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# Effects of Habitat Disturbance on Stream Salamanders: Implications for Buffer Zones and Watershed Management

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**Abstract:** *With human populations increasing worldwide, habitat destruction and degradation are among the greatest threats facing wildlife. To minimize the impacts of development on aquatic habitats, numerous conservation measures have been implemented, including the use of riparian buffer zones along streams and rivers. We examined the effectiveness of current buffer-zone systems for management of small watersheds in conserving stream-dwelling salamander populations in 10 small streams (draining <40.5 ha) in the western Piedmont of North Carolina. We captured salamanders by means of funnel traps and systematic dipnetting and used a geographic information system to calculate the percentage of disturbed habitat within the watershed of each stream and within 10.7-, 30.5-, and 61.0-m buffer zones around each stream, upstream from our sampling locations. Although the relative abundance of salamanders was strongly inversely proportional to the percentage of disturbed habitat in the entire watersheds ( $R^2 = 0.71$  for *Desmognathus fuscus* and 0.48 for *Eurycea cirrigera*), we found little to no correlation between the relative abundance of salamanders and the percentage of disturbed habitat present within buffer zones ( $R^2 = 0.06-0.27$  for *D. fuscus* and 0.01-0.07 for *E. cirrigera*). Thus, conservation efforts aimed at preserving salamander populations in headwater streams must consider land use throughout entire watersheds, rather than just preserving small riparian buffer zones.*

Efectos de la Perturbación de Hábitat sobre Salamandras de Arroyo: Implicaciones para Zonas de Amortiguamiento y Manejo de Cuencas

**Resumen:** *La destrucción y degradación del hábitat se encuentra entre las mayores amenazas a la vida silvestre, junto con el aumento global de la población humana. Para minimizar los impactos del desarrollo sobre hábitats acuáticos, se han instrumentado numerosas medidas de conservación, incluyendo el uso de zonas de amortiguamiento riparias a lo largo de arroyos y ríos. Examinamos la efectividad de los actuales sistemas de zonas de amortiguamiento usados en el manejo de cuencas pequeñas para la conservación de poblaciones de salamandras de arroyo en 10 arroyos pequeños (que drenan <40.5 ha) al pie de monte del occidente de Carolina del Norte. Capturamos salamandras con trampas de embudo y mediante el uso sistemático de redes y utilizamos un sistema de información geográfica para calcular el porcentaje de hábitat perturbado dentro de la cuenca de cada arroyo y dentro de zonas de amortiguamiento de 10.7-, 30.5- y 61.0-m alrededor de cada arroyo, río arriba de nuestros sitios de muestreo. Aunque los valores de abundancia relativa de salamandras fueron inversamente proporcionales al porcentaje de hábitat perturbado en el total de las cuencas ( $R^2 = 0.71$  para *Desmognathus fuscus* y 0.48 para *Eurycea cirrigera*), encontramos una correlación débil o inexistente entre las abundancias relativas de salamandras y el porcentaje de hábitat perturbado en las zonas de amortiguamiento ( $R^2 = 0.06-0.27$  para *D. fuscus* y 0.01-0.07 para *E. cirrigera*). Por lo tanto, los esfuerzos de conservación dirigidos a preservar poblaciones de salamandras de arroyos de cabecera deben tomar en cuenta el uso de la tierra en la superficie entera de las cuencas, en lugar de preservar pequeñas zonas de amortiguamiento riparias.*

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## Introduction

Most scientists consider anthropogenic habitat loss and degradation the most important threat to amphibian populations (e.g., Alford & Richards 1999). Consequently, efforts to conserve amphibians have focused on habitat preservation, particularly preservation of aquatic ecosystems. In the United States, development around water bodies is often regulated in an effort to preserve the aquatic ecosystems of the area (Schlosser & Karr 1980; Allan 1995; Burke & Gibbons 1995; Mecklenburg County Department of Environmental Protection [MCDEP] 2001). Typically, regulations delineate terrestrial "buffer zones" in which development is limited (Barton et al. 1985; Allan 1995). These buffers are designed to prevent erosion and filter runoff of contaminants (U.S. Environmental Protection Agency) and to protect the diverse fauna that requires both aquatic and associated terrestrial habitats (Ahola 1990; Décamps 1993).

Buffer zones required by law around temporary wetland areas are of insufficient size to protect many of the animals that utilize those habitats (Burke & Gibbons 1995; Findlay & Houlahan 1997; Semlitsch 1998; Richter et al. 2001). Like temporary wetlands, small streams also support large populations of amphibians (Petranka & Murray 2001) and are subject to buffer-zone regulations (Omernik et al. 1981; Allan 1995; Cooper et al. 1987). Small streams receive runoff directly from rain and thus are often the first aquatic habitats to be affected by development and pollution (Hoffman et al. 1995).

Buffer-zone regulations for small watersheds have been imposed at numerous jurisdictional levels, primarily to maintain water-quality standards. For example, in Mecklenburg County, North Carolina, currently one of the fastest developing regions in the country (Rice et al. 2001), watershed development is regulated at both county and local levels. Mecklenburg County requires that a 10.7-m forested buffer zone be left alongside creeks and small streams that drain <40.5 ha (MCDEP 2001). Within the county, local regulations vary, requiring stream buffers of between 10.7 and 30.5 m.

In light of increasing development pressures in this region, it is important to determine whether the current buffer-zone system of small-watershed management is sufficient to conserve stream-dwelling salamander populations. In North Carolina, salamanders can constitute much of the animal biomass of small stream habitats and thus play an important role in trophic transfer and energy flow in these ecosystems (Orser & Shure 1975; Petranka & Murray 2001). In addition, salamanders have been touted as bioindicators of environmental integrity (Barinaga 1990; Vitt et al. 1990). The northern dusky salamander (*Desmognathus fuscus*) and southern two-lined salamander (*Eurycea cirrigera*) are the most common stream-dwelling amphibians in the western Pied-

mont of North Carolina (Brown 1992; Petranka 1998). Although the life history and behavioral ecology of these species have been studied, the effectiveness of conservation measures for these species has seldom, if ever, been addressed (Orser & Shure 1972; Petranka 1998).

We investigated the effectiveness of riparian buffer zones in conserving populations of stream-dwelling salamanders in 10 streams within the western piedmont of North Carolina, an area with a broad range of anthropogenic disturbance, ranging from watersheds that are predominantly residential developments to those comprised largely of second-growth forest. Our goal was to evaluate the relationship between buffer zones and salamander abundance by correlating the number of salamanders captured in each stream with the land use within delineated buffer zones and within each watershed.

## Methods

### Description of Study Locations

We selected 10 small (average width, 0.5–1.0 m; draining <40.5 ha), first-order streams located within 8 km of Davidson, North Carolina (Table 1). This region is a mosaic of second-growth (30–60 years old), mixed hardwood-pine forest, agricultural fields and pastures, and recent residential development. Without prior knowledge of salamander abundances, we examined habitat surrounding the stream and its proximity to homes, paved roads, parking lots, cleared fields, and agricultural land to select streams representing a broad range of watershed development. Each stream was a unique subwatershed within the Rocky River Drainage (HUC 03040105), and all were fed predominantly by runoff from precipitation. Although fluctuations in precipitation resulted in most streams being ephemeral during the dry summer months, all streams flowed regularly throughout the study period (February–April 2001).

Sample sections on each stream were chosen based on comparability of width, depth, and current velocity under base-flow conditions. We used a principal components analysis on water temperature, pH, dissolved oxygen, conductivity, mean change in cross-sectional area between base and peak flow periods, percentage of the streambed covered by debris, macroinvertebrate diversity, and percentage of disturbed habitat in each watershed to separate the 10 streams into high, moderate, and low disturbance categories (Fig. 1). All variables used in the principal components analysis were normally distributed when tested for univariate normality, and we standardized them using a correlation matrix.

Streams A–D are low-disturbance streams (Table 1). Streams A and D are located on the Davidson College Ecological Preserve, a protected area of mixed hardwood-pine forest on the Davidson College Campus.

**Table 1. Habitat composition within watersheds<sup>a</sup> of 10 streams in Mecklenburg County, North Carolina.<sup>b</sup>**

Stream	Disturbance level	Forested (%)	Field or agriculture (%)	Residential (%)	Impervious surface (%)	Water (%)	Total disturbed (%)
A	low	91.8	4.7	0.0	0.2	0.0	4.9
B	low	84.4	8.2	2.0	3.9	1.4	14.1
C	low	95.3	8.0	0.0	0.0	0.0	8.0
D	low	80.5	6.5	8.0	4.3	0.7	18.8
E	moderate	66.6	31.0	0.0	2.0	0.4	33.0
F	moderate	79.5	19.4	0.0	1.0	0.0	20.4
G	moderate	60.6	38.8	0.0	0.0	0.7	38.8
H	high	9.7	8.4	46.9	34.2	0.8	89.5
I	high	27.7	26.1	23.0	23.1	0.0	72.2
J	high	25.2	7.6	45.7	21.5	0.0	74.8

<sup>a</sup>Watersheds were delineated with the ArcView script Basin1 (Petras 2000).

<sup>b</sup>Habitat areas were delineated visually with aerial photograph layers in a geographic information system. Streams were separated into high-, moderate-, and low-disturbance categories by a principal components analysis based on water temperature, pH, dissolved oxygen, conductivity, change in flow between base and peak flow periods, percentage of disturbed habitat in the watershed, invertebrate diversity, and percentage of stream bed covered by leaves and debris. Disturbed habitats were classified as field/agricultural, residential, or impervious surfaces.

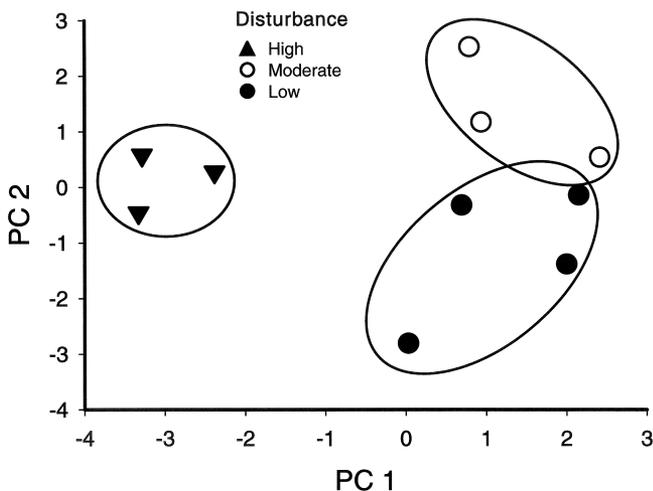
Stream B is located on land owned by the Runny Meade Equestrian Center. This large forested tract of land is subject to minimal disturbance by hikers and riders on horseback. Stream C is located on privately owned, forested land, adjacent to the Davidson College campus and drains some light residential areas.

Streams E–G are moderate-disturbance streams (Table 1). Streams E and F are located on privately owned land about 8 km southeast of Davidson College. The watersheds of these two streams are split between large expanses of second-growth forest and cleared fields or agricultural areas. Siltation as a result of runoff from these fields is evident in both streams. Stream G is also located on privately owned land, <2 km from the Davidson College campus. This stream, though surrounded by a

buffer (approximately 80 m) of forest, drains a large expanse of cattle pasture.

Streams H–J are high-disturbance streams (Table 1). Stream H is located in a residential area of Davidson, North Carolina, eventually emptying into Lake Norman. This stream drains many roads and residential areas with very little forest present within the watershed. Streams I and J flow directly through the Davidson College campus. Although these streams are bordered by forested buffers, large portions of their watersheds are comprised of parking lots, athletic fields, and paved roads.

We used a geographic information system (GIS; ArcView, version 3.2, Environmental Systems Research Institute, Redlands, California) to characterize and quantify the land cover within the watersheds of each of the 10 streams sampled and within the buffer zones required by the county (10.7 m) and town of Davidson (30.5 m) and at double the requirements of Davidson (61.0 m) around each stream. First, we used a handheld global positioning system unit (GPS-12, Garmin Corp., Olathe, Kansas) to pinpoint sampling locations on an aerial photographic layer (1-m resolution, flown in Spring 1999) within the GIS. Next, we used 0.7-m-resolution topographic layers to create an elevation grid, which we then used in conjunction with the ArcView script Basin1 (Petras 2000) to delineate the watershed of each stream. We used the “create buffers” feature in the GIS to delineate 10.7-, 30.5-, and 61.0-m buffers surrounding each stream, upstream from our sampling locations. Within the watersheds and buffer areas, different land-cover types were outlined from the aerial photograph and classified as forest, residential, field/agricultural, impervious surface (such as roads or other paved areas), or water. We calculated (GIS) the areas of these land-cover types and the percentage of each watershed and buffer covered by each. For comparisons with number of salamanders captured, “disturbed” habitats were defined as field/agricultural, residential, or impervious surfaces.



**Figure 1. Principal components analysis based on stream environmental characteristics. Disturbance categories were assigned based on the amount of disturbed habitat present in the watershed and on salamander abundance (see text).**

## Sampling Techniques

We determined relative abundances of instream larval and adult salamanders using a combination of funnel trapping and systematic dipnetting. Our catch consisted predominantly of two salamander species, *Desmognathus fuscus* and *Eurycea cirrigera*. We sampled in early spring, at which time salamanders of both species are concentrated in and around streams (Petranka 1998). *Desmognathus fuscus*, in particular, do not venture far from the stream edge throughout the year and are most active in cool weather (Petranka 1998). Although *E. cirrigera* have been reported at distances of >100 m from streams, we sampled this species during the breeding season, at which time adults remain close to the stream (MacCulloch & Binder 1975; Ashton & Ashton 1978; Petranka 1998). In addition, overwintered larvae of both species were abundant in streams at this time (Petranka 1998). Because of the life-history differences between these two species, we predominantly sampled the breeding population of *E. cirrigera*, whereas our sampling of *D. fuscus* was a more complete population sample.

Each stream was trapped for two 1-week sessions, once between mid-February and early March 2001 and again between mid-March and early April 2001. We used plastic soda-bottle funnel traps (Griffiths 1985; Richter 1995) to capture the salamanders. Each trapping session was conducted in a different 10-m section of stream. Within each section, 12 unbaited funnel traps were anchored with bamboo garden stakes along the stream edge facing into the current (Willson & Dorcas in press). Each set of 12 traps contained a variety of trap sizes (one 3.0-L, four 2.0-L, three 1.0-L, and four 0.6-L bottles) to allow for trapping in a variety of depth and current-velocity locations. During each week-long trapping session, traps were checked every other day, at which time all animals captured were recorded and removed. After checking, we moved each trap a short distance (e.g., 1 m) to a different location within the 10-m stream section to assure that the entire section was trapped thoroughly. Water temperature and pH for each stream were measured with a pH/temperature meter (Piccolo Plus pH/°C, Hanna Instruments, Woonsocket, Rhode Island) each time traps were checked.

All salamanders captured in traps were taken to the laboratory for the remainder of each 1-week trapping session to avoid recaptures. At the end of each trapping session we returned all salamanders to their capture location.

We conducted systematic dipnetting for two 2-day periods, once in late February and once in mid-April. During each period, all streams were netted for a period of 30 minutes per stream. Each netting session was conducted on a different 10-m section of stream (also separate from trapping sections). We focused our efforts on submerged leaves and other underwater cover areas. At the end of each 30-minute netting session, all sala-

manders captured were returned to the stream. During the dipnetting in mid-April, we remeasured water temperature, pH, dissolved oxygen, and conductivity. Additionally, within each 10-m section of stream sampled we estimated the percentage of streambed covered by leaves, debris, and other cover. Estimates were made visually to the nearest 10%.

Because *D. fuscus* and *E. cirrigera* feed largely on aquatic invertebrates and because macroinvertebrate diversity is often used an indicator of stream health, we evaluated macroinvertebrate species richness within each stream. While dipnetting, we retained all macroinvertebrates captured, preserved them in 70% ethanol, and identified them to the most specific taxon possible.

To assess the change in flow between base and peak flow periods, we measured three points in each stream for width and depth within 3 hours of a short but intense rainstorm in early April. The same locations in each stream were measured under base-flow conditions in late April after more than 1 week without precipitation. Because the greatest distance between any two streams was 8 km, and because disturbed and undisturbed streams were not clustered geographically, the effects of uneven rainfall across the study area were minimal. We used linear regression to examine the relationship between numbers of salamanders captured and percentage of disturbed habitat within each watershed and within the delineated buffer zones. We used stepwise multiple regression to examine relationships between numbers of salamanders captured and environmental parameters.

## Results

The principal components analysis based on stream characteristics divided the 10 streams into three distinct disturbance categories (Fig. 1). The first three principal components generated explained 76.4% of the variation in nine stream characteristics. Positive values of principal component (PC) 1 represented low February water temperature, low percentage of streambed covered by leaves and debris, high conductivity, high change in stream cross-sectional area between base and peak flow periods, and high percentage of the watershed composed of disturbed habitat. Positive values of PC 2 represented high April water temperature, low dissolved oxygen, high conductivity, and low macroinvertebrate richness.

Low-disturbance streams all contained <20% disturbed habitat in their watershed (Table 1) and were characterized by low conductivity, high dissolved oxygen, moderate change in cross-sectional area between base and peak flow periods, moderate amounts of leaves, debris, and other cover objects on the streambed, and high macroinvertebrate diversity (Fig. 1). Moderate-disturbance

streams typically had watersheds that were split between forest and field or agricultural areas, including cattle pasture (Table 1). These streams were characterized by moderate conductivity, low dissolved oxygen, low change in cross-sectional area between base and peak flow periods, high amounts of cover on the streambed, and moderate macroinvertebrate diversity (Fig. 1). High-disturbance streams were typically located in highly developed areas and often drained large residential areas and impervious surfaces (Table 1). These streams were characterized by high conductivity, high dissolved oxygen, high change in cross-sectional area between base and peak-flow periods, low amounts of cover on the streambed, and low macroinvertebrate diversity (Fig. 1).

Several stream parameters showed strong correlations with the amount of disturbed habitat present in the watershed. Conductivity rose almost fourfold as the amount of disturbed habitat in the watershed increased from lowest

to highest (Fig. 2a). The change in average cross-sectional area between base and peak flow periods also increased substantially as the amount of disturbed habitat within the watershed increased (Fig. 2b). Invertebrate diversity and the percentage of the streambed covered by leaves and debris were both inversely correlated with the amount of disturbed habitat in the watershed (Fig. 2c & 2d).

Trapping and dipnetting of the 10 study streams yielded 324 salamanders (Fig. 3), predominantly *D. fuscus* and *E. cirrigera*. Three *Pseudotriton ruber* larvae were captured in low- and moderate-disturbance streams but were not included in the analyses. The majority (88%) of the salamanders captured were larvae (Fig. 3). The number of salamanders found per stream ranged between 1 and 75 (Fig. 3).

We found no significant correlation between the amount of disturbed habitat within a 10.7-m stream buffer and the number of salamanders captured in each

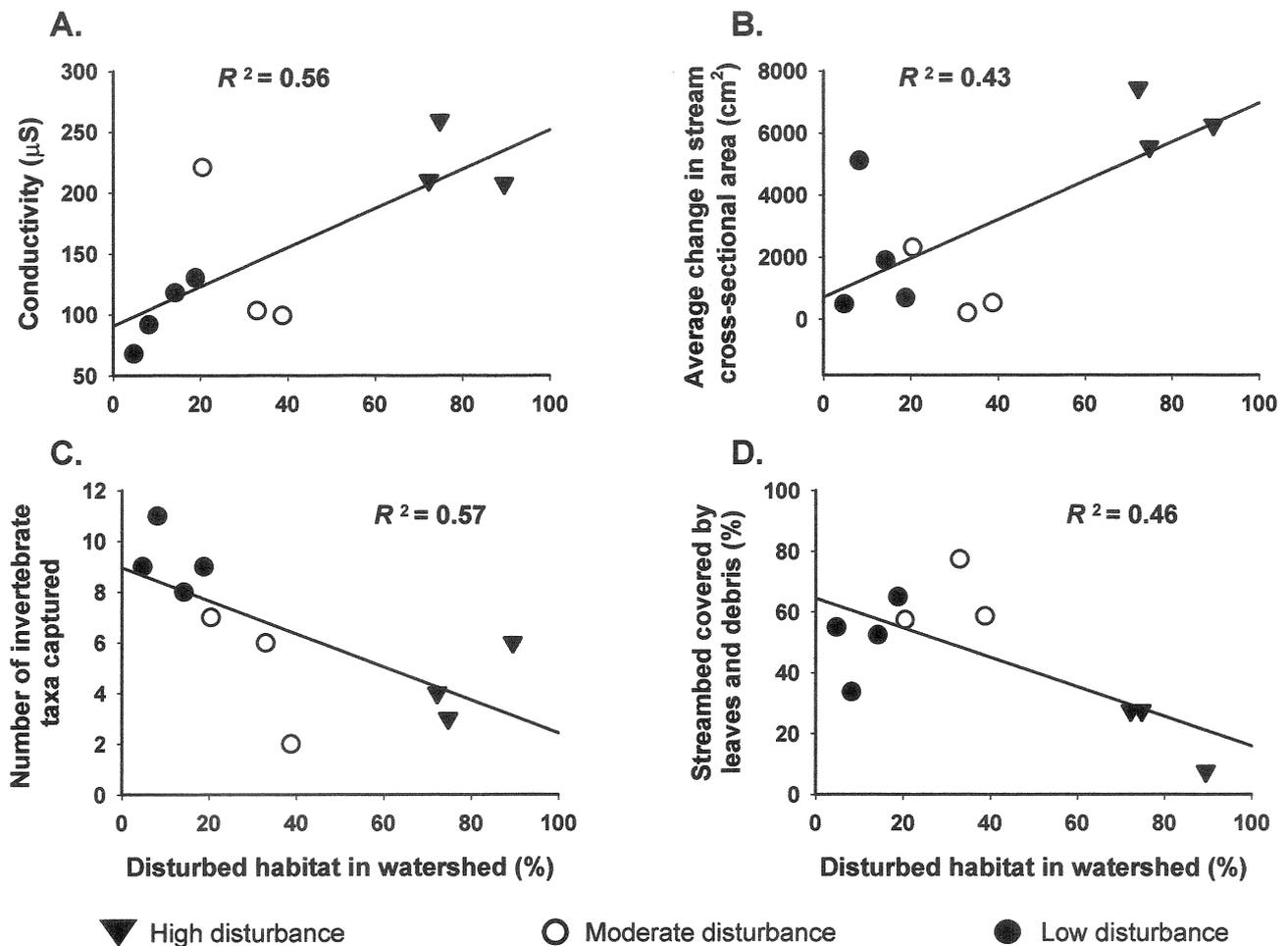


Figure 2. Relationships between (a) conductivity, (b) average change in stream cross-sectional area between base and peak flow periods, (c) invertebrate diversity, and (d) percentage of stream bed covered by leaves and debris and percentage of disturbed habitat present in the watershed. Disturbance categories (high, moderate, low) defined by principal components analysis (Fig. 1). Disturbed habitats included field/agricultural, residential, and impervious surfaces.

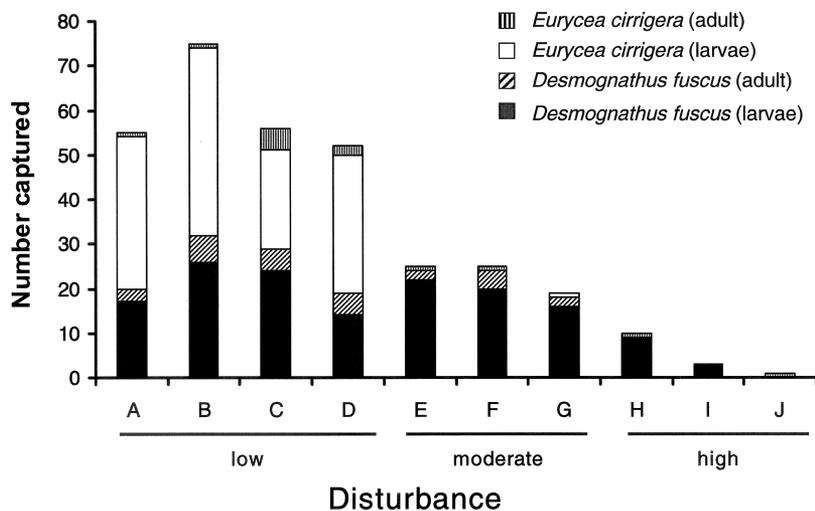


Figure 3. Relative abundance of salamanders among streams with varying levels of disturbance. Letters are stream labels (Table 1). Streams are separated into high-, moderate-, and low-disturbance categories by a principal components analysis (Fig. 1).

stream (Table 2; Fig. 4a), although a lack of samples between 20% and 70% prevents definitive conclusions. As the buffer size increased, we found negative but weak correlations between the relative abundance of salamanders and the percentage of disturbed habitat (Table 2; Fig. 4b & 4c). We found a strong inverse relationship, however, between the amount of disturbed habitat present in each stream’s watershed and the number of salamanders captured in that stream (Table 2; Fig. 4d).

We observed a differential response to habitat disturbance by *D. fuscus* and *E. cirrigera*. Although *D. fuscus* captures declined linearly as disturbance increased, *E. cirrigera* captures decreased more rapidly, exhibiting a threshold effect at 20% disturbed habitat within the watershed (Fig. 4d). We captured only one larva, *E. cirrigera*, in a stream of moderate disturbance level (Fig. 3).

Stepwise multiple regression of the number of each species of salamander captured and environmental parameters revealed that the number of invertebrate taxa captured ( $R^2 = 0.64, p = 0.006$ ) and dissolved oxygen ( $R^2 = 0.11, p = 0.03$ ) accounted for most of the variation in the number of *E. cirrigera* captured. For *D. fuscus*, the average change in cross-sectional area ( $R^2 =$

$0.71, p = 0.002$ ) and the number of invertebrate taxa captured ( $R^2 = 0.23, p = 0.001$ ) accounted for most of the variation in the number of salamanders captured. February water temperature ( $R^2 = 0.03, p = 0.03$ ) and conductivity ( $R^2 = 0.01, p = 0.03$ ) also accounted for statistically significant but small amounts of variation in the number of *D. fuscus* captured.

Discussion

Our results suggest that the current buffer-zone system of watershed management is not effective in conserving stream salamander populations in small riparian ecosystems embedded within landscapes with high human use. Current regulations of Mecklenburg County, North Carolina, require a 10.7-m forested buffer zone along streams draining <40.5 ha of land (MCDEP 2001). We found a very low correlation between the percentage of disturbed habitat within a 10.7-m forested buffer and the relative abundance of salamanders. Although all but one of our study streams experienced virtually no disturbance within the 10.7-m buffer, the number of salamanders captured ranged from 1 to 75, indicating that the presence or absence of such a buffer along a stream has negligible beneficial effects on salamanders in that stream. Although we observed some correlation between the amount of disturbed habitat within larger buffer zones and the relative abundance of salamanders, even a 61.0-m buffer, twice the distance required by the most restrictive regulations in the region (MCDEP 2001), produced only a slightly stronger correlation than those required by current regulations. We did, however, observe strong negative correlations between the percentage of the entire watersheds composed of disturbed habitat and the relative abundance of salamanders. Our data suggest that, although the size of a buffer around a stream may have some effect on the relative abundance of salamanders, the amount of undisturbed

Table 2. Linear regressions of relative abundance of salamanders and the percentage of disturbed habitat in each buffer zone or watershed.

	Slope (SD)	F	df	p	R <sup>2</sup>
<b>Desmognathus fuscus</b>					
Buffer zone (m)					
10.7	-0.188 (-0.154)	1.480	1, 8	0.258	0.051
30.5	-0.268 (-0.127)	4.450	1, 8	0.068	0.270
61.0	-0.268 (-0.101)	7.030	1, 8	0.029	0.401
watershed	-0.300 (-0.063)	22.870	1, 8	0.001	0.708
<b>Eurycea cirrigera</b>					
Buffer zone (m)					
10.7	-0.224 (-0.269)	0.690	1, 8	0.430	0.001
30.5	-0.308 (-0.241)	1.620	1, 8	0.238	0.065
61.0	-0.295 (-0.206)	2.040	1, 8	0.191	0.103
watershed	-0.429 (-0.139)	9.590	1, 8	0.015	0.480

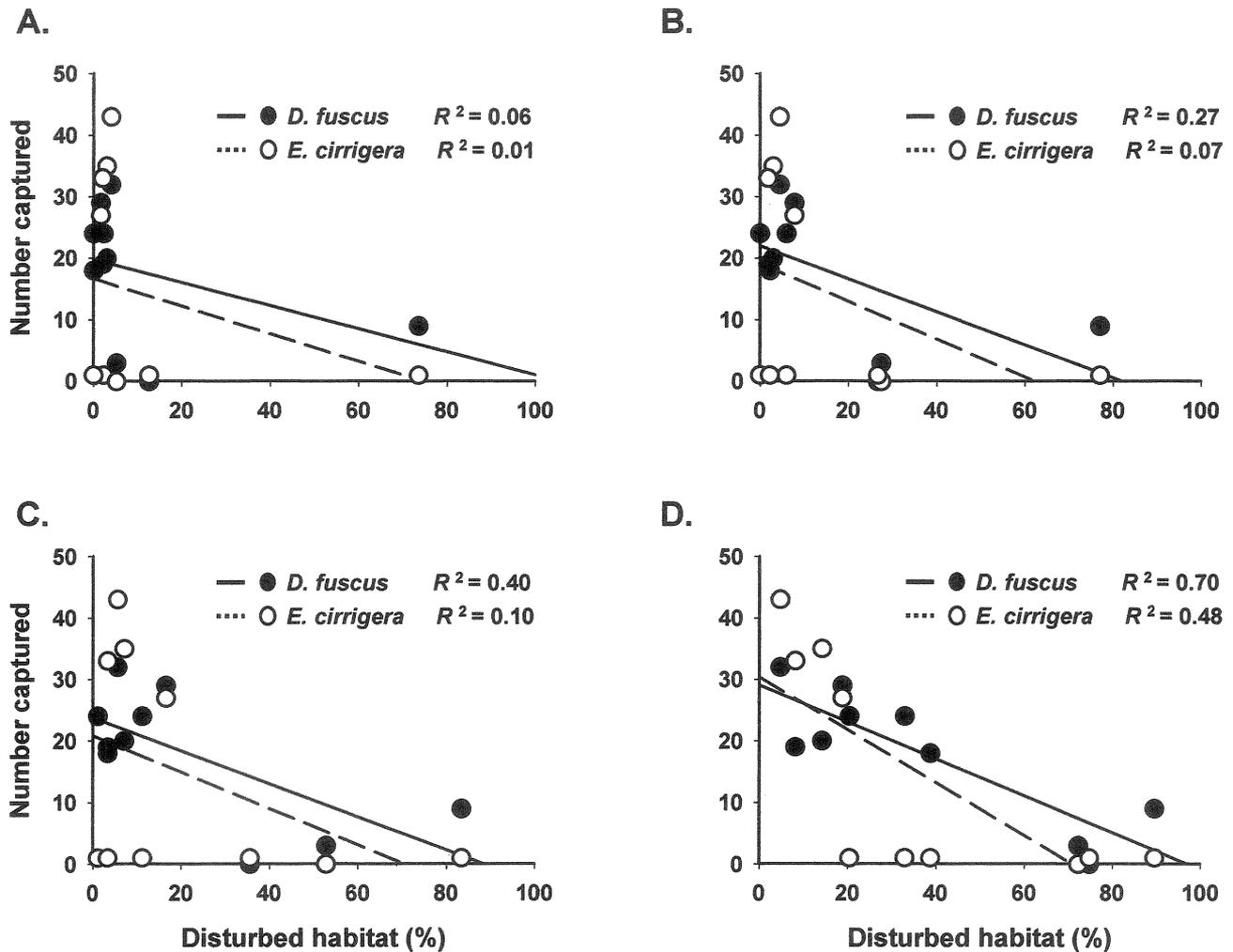


Figure 4. Number of salamanders captured in each stream versus the percentage of disturbed habitat present within (a) a 10.7-m buffer (regulations of Mecklenburg County, North Carolina) around all areas of the stream upstream of the sampling location, (b) a 30.5-m buffer (regulations of Davidson, North Carolina), (c) a 61.0-m buffer, and (d) the entire watershed upstream of the sampling location. Disturbed habitats included field/agricultural, residential, and impervious surfaces.

habitat present within the entire watershed has the greatest impact on salamander abundance.

Research suggests that current buffer-zone regulations are insufficient to protect populations of semiaquatic reptiles and amphibians. For example, Burke and Gibbons (1995) suggest that a 275-m buffer would be needed to preserve the nesting and hibernation habitats of semiaquatic turtles inhabiting Carolina Bays. Semlitsch (1998) determined that a 164-m buffer would be necessary to protect 95% of adult individuals of pond-breeding salamanders (*Ambystoma* sp.). These studies consider buffer zones as preserves and more accurately address the issue of "critical upland habitat," that is, the upland habitat around a water body used by semiaquatic organisms inhabiting that water body (Buhlmann & Gibbons 2001). What these studies do not address is the concept of a true buffer zone: the amount of habitat that

must be left around a water body to maintain the water-quality attributes required by organisms inhabiting it (Brosofske et al. 1997). Although the size of buffers undoubtedly varies with stream size, geography, and habitat, some researchers suggest that buffers up to 300 m wide may be necessary to maintain microclimates in small streams in the Pacific Northwest (Chen et al. 1995).

Our study differs from previous studies of the effects of buffer zones on reptiles and amphibians in that it evaluates the effectiveness of true buffer zones and critical upland habitat around small streams. *Desmognathus fuscus* do not venture far from stream edges and thus apparently do not utilize buffers as critical upland habitat. Instead, *D. fuscus* apparently respond to the effectiveness of buffer zones in maintaining favorable environmental conditions within the stream. The more terrestrial *E. cirrigera*, on the other hand, apparently use

buffers as preserves and are thus more strongly affected by watershed development.

Our study indicates a complex relationship between the relative abundance of salamanders, stream conditions, and the amount and type of disturbed habitat present in the watersheds. Certain types of disturbed habitat affect conditions within a stream, making them inhospitable for salamanders. For example, high-disturbance streams had much more impervious surface in their watersheds than other streams (Table 1). These streams exhibited elevated conductivity levels, likely caused by contaminants carried from roads by runoff (Pratt et al. 1981; Maltby et al. 1995). In watersheds containing large expanses of impervious surfaces, rain results in rapid and extensive swelling of streams and the washing away of leaves and other cover objects from the streambed (Pratt et al. 1981; Maltby et al. 1995). It is possible that adult salamanders and larvae are washed away by high flow rates following heavy rains, but it is more likely that salamanders are unable to survive in areas where high flow rates have dislodged protective cover and food organisms (Orser & Shure 1972).

In streams with moderate disturbance, high amounts of cover did not correspond to high salamander abundances. In these streams, low dissolved oxygen and low macroinvertebrate diversity may be factors limiting salamander abundance (Orser & Shure 1972). It is also possible that runoff from agricultural land or cattle pasture in these areas contains undetected contaminants that adversely affect salamanders (Omernik et al. 1981; Osborne & Wiley 1988; Liess & Schulz 1999; Rouse et al. 1999; Lindsay & Dorcas 2001). Our results suggest that the best predictors of *E. cirrigera* abundance are the number of invertebrate taxa and dissolved oxygen, and the best predictors for *D. fuscus* abundance are the average change in cross-sectional area between base and peak flow and the number of invertebrate taxa captured. However, our study has only begun to unravel the complex and dynamic connection between habitat disturbance, stream conditions, and the relative abundance of salamanders. Further investigation is warranted to determine the exact mechanisms at play in these relationships.

Minnows (family Cyprinidae) were present in five of the streams sampled, (A, B, C, D, and H). Because four of these streams also had the highest relative abundances of salamanders, we believe that fish predation is not a factor limiting salamander abundance.

Amphibians have been touted as sensitive bioindicators in aquatic systems (Barinaga 1990; Vitt et al. 1990). The salamanders we considered are apparently particularly sensitive to environmental degradation because they spend much of their life cycle within streams or their immediate vicinity (Petranka 1998). Also, as plethodontid (i.e., lungless) salamanders, they absorb oxygen across their integument, resulting in increased capacity for contaminant uptake. In our study, the high correla-

tions between watershed disturbance and the relative abundance of salamanders supports the supposition that plethodontid salamanders are excellent indicators of environmental integrity (Welsh & Droege 2000).

The differential response of *D. fuscus* and *E. cirrigera* to habitat disturbance may provide more resolution than would be available from a single species. *Eurycea cirrigera* exhibited a threshold effect when the amount of watershed composed of disturbed habitat reached about 20%, whereas *D. fuscus* showed a relatively linear decrease in relative abundance due to increasing environmental disturbance. Although *E. cirrigera* may be intolerant of even minimal habitat disturbance within their watershed, it is more likely that the threshold effect we observed was due to the fact that we were sampling only breeding populations of *E. cirrigera*. Other purported environmental indicators (e.g., macroinvertebrates) showed similar negative relationships with the level of watershed habitat disturbance.

Our data suggest that in small stream ecosystems, a simple buffer zone of forested habitat is insufficient to maintain the stream conditions that support high salamander abundances. Instead, we found that salamander abundance was most closely related to the amount and type of disturbed habitat within the entire watershed. Consequently, we suggest that it is necessary to evaluate the current system of watershed management on multiple scales. Instead of simply requiring a forested buffer along all streams, development plans must be constructed on a case-by-case basis, taking into account the potential effects of disturbance, on both subwatershed and watershed levels. In each case, the amount, type, and location of disturbed habitat must be taken into account across the entire subwatershed, along with the life history of potentially affected organisms. Ideally, this should be accompanied by landscape-level development schemes such as aquatic reserve systems (Cissel et al. 1998, 1999). In this way, impacts on the entire watershed would be gauged according to regional vulnerability, protecting the most valuable areas completely while allowing other, less important, areas to be developed with less regulation. Unfortunately, balancing economic and conservation objectives is difficult and often complicated by land ownership and development patterns. While such an ideal development plan may not be possible under all circumstances, more comprehensive regulation than the current buffer-zone system is needed.

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