracy assessment using 252 randomly generated points, with half in areas classified as impervious and half in areas classified as pervious (Congalton 1991). We compared the Feature Analyst classification to the imagery for each point. Using a classification error matrix (Landis and Koch 1977; Congalton 1991), we calculated the overall accuracy to be 91.7%. To determine the agreement between the Feature Analyst classification and the true ground cover, as represented in the imagery, a Kappa Test was used. The Kappa statistic ranges from 0 or no agreement to 1, perfect agreement. We calculated a Kappa of 0.83, $p<0.0001$ (Miller 2005), indicating "almost perfect" agreement between the Feature Analyst classification and imagery (Landis and Koch 1977).

Forested buffer width

We chose to measure forested riparian buffers by width, as that is how they typically are regulated (Lee et al. 2004). Using the USGS 2003 high-resolution, true color, digital orthoimagery of the Raleigh–Durham area, we measured forested riparian buffer width with the ArcGIS measure tool. The total buffer width was measured three times, once at each 10-m segment, and averaged for each reach.

Data analysis

We used the square-root transformation of larval *E. cirrigera* abundance, averaged over April, May, and November as the response variable. The square-root transformation improved the normality of the data. The data analysis for our research was performed using SAS software, version 9.1 (SAS Institute 2003). Stepwise and Mallow's C_p selection methods were used to select significant explanatory variables and develop a linear regression model for the 43 streams. Points of inflection were estimated for quadratic parameters using the formula:

$$-(\beta_1/2\beta_2)$$

where β_1 is the parameter estimate for the first order term and β_2 is the parameter estimate for the quadratic term.

Upon examining the results of our initial analysis, we identified 13 sites that had few or no salamanders despite what appeared to be high-quality habitat. This is a common occurrence in urban and suburban areas of Wake County (Braswell, personal communication). These sites were not outliers; however, we felt they could be better described than with the original model. During June sampling, many streams were noted as being intermittent or having very low surface flow. Streams observed to be flowing during all four field visits were identified as perennial, and streams not flowing in June were identified as intermittent. To investigate this relationship further, we included the interaction between a categorical variable indicating intermittent or perennial flow and all other measured variables. Using stepwise and Mallow's C_p selection methods, a second linear regression model was selected.

Results

Stepwise and Mallow's C_p methods selected impervious surface cover, detritus, pebble substrate, and water conductivity as significant variables with an R^2 of 0.59. Impervious surface cover and detritus had the best fit in a quadratic form (Table 1). Larval *E. cirrigera* abundance declined with increasing impervious surface cover from 0 to 26.6% and

Table 1 Parameter estimates for linear regression model with larval *E. cirrigera* abundance as the dependent variable (R^2=0.59) with points of inflection shown for variables with quadratic terms

Variable (data range)	Mean (standard deviation)	Parameter estimate	*p* values	Inflection point
Intercept		2.69	0.010	
Impervious surface cover (0–40%)	22.5% (9.9%)	−21.74	0.025	
Squared impervious surface cover (0–16%)	6.0% (4.0%)	40.83	0.007	26.6%
Detritus (0–25%)	8.5% (6.6%)	23.11	0.035	
Squared detritus (0–6%)	1.2% (1.7%)	−149.97	0.019	11.4%
Pebble substrate (0–83%)	38.8% (24.5%)	3.93	0.007	
Water conductivity (49–384 μS)	126.9 (73.3)	−0.01	<0.0001	

These estimates are based on data from 43 sites in Wake County, NC, USA collected in 2004

increased with increasing impervious surface cover greater than 26.6%. Abundance increased with detritus to 11.4%, after which abundance decreased with increasing detritus. Abundance increased with pebble substrate and decreased with increasing water conductivity (Fig. 2). Forested riparian buffer width had little effect on larval *E. cirrigera* abundance (p=0.21).

When we included the categorical variable for intermittent or perennial flow, a similar model was selected and overall predictability improved to an R^2 of 0.73 (Fig. 3). However, impervious surface cover was significant as a linear, not quadratic, relationship, and water conductivity was no longer significant (Table 2). The interaction of the variables pebble substrate and perennial was significant. We kept the non-significant variables of pebble substrate and perennial in the model to allow the interaction variable to have different intercepts as well as different slopes for each value of the class variable. In perennial streams, larval *E. cirrigera* abundance increased with pebble substrate (Fig. 4a). In intermittent streams, pebble substrate had no effect on larval *E. cirrigera* abundance (Fig. 4b). None of the predictor variables were correlated with percent impervious surface cover.

Discussion

Impervious surface cover, but not forested riparian buffer width, correlated with larval *E. cirrigera* abundance. In our initial analysis, larval *E. cirrigera* abundance decreased as impervious surface cover increased from 0 to 27% impervious surface cover, after which larval abundance increased. The increase after 27% is likely a statistical artifact caused by a shortage of observations at impervious surface levels greater than 35%. After further investigation, we found that larval *E. cirrigera* abundance decreased linearly with increased impervious surface cover. More catchments with high impervious surface cover must be sampled to fully define this relationship.

Other researchers have observed a decline in stream salamander abundance with increasing impervious surface cover (Minton 1968; Orser and Shure 1972; Willson and Dorcas 2003). This trend also has been observed in other aquatic taxa. Mussels experience a 73% loss of species with high impervious surface cover (Gillies et al. 2003), and impervious surface cover negatively affects fish communities (Paul and Meyer 2001; Wang et al. 2001; Wang et al. 2003; Weber and Bannerman 2004). Environmental Protection

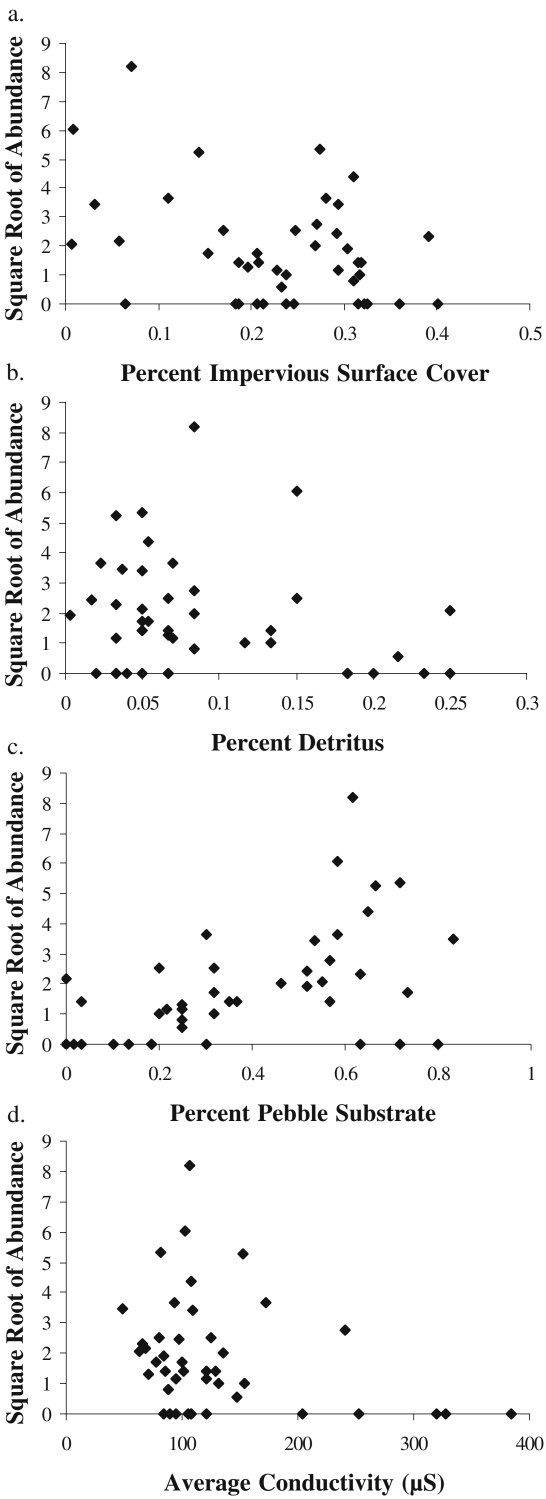
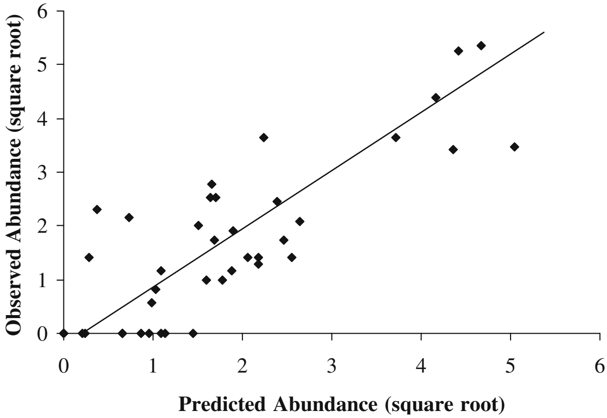


Fig. 2 Relationship between the square root of larval *E. cirrigera* abundance and (a) percent impervious surface cover, (b) percent detritus, (c) percent pebble substrate, and (d) average conductivity

Fig. 3 Observed values of larval *E. cirrigera* abundance versus values predicted by the linear regression model with the intermittent or perennial categorical variable



Agency data in Ohio revealed a loss of sensitive fish species at 5% impervious surface cover (Paul and Meyer 2001).

Our results indicate that the width of forested buffer immediately adjacent to a site does not predict salamander abundance for that site. Buffers protect stream water quality by slowing runoff traveling to the stream, allowing it to percolate into the soil, and intercepting sediment and chemical pollutants (Muscott et al. 1993; Tomer et al. 2003). To be effective, buffers must be implemented catchment-wide, including small headwater streams. This is frequently not the case in urban and suburban areas, including Wake County, NC. Furthermore, culverts, piping, and ditches, common in urban and suburban areas, bypass the buffers, allowing contaminated water to flow directly into the stream, as demonstrated in agricultural settings (Muscott et al. 1993). Although the buffers along our 50-m reaches were not bypassed, there were breaches upstream, including within the designated greenway areas. Managers of buffers, including greenways, should remove existing bypasses and prevent future breaches to maintain an intact, effective buffer. Future research should incorporate an improved predictive variable, quantifying buffers catchments-wide and accounting for culverts and other breaches.

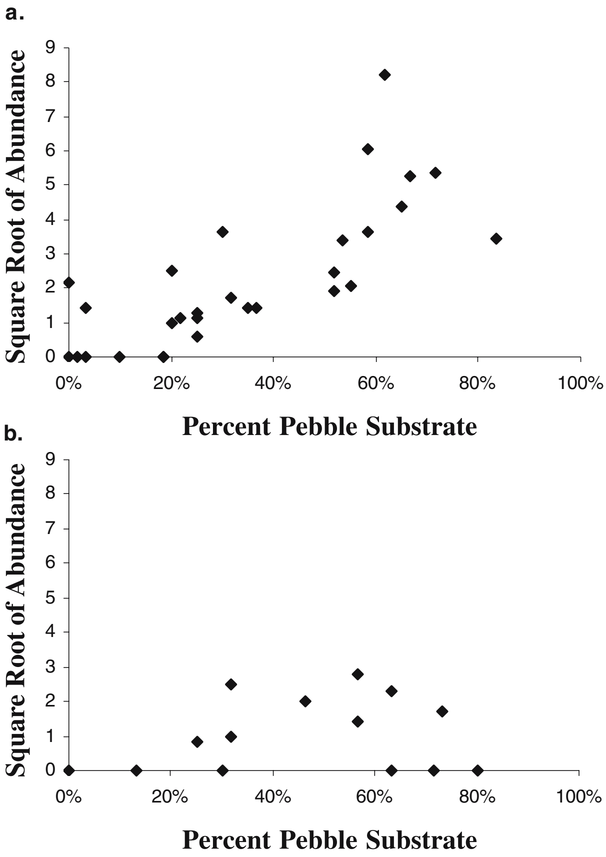
Local habitat is also important to larval *E. cirrigera* abundance. Larval *E. cirrigera* abundance increased with detritus to 12% detritus cover, above which larval *E. cirrigera* abundance declined. Some detritus provides shelter and food for salamanders and their prey, such as aquatic invertebrates, but high levels of detritus might lead to high bacterial

Table 2 Parameter estimates for additional linear regression model, using the categorical variable for perennial and intermittent streams, with larval *E. cirrigera* as the dependent variable (R^2=0.73) with points of inflection are shown for variables with quadratic terms

Variable (data range)	Parameter estimate	*p* values	Inflection point
Intercept	−0.17	0.891	
Impervious surface cover (0–40%)	−3.78	0.043	
Detritus (0–25%)	36.76	0.003	
Squared detritus (0–6%)	−154.72	0.001	11.8%
Pebble substrate (0–83%)	1.52	0.283	
Perennial (0=no, 1=yes)	−0.34	0.675	
Pebble×perennial interaction (0–0.83)	5.12	0.003	

These estimates are based on data from 43 sites in Wake County, NC, USA collected in 2004

Fig. 4 Relationship between the square root of larval *E. cirrigera* abundance and percent pebble substrate in (a) perennial and (b) intermittent streams



decomposition rates and anoxic conditions detrimental to salamanders. Larval *E. cirrigera* abundance increased with increasing pebble substrate, which supports Orser and Shure's (1972) finding that salamander densities increase with available cover. Pebble substrate provides foraging habitat, breeding sites, and cover from predators. In our model, stream water conductivity was not a significant predictor of larval *E. cirrigera* abundance. Water conductivity has been demonstrated to increase with increasing disturbed area within the watershed, and especially with increasing impervious surface cover (Lenat and Crawford 1994; Paul and Meyer 2001; Willson and Dorcas 2003). However, the average water conductivity at each salamander collection site was not correlated with percent impervious surface cover in the watershed or with the abundance of larval *E. cirrigera*, which are relatively insensitive to contaminants.

We noted that several streams with what appeared to be good habitat contained few or no larval *E. cirrigera*. We determined that this was caused by an interaction between low stream flow and substrate composition. Low larval *E. cirrigera* abundance occurred in intermittent streams with sediment-filled interstices. During dry periods in intermittent streams, salamanders migrate down with the water column into the hyporheic zone, or the area below the streambed where water percolates through the spaces between rocks. If these interstices become filled with sediment, salamanders are unable to migrate down with the water column as it falls. Our measure of pebble substrate did not reflect this phenomenon, because it did not include an assessment of sedimentation below the surface. Subsurface characterization of substrate is less important in perennial streams because salamanders do not need to migrate down into the hyporheic zone.

Willson and Dorcas (2003) determined that salamander abundance declined with increasing levels of disturbance (agriculture, residential development, and impervious surface) in a watershed. Time since disturbance (e.g. building a housing subdivision) might be another important variable influencing larval *E. cirrigera* abundance. Some of our sites had high levels of impervious surface constructed predominately in the 1950s and 1960s. These sites had relatively high larval *E. cirrigera* abundance, whereas sites with less impervious surface cover but more recent disturbance had lower larval *E. cirrigera* abundance. In an exploratory analysis using 2005 Wake County tax parcel data (Wake County 2006) to estimate the percent of the catchment built-up for 5-year periods (2000–2005, 1995–1999, 1990–1994, etc.), larval *E. cirrigera* abundance decreased with increased disturbance in a catchment between 2000 and 2005 ($p=0.06$). We suspect increased sediment and run-off associated with new construction reduces abundance. Management to minimize these effects and decrease the time needed to establish a new hydrologic equilibrium might improve colonization in developed streams. Accordingly, temporal and spatial distribution of impervious surface cover should also be considered in future research.

Ecological relationships within a stream are also important. Fish predation was not significant in previous research (Willson and Dorcas 2003) and was not measured for our research. For most streams, the effects of fish are believed to be similar. Three of our sites were located near larger streams or ponds. These sites had lower than expected abundances. It is possible that during high flow events, fish and other predators are introduced into these small streams, reducing salamander abundance. Crayfish interactions also should be considered in future research, as crayfish are a predator of salamander larvae but improve low quality habitat by excavating tunnels through sediment, providing cover for salamanders in sedimented substrate. Anecdotal observations of crayfish suggest that abundances will vary differently than salamander abundances. The effect of macro-invertebrates on salamander abundance is also unclear. Orser and Shure (1972) did not consider macroinvertebrate abundance and diversity to be a limiting factor for salamanders. However, Willson and Dorcas (2003) found both macroinvertebrate and salamander diversity to decline with increased disturbance.

Conclusions

Buffer width at the point of sampling was not sufficient to predict salamander abundance, which suggests that specifying buffer width alone is not an effective strategy for protecting water quality. Rather, buffer systems free of culverts, piping, and ditches should be maintained catchment-wide. Consideration of the temporal and spatial distribution of disturbance may be important when determining the buffer necessary to protect water quality, as a stream might be able to recover, to some degree, with time. Further research spanning multiple years and accounting for breaches of buffers might improve our understanding of the effect of buffers. However, it is important to note that four common salamander species have already been lost or greatly reduced in number in Wake County streams. We suspect this is due to the loss of rocky bank habitat needed by these more sensitive species.

Our findings support the growing body of evidence that increasing impervious surface cover negatively affects stream ecosystems. Larval *E. cirrigera* abundance decreased with increasing impervious surface cover. Previous research has suggested the scouring effects of high flow events to be the cause of reduced salamander abundance (Orser and Shure 1972; Willson and Dorcas 2003). In our study, low flow events were associated with decreased salamander abundance. Salamanders in intermittent streams with sediment-filled substrate interstices are unable to migrate with the water column during dry periods, resulting in lower abundances. More attention needs to be given to hydrologic changes resulting in reduced base flow. Considered with the findings of other researchers, our findings suggest that a combination of hydrologic changes caused by impervious surfaces—increased peak flows, increased sedimentation, reduced base flow, and chemical changes—reduces the abundance of salamanders in urban and suburban streams.

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