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[Article]

Habitat Suitability of the Carolina Madtom, an Imperiled, Endemic Stream Fish

STEPHEN R. MIDWAY
North Carolina Cooperative Fish and Wildlife Research Unit, Department of Biology, North Carolina State University, Campus Box 7617, Raleigh, North Carolina 27695, USA

THOMAS J. KWAK*
U.S. Geological Survey, North Carolina Cooperative Fish and Wildlife Research Unit, Department of Biology, North Carolina State University, Campus Box 7617, Raleigh, North Carolina 27695, USA

D. DEREK ADAY
Department of Biology, North Carolina State University, Campus Box 7617, Raleigh, North Carolina 27695, USA

Abstract.—The Carolina madtom *Noturus furiosus* is an imperiled stream ictalurid that is endemic to the Tar and Neuse River basins in North Carolina. The Carolina madtom is listed as a threatened species by the state of North Carolina, and whereas recent distribution surveys have found that the Tar River basin population occupies a range similar to its historical range, the Neuse River basin population has shown recent significant decline. Quantification of habitat requirements and availability is critical for effective management and subsequent survival of the species. We investigated six reaches (three in each basin) to (1) quantify Carolina madtom microhabitat use, availability, and suitability; (2) compare suitable microhabitat availability between the two basins; and (3) examine use of an instream artificial cover unit. Carolina madtoms were located and their habitat was quantified at four of the six survey reaches. They most frequently occupied shallow to moderate depths of swift moving water over a sand substrate and used cobble for cover. Univariate and principal components analyses both showed that Carolina madtom use of instream habitat was selective (i.e., nonrandom). Interbasin comparisons suggested that suitable microhabitats were more prevalent in the impacted Neuse River basin than in the Tar River basin. We suggest that other physical or biotic effects may be responsible for the decline in the Neuse River basin population. We designed instream artificial cover units that were occupied by Carolina madtoms (25% of the time) and occasionally by other organisms. Carolina madtom abundance among all areas treated with the artificial cover unit was statistically higher than that in the control areas, demonstrating use of artificial cover when available. Microhabitat characteristics of occupied artificial cover units closely resembled those of natural instream microhabitat used by Carolina madtoms; these units present an option for conservation and restoration if increased management is deemed necessary. Results from our study provide habitat suitability criteria and artificial cover information that can inform management and conservation of the Carolina madtom.

Warmwater streams in the southeastern United States support substantial biological diversity on broad spatial scales (Meffe and Sheldon 1988; Lydeard and Mayden 1995). Because these systems are dynamic, management becomes a challenging task, compounded by the fact that fish often require conditions that differ from those of other aquatic species (e.g., flow conditions; Hubert and Rahel 1989; Aadland 1993). Particularly vulnerable to habitat loss, exotic species, and pollution, stream fishes in the southeastern United States are disproportionately imperiled in comparison with those in other U.S. regions (Wilcove et al. 1998; Jelks et al. 2008). In particular, disproportionate rates of imperilment and extirpation are occurring among benthic fishes (e.g., sculpins, darters, and madtoms *Noturus* spp.) as stream bottoms are often the first impacted habitat type (Angermeier 1995; Etnier 1997; Warren et al. 1997). Aadland (1993) also noted higher rates of imperilment for nongame species because they are generally less intensively managed than species of commercial and recreational interest. Endemic species are particularly susceptible to extirpation because their isolation increases vulnerability to both human activity and natural catastrophic events (Warren and Burr 1994; Burkhead et al. 1997).

An understanding of habitat requirements is critical for conservation of endemic species. Habitat quality and quantity influence species diversity; a greater diversity of quality correlates to higher fish diversity (Gorman and Karr 1978; Schlosser 1982; Reeves et al.

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*Corresponding author: tkwak@ncsu.edu

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1993; Ricciardi and Rasmussen 1999). The difficulty from a conservation and management standpoint is selecting appropriate habitat metrics to quantify, particularly because of myriad species-specific habitat requirements and life history strategies (Pajak and Neves 1987; Aadland 1993; Vadas and Orth 2000).

The Carolina madtom *N. furiosus* is a small, nongame, endemic stream-dwelling ictalurid that is one of the 28 described madtom species (Burr et al. 2005). To date, there is only one existing publication that outlines Carolina madtom ecology (Burr et al. 1989). The species is presently on the Red List of Threatened Species (published by the International Union for the Conservation of Nature) but is considered data deficient (Baillie et al. 2004), and most information for its management has been inferred from studies of congeners. The native range of the Carolina madtom includes only two North Carolina drainage basins: the Tar and Neuse rivers (Burr et al. 1989). Within these basins, the species inhabits clear to tannin-stained, free-flowing streams in both the Piedmont and Coastal Plain physiographic regions (Burr et al. 1989). The Neuse River basin is considered an impacted basin (Powers et al. 2005; Fries et al. 2008), showing a recent decline in Carolina madtom distribution and population density (Wood and Nichols 2008). The Tar River basin has historically supported greater numbers of Carolina madtoms (Burr et al. 1989), with some of the densest subpopulations located in the Piedmont region just above the Fall Zone (North Carolina Wildlife Resources Commission [NCWRC], unpublished data).

Habitat associations of the Carolina madtom appear to be similar to those described for most of its congeners (Taylor 1969; Burr and Stoeckel 1999). Suitable stream microhabitats have been anecdotally described as riffles, runs, and pools, with highest occurrences observed in swift current during warm months at depths of 0.3–1.0 m (Burr et al. 1989). Due to the benthic behavior of Carolina madtoms, stream substrate composition is of particular importance. Leaf litter, sand, gravel, and small cobble are all common substrates associated with the species; Burr et al. (1989) noted frequent occurrence in sand mixed with gravel in leaf litter. Areas of moderate to slow flow with abundant cover are the typical habitat during reproduction, which occurs principally between May and July (Burr et al. 1989), although substrate preferences of Carolina madtoms may change seasonally in relation to life history stage. Population densities are for the most part unknown and assumed to be low. Based on years of sampling, Burr and Stoeckel (1999) noted that Carolina madtom densities never reached those associated with most other stream-dwelling fishes. Additionally, because Carolina madtoms have a restricted range and produce relatively small clutches, they are thought to be particularly sensitive to environmental changes, much like other endemic freshwater species (Angermeier 1995; Burr and Stoeckel 1999).

A number of investigators have studied other madtom species, often focusing on life history (Mayden et al. 1980; Mayden and Walsh 1984; Starnes and Starnes 1985; Gagen et al. 1998) or habitat use (Orth and Maughan 1982; Vadas and Orth 2000; Wildhaber et al. 2000). The federally endangered Neosho madtom *N. placidus* has been most intensively studied, including quantification of habitat use and population structure (Fuselier and Edds 1994; Wildhaber et al. 2000; Bulger and Edds 2001). Habitat suitability functions have also been developed for the federally endangered freckled madtom *N. nocturnus* (Orth and Maughan 1982; Simonson and Neves 1992). To date, however, habitat use, suitability, and preference have not been quantified for the Carolina madtom. This information is fundamental for understanding the ecology of the species and for guiding management decisions.

Given the general decline in suitable habitat for madtoms (Robison and Harp 1985; Etnier and Starnes 1991), management efforts aimed at conserving or restoring species must often consider habitat augmentation. Any documented interaction of madtoms with artificial habitat has primarily been anecdotal. Indeed, there are few studies of any nongame stream-dwelling fish and associations with artificial habitat. Kottcamp and Moyle (1972) investigated use of beverage cans and documented six stream fishes—including two catfish species—inhabiting discarded cans. Although Burr et al. (1989) noted anecdotal use of human-discarded cans, bottles, and jars by Carolina madtoms, their conclusions were limited. Given the potential utility of artificial habitat augmentation, such devices could be used to enhance Carolina madtom populations if protective shelter or spawning cavities are limited in availability and if that limitation is a source of population endangerment (Gowan and Fausch 1996; Burr and Stoeckel 1999). If it can be shown that Carolina madtoms readily use artificial habitat, then habitat augmentation efforts in combination with suitable flow regimes could aid in returning Carolina madtom populations toward more robust, historic levels.

Our study was designed to quantify Carolina madtom instream habitat associations. Our primary objectives were to (1) determine instream habitat use and suitability for the species, (2) compare suitable habitat between an impacted basin and a rural basin,

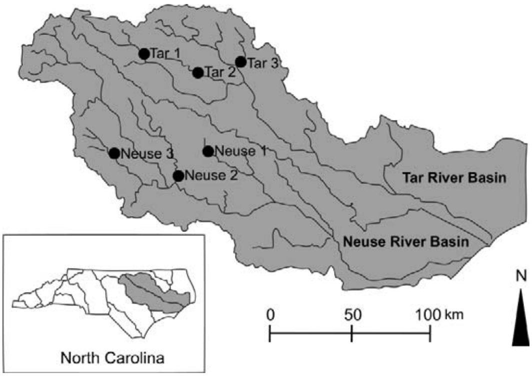

FIGURE 1.—Map of Carolina madtom study reaches in the Tar and Neuse River basins, North Carolina (Tar 1 = main-stem Tar River; Tar 2 = Swift Creek; Tar 3 = Little Fishing Creek; Neuse 1 = Contentnea Creek; Neuse 2 = Little River; Neuse 3 = Swift Creek).

and (3) quantify instream use of an artificial cover unit. Results of this habitat evaluation could assist stream and fisheries managers in understanding habitat requirements for an endemic, imperiled stream fish and can supplement current knowledge of biologically diverse southeastern U.S. streams.

Study Area

Our study took place in the Tar and Neuse River basins in eastern North Carolina (including Franklin, Halifax, Nash, Wilson, Wayne, and Johnston counties). Historical occurrences of Carolina madtoms are documented in these basins around the Fall Line in the lower Piedmont and upper Coastal Plain physiographic regions. Streams in these areas range from low gradient with sluggish pools and intermittent riffles to blackwater streams and low-lying swamps (NCDENR 2008).

The Tar River basin (14,429 km^2) covers a relatively rural part of the state, and a recent assessment found that 55% of the basin area was forested or wetland, 28% was agricultural, and only 1% was urban (NCDENR 2004). Though the Neuse River basin (16,149 km^2) has comparable percentages of forest or wetland (56%) and agriculture (23%), much more of the basin area (8%) is urban (Whitall et al. 2003; NCDENR 2008). The Neuse River's biotic integrity is threatened by ongoing urban development and by wastewater and fertilizer releases that cause eutrophication (Pinckney et al. 1997; Paerl et al. 1998; American Rivers Foundation 2007).

We studied three reaches in both the Tar and Neuse River basins for a total of six reaches, effectively covering the Carolina madtom's range (Figure 1; see Midway 2008 for additional details). The three Tar River basin reaches were sampled in 2007, and the three Neuse River basin reaches were sampled in 2008. In the Tar River basin, we sampled the main-stem Tar River (Tar 1), Swift Creek (Tar 2), and Little Fishing Creek (Tar 3). In the Neuse River basin, we sampled Contentnea Creek (Neuse 1), Little River (Neuse 2), and Swift Creek (Neuse 3). Reaches varied from 60 to 100 m in length and were delineated based on our ability to snorkel the habitat. All reaches also had historical documentation of Carolina madtom presence (W. C. Starnes, North Carolina Museum of Natural Sciences, unpublished data).

Methods

Habitat use, availability, and suitability.—We identified Carolina madtom microhabitats over two spring and summer seasons between 5 May 2007 and 18 July 2008. During both years, drought conditions occurred in both basins, and portions of each basin experienced extreme to exceptional drought during fall 2007. All six sampled reaches were surveyed using snorkeling techniques. Specifically, each reach was sampled 12 times, with each sampling event lasting 2 person-hours/survey (for a total effort of 24 h/reach) to quantify Carolina madtom occurrence and instream habitat use. Two snorkelers began at the downstream limit of the reach and proceeded upstream, visually surveying the entire stream bottom. Carolina madtom locations were marked by placing a small weight attached to a float at the exact point of observation. Upon conclusion of each survey, water depth (m), bottom velocity (m/s), mean column velocity (m/s), substrate composition, cover, and location within the reach were recorded for each Carolina madtom point location. Depth, bottom velocity, and mean column velocity were measured with a top-set wading rod and a Marsh-McBirney Model 2000 digital flowmeter. Mean column velocity was measured at 60% of the total depth from the surface (for depths $\leq$ 0.80 m) or was calculated as the average of measurements at 20% and 80% of total depth (for depths $>$ 0.80 m). Substrate was determined as the greatest percent coverage of a substrate type according to a modified Wentworth particle size classification (Bovee and Milhous 1978) at the exact location of the fish. For analyses, substrate categories were combined into five groups (boulder, cobble, gravel, sand, and silt/clay). Cover was recorded as the physical object under which the Carolina madtom was found; alternatively, if the fish was not under cover, then cover was recorded as the closest cover type in a 1-m^2 quadrat for which the fish served as the center point. Cover categories included none (no cover in the 1-m^2 quadrat), leaf pack, woody debris, cobble, boulder, and mussel shell. Fish were not handled during sampling.

We quantified available stream microhabitat for each reach under base flow conditions in June after half (i.e., six) of the snorkel surveys were complete. Within each study reach, cross-sectional transects were delineated at 5-m intervals (12–20 transects/reach). The location of the first transect was selected randomly. Along each transect, the water depth, bottom velocity, mean column velocity, substrate, and cover were recorded at 1-m intervals using methods described above. Depth and velocity measurements were taken in the middle of the 1-m^2 quadrat, whereas substrate and cover included the entire quadrat.

Habitat use was analyzed with both univariate and multivariate approaches (Bovee 1986) in an effort to gain insight into individual microhabitat parameters (e.g., depth, substrate) and overall habitat type (e.g., thalweg, riffle). We pooled all Carolina madtom observations and calculated arithmetic means for water depth, bottom velocity, and mean column velocity. Microhabitat suitability was estimated to identify optimal ranges within each habitat parameter. Suitability was calculated by dividing microhabitat use by availability for a range of the variable or category, standardizing to a maximum of 1, summing the values for each category among all reaches, and again standardizing to 1 (Bovee 1986). Analyzing individual reaches prior to pooling allowed us to develop a composite suitability function for the species by avoiding comparisons of one reach's use to a different reach's availability. The most suitable, or optimal, range or category was that with a value of 1. In cases where multiple ranges or categories were equivalently high, the combined range was considered optimal (i.e., suitability = 1.0).

To determine univariate microhabitat selectivity (nonrandom microhabitat use), we compared microhabitat use with availability for each parameter. A Kolmogorov–Smirnov (K–S) two-sample test was used for continuous variables (water depth, bottom velocity, mean column velocity, and substrate), and a log-likelihood ratio *G*-test for independence was used for the categorical cover variable. Microhabitat selectivity or nonrandom microhabitat use was indicated when the *P*-value was less than 0.05.

We also analyzed habitat using a multivariate principal components analysis (PCA) of the four continuous microhabitat variables. Cover was not incorporated into this analysis because it could not be converted into a continuous variable. Principal components were developed based on the correlation matrix of these variables from habitat availability surveys. The PCA extracted linear descriptions of the combined univariate parameters that explained the maximum amount of variation within the data. Two principal components were retained in each analysis and generally conformed to the recommendation to retain components with eigenvalues greater than 1.0 (Kwak and Peterson 2007). Microhabitat use component scores were then calculated using the coefficients derived from the availability components. Dimensions (linear components) were described by two or more of the variables based on significant component loadings. Microhabitat use and availability scores were plotted, and a K–S two-sample test was performed on each component to test for statistically different distributions. Significant *P*-values ($P < 0.05$) indicated nonrandom habitat use for that component's combination of variables.

Interbasin habitat comparison.—We compared microhabitat availability distributions between basins (sample sizes were comparable between basins; Tar River basin: $N = 828$ survey points; Neuse River basin: $N = 797$ survey points) to assess whether suitable habitat was lacking in the Neuse River basin, where the Carolina madtom is rare and declining. By testing for differences in microhabitat parameter distributions (K–S test, *G*-test), we were able to discern whether available microhabitat varied significantly between basins. By quantifying the amount of optimal habitat in the Neuse River reaches, we were able to determine whether suitable habitat was lacking and potentially contributing to population decline. Different distributions of available microhabitat were indicated when the *P*-value was less than 0.05. Comparisons of suitable habitat ranges (from previously calculated suitabilities) between basins provided further insight regarding the quantity of suitable habitat in Neuse River basin streams.

Artificial cover assessment.—Artificial cover units were constructed by cutting a small opening (approximately 25 mm) and vent slots into an upside-down 100-mm clay flowerpot saucer (Figure 2). This saucer was then glued to an upside-down 150-mm flowerpot saucer. Commercially available landscaping river rocks, approximately 10–30 mm in diameter, were glued to the underside of the larger saucer to provide additional weight and stability. Upon conclusion of the microhabitat availability surveys (after the sixth snorkel survey was complete), artificial cover units were deployed in a randomly selected treatment half of each study reach. Artificial cover units were distributed uniformly in a grid pattern, with a single unit occupying the middle of a 6-m-wide × 5-m-long quadrat. The total number of artificial cover units per reach was determined based on the size of the reach so that comparisons among reaches would be standardized

FIGURE 2.—Photograph of an artificial cover unit used in this study of Carolina madtoms.

to a uniform artificial cover unit density. After a soak period of 10–14 d, artificial cover units were observed for fish occupancy as part of the final six snorkel surveys. When stream snorkeling conditions were poor (e.g., high turbidity), artificial cover units were removed from the water to be checked and were gently placed back in the original stream location. In addition to documenting fish use, all continuous microhabitat parameters were measured each time an artificial cover unit was sampled.

A before–after, control–impact (BACI) statistical analysis (Underwood 1994) was used to determine whether artificial cover units increased abundance of Carolina madtoms in our six study reaches. The before–impact period included the six surveys prior to application of the treatment (cover units), and the after–impact period included the final six surveys during which the treatment was in place. Surveys were treated as subsamples within each reach to produce mean abundance estimates before and after impact for both the control and treatment reach halves. For each reach, a D-statistic was calculated as the difference of differences (i.e., a comparison of the treatment half before and after to the control half before and after). All D-statistics were combined to calculate a mean and standard error, the latter of which was then used to calculate a t-statistic and corresponding P-value. Significant P-values ($P < 0.05$) indicated that artificial cover units were effective in increasing Carolina madtom abundance in stream reaches where they were uniformly deployed.

Results

We observed a total of 274 Carolina madtoms (including 154 using artificial cover units) from May 2007 to July 2008. Carolina madtoms were observed in four of six sampled reaches; all reaches in the Tar River basin and one site (Neuse 1) in the Neuse River basin supported populations. No individuals were detected at the Neuse 2 and Neuse 3 study reaches. Water temperature during instream sampling ranged from 20°C to 28°C.

Habitat Use, Availability, and Suitability

Overall, Carolina madtoms occupied instream microhabitats with a mean water depth of 0.42 m (95% confidence interval [CI] = 0.39–0.45 m; range = 0.01–0.92 m), mean bottom velocity of 0.14 m/s (95% CI = 0.12–0.16 m/s; range = 0.00–0.43 m/s), and mean column velocity of 0.22 m/s (95% CI = 0.20–0.24 m/s; range = 0.00–0.58 m/s). The most frequently used substrate and cover were sand and cobble. Instream microhabitat use and availability varied among reaches (Midway 2008). Overall, Carolina madtom instream densities per survey averaged 1.1–1.5 fish/reach (Table 1).

Univariate analysis of habitat selectivity pooled from all Tar River basin reaches showed that for all five microhabitat variables, Carolina madtoms selected habitat nonrandomly (Table 2; Midway 2008). A wide range of depth was available, but fish tended to occupy shallower (<0.50 m) microhabitats. The slowest waters (<0.05 m/s) were the most available bottom velocities, although fish use was most frequent around slow to moderate velocities. The distributions of available and used mean column velocities were similar to those of

TABLE 1.—Mean densities of Carolina madtoms in control and treatment areas within reaches of the Tar and Neuse River basins, North Carolina (Figure 1), before and after deployment of artificial cover units.

		Pretreatment				Posttreatment			
		Control		Treatment		Control		Treatment	
Stream reach	Cover units	Fish/reach	Fish/ha	Fish/reach	Fish/ha	Fish/reach	Fish/ha	Fish/reach	Fish/ha
Tar 1	36	0.3	5.1	1.7	25.6	1.2	17.9	10.2	156.4
Tar 2	28	1.5	21.7	2.3	32.5	1.7	24.1	13.0	187.7
Tar 3	24	1.3	20.6	0.8	12.3	3.4	56.4	4.7	77.6
Neuse 1	29	1.3	17.2	1.2	15.1	0.8	10.8	3.0	38.7
Mean	29.3	1.1	16.1	1.5	21.4	1.8	27.3	7.7	115.1

TABLE 2.—Statistical comparisons of Carolina madtom microhabitat use and availability and interbasin microhabitat availability in the Tar and Neuse River basins, North Carolina. Continuous variables were tested using a Kolmogorov–Smirnov two-sample test (*D*-statistic), and categorical variables were tested with a log-likelihood ratio *G*-test.

	Use versus availability		Interbasin availability	
Microhabitat variable	Statistic	*P*	Statistic	*P*
Depth	$D = 0.156$	0.032	$D = 0.353$	<0.001
Bottom velocity	$D = 0.452$	<0.001	$D = 0.256$	<0.001
Mean column velocity	$D = 0.373$	<0.001	$D = 0.112$	<0.001
Substrate	$D = 0.377$	<0.001	$D = 0.268$	<0.001
Cover	$G = 22.34$	<0.001	$G = 167.96$	<0.001

bottom velocity, showing an abundance of slow water and fish selection of moderately flowing water. Available substrate was dominated by sand and silt, while use occurred primarily over sand and gravel substrates. Silt was clearly avoided. Cover associations were nonrandom, showing selection for cobble and boulder (though sample sizes were limited), with woody debris more marginally selected but used widely in reaches where cobble substrate was scarce.

Habitat suitability was calculated based on microhabitat use and availability data from the Tar River basin ($N = 95$). The small number of Neuse River basin samples ($N = 25$) were withheld so that habitat suitability would be based on a nonimpacted basin and any potential Neuse River basin habitat effects would be avoided. Suitability distributions were developed for each of the three Tar River basin reaches and then combined and standardized for a composite basin distribution. The range of optimal (i.e., highest suitability) water depth was 0.10–0.19 m, the range of optimal bottom velocity was 0.10–0.24 m/s, and the optimal mean column velocity range was 0.20–0.29

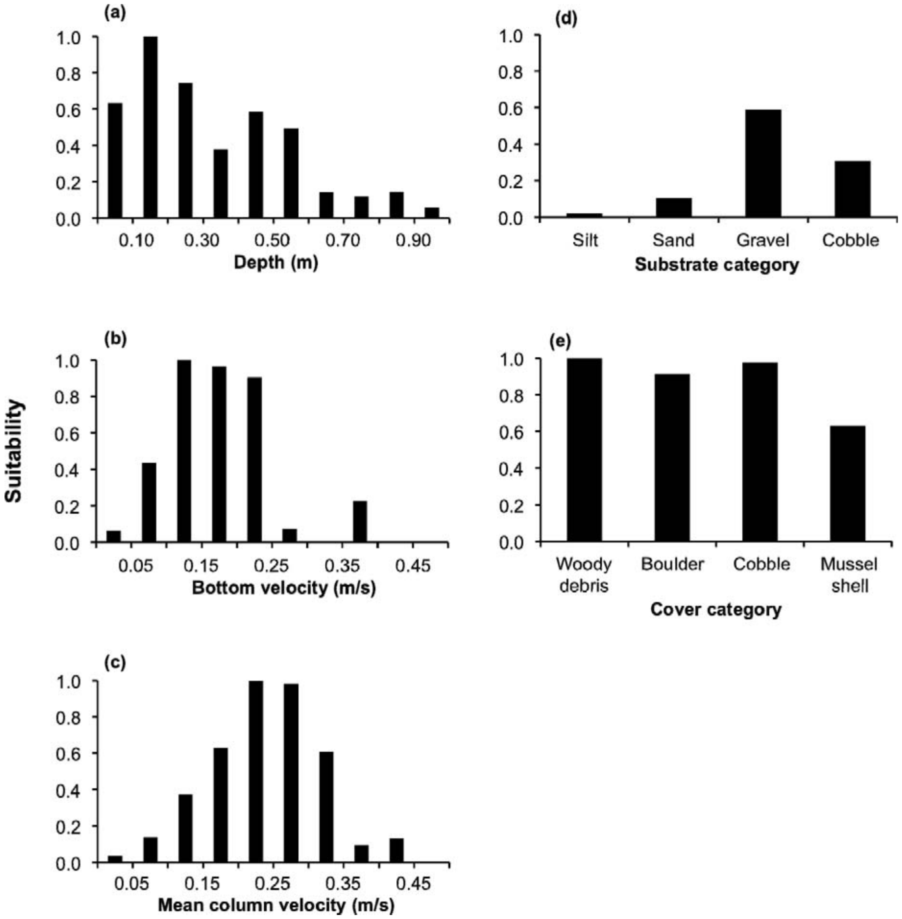

FIGURE 3.—Microhabitat suitability for Carolina madtoms based on data collected from the Tar River basin, North Carolina, during 2007: **(a)** depth, **(b)** bottom velocity, **(c)** mean column velocity, **(d)** substrate, and **(e)** cover.

TABLE 3.—Comparison of suitable microhabitat ranges and percentage of suitable microhabitat available for Carolina madtoms during spring and summer 2007–2008 in the Tar and Neuse River basins, North Carolina (Figure 1), according to habitat variables and based on the four reaches where the species was present.

Reach	Suitable range	Percent available
	Depth (m)	
Tar 1	0.10–0.19	19
Tar 2	0.0–0.19	12
Tar 3	0.40–0.49	9
Neuse 1	0.30–0.39	5
	Bottom velocity (m/s)	
Tar 1	0.10–0.14	9
Tar 2	0.20–0.24	1
Tar 3	0.15–0.24	5
Neuse 1	0.20–0.24	7
	Mean column velocity (m/s)	
Tar 1	0.20–0.24	7
Tar 2	0.25–0.29	4
Tar 3	0.20–0.34	12
Neuse 1	0.35–0.39	2
	Substrate	
Tar 1	Gravel	1
Tar 2	Gravel	12
Tar 3	Cobble	3
Neuse 1	Cobble	2
	Cover	
Tar 1	Woody debris	32
Tar 2	Boulder	4
Tar 3	Cobble	28
Neuse 1	Cobble	8

TABLE 4.—Retained component loadings (based on a correlation matrix) from principal components analysis of microhabitat availability in study reaches of the Tar and Neuse River basins, North Carolina (Figure 1). Significant loadings are in bold.

Variable	Component 1	Component 2
	Tar 1 ($N = 273$)	
Depth	**0.30**	**0.86**
Bottom velocity	**0.59**	**−0.16**
Mean column velocity	**0.62**	0.06
Substrate	**0.43**	**−0.48**
Eigenvalue	2.35	0.95
Variance explained (%)	59	25
	Tar 2 ($N = 278$)	
Depth	0.08	**0.96**
Bottom velocity	**0.61**	−0.03
Mean column velocity	**0.63**	0.11
Substrate	**0.47**	**−0.27**
Eigenvalue	1.95	1.02
Variance explained (%)	49	26
	Tar 3 ($N = 277$)	
Depth	**0.26**	**0.88**
Bottom velocity	**0.58**	**−0.37**
Mean column velocity	**0.61**	**−0.19**
Substrate	**0.47**	**0.23**
Eigenvalue	2.33	0.99
Variance explained (%)	58	25
	Neuse 1 ($N = 330$)	
Depth	**0.35**	**0.93**
Bottom velocity	**0.57**	**−0.30**
Mean column velocity	**0.59**	**−0.12**
Substrate	**0.46**	**−0.18**
Eigenvalue	2.55	0.80
Variance explained (%)	64	20

m/s (Figure 3). The optimal substrate was gravel, and the optimal cover included woody debris, cobble, and boulders (Figure 3). Generally, the most suitable microhabitats were also the most used. For the continuous variables of depth, bottom velocity, and mean column velocity, all of the most suitable ranges were also the most frequently occupied. Microhabitat use of the categorical variables, substrate and cover, differed slightly from suitabilities. Substrate use was highest for sand and slightly lower for gravel, although gravel was clearly the most suitable substrate. The frequent use of sand substrate is probably related to the extremely high availability of sand in these systems. Cover use was skewed slightly towards woody debris. As was the case with substrate, more woody debris was available for use, and woody debris and cobble were equally suitable cover types.

Availability of suitable habitat varied among the four reaches where Carolina madtoms were present (Table 3). All reaches contained suitable depths, but less than 10% of available depth in Tar 3 and Neuse 1 was in the suitable range. Availability of suitable bottom velocities was low for all reaches (<10%). Suitable mean column velocities were also limited, with only one reach exhibiting availability greater than 10%. Although suitable velocities were low, this might be expected when investigating a rheotactic species in low-velocity systems. Except for one reach, Tar 2, suitable substrates were all less than 5% available. Suitable cover was highly available (≥28%) in Tar 1 and Tar 3 but not in other reaches.

Habitat use and suitability were also analyzed using a multivariate PCA, which provided further evidence that Carolina madtoms use habitat nonrandomly. For each of the analyses among four reaches, two components were sufficient to describe stream habitat (Table 4). Components were based on microhabitat loadings and described microhabitat gradients from eddy to thalweg, from riffle to pool, or from scour pool to run (Bain and Stevenson 1999). For all reaches, Carolina madtoms occupied habitat nonrandomly in principal component 1 and nonrandomly in two of four reaches for principal component 2 (K–S two-sample test; Table 5).

In all analyses, principal component 1 demonstrated that Carolina madtom habitat use was nonrandom among those microhabitats available. Carolina mad-

TABLE 5.—Statistical comparisons (Kolmogorov–Smirnov two-sample test (*D*-statistic) of Carolina madtom microhabitat use and availability scores for individual components in the reach-specific principal components analyses for the Tar and Neuse River basins, North Carolina (Figure 1).

Component	*D*-statistic	*P*
	Tar 1	
1	0.337	0.024
2	0.183	0.530
	Tar 2	
1	0.530	<0.001
2	0.236	0.057
	Tar 3	
1	0.610	<0.001
2	0.338	0.001
	Neuse 1	
1	0.745	<0.001
2	0.487	<0.001

toms disproportionately occupied areas of high velocity and coarse substrate that were frequently associated with a thalweg or riffle complex (Figure 4). Habitat use described in principal component 2 was nonrandom in two of four analyses (Tar 3 and Neuse 1). Trends were similar to those of principal component 1; Carolina madtoms selected habitat characterized by the medium-depth and high-velocity areas associated with a run (Figure 4).

Interbasin Habitat Comparison

Microhabitat availability between basins was significantly different for all parameters (Table 2). In addition, as much or more suitable habitat was present in the impacted Neuse River basin (Figure 5), where the Carolina madtom is rare and where populations have declined. The Tar River basin displayed a more even distribution of available depths than the Neuse River basin, which had a distribution skewed with a higher frequency of shallow depths (Figure 5). The Neuse River basin had over twice as much optimal depth (0.10–0.19 m) as the Tar River basin, as defined by the suitability indices. In both basins, the greatest frequency of bottom velocities was in the slowest interval. Bottom velocity availabilities in the Tar River basin quickly diminished after the first interval, while the Neuse River basin had a small amount of moderate bottom velocities. This represented the optimal range of bottom velocities (0.10–0.24 m/s) and, as with depth, much more was available in the Neuse River basin than in the Tar River basin (Figure 5). Optimal mean column velocity (0.20–0.29 m/s) was slightly more abundant in the Neuse River basin, but overall

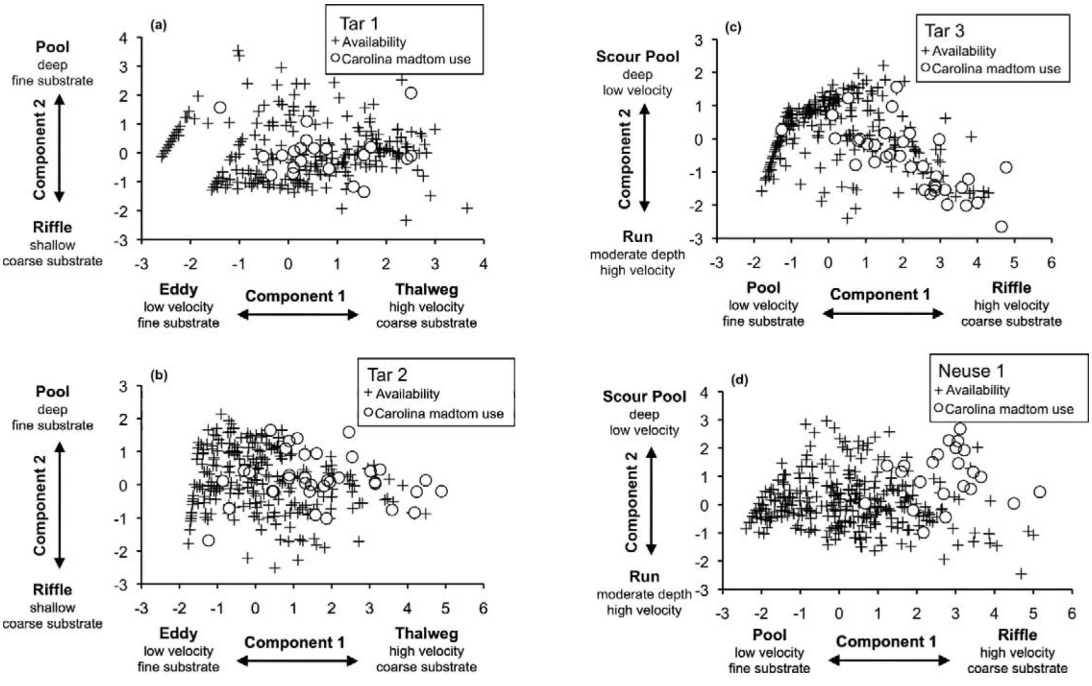

FIGURE 4.—Plots of principal component scores for Carolina madtom microhabitat use and available habitat in three Tar River basin study reaches (Tar 1–3) and one Neuse River basin study reach (Neuse 1), North Carolina. Component loadings appear in Table 4, and statistical comparisons appear in Table 5.

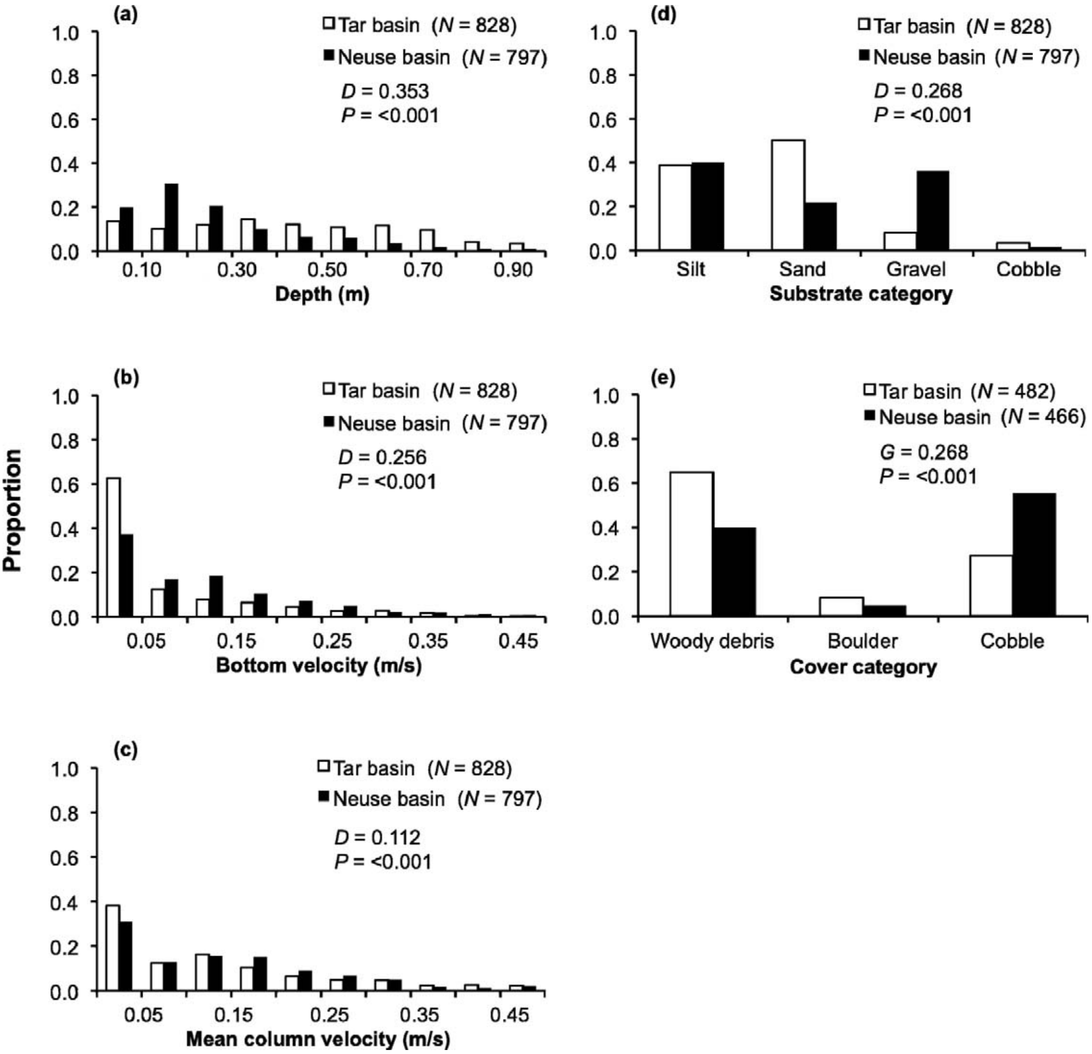

FIGURE 5.—Frequency distributions of microhabitat availability for Carolina madtoms in the Tar and Neuse River basins, North Carolina: **(a)** depth, **(b)** bottom velocity, **(c)** mean column velocity, **(d)** substrate, and **(e)** cover. For depth, bottom velocity, and mean column velocity, use and availability were compared using a Kolmogorov–Smirnov two-sample test (K–S test); optimally suitable habitat ranges were 0.10–0.19 m for depth, 0.10–0.24 m/s for bottom velocity, and 0.20–0.29 m/s for mean column velocity. Use and availability were compared by using a K–S test for substrate and a log-likelihood ratio *G*-test for cover; optimally suitable habitat categories were gravel for substrate and woody debris, boulder, and cobble for cover.

values were more similar than those of bottom velocities. Gravel, the optimal substrate, was more widely available in the Neuse River basin than in the Tar River basin (Figure 5). Three cover types were equally optimal: woody debris, boulder, and cobble. Trends in cover availability varied between basins; boulder was available at about the same proportion in each basin, the Tar River basin contained more woody debris, and the Neuse River basin had more cobble. Together, these trends in available habitat suggest that instream microhabitat is not limiting in the Neuse River basin and may not be the primary cause of the associated species decline.

Artificial Cover Assessment

Six surveys at each of the six reaches resulted in a total sample of 606 artificial cover units. We observed a total of 154 Carolina madtoms using the artificial cover unit, which translates to a 25.4% occupancy rate. While other species were found occupying the artificial cover units, their presence was rare and did not suggest significant interference with Carolina madtom use.

TABLE 6.—Statistics describing microhabitat characteristics of instream cover (natural microhabitats) used by Carolina madtoms, artificial cover units occupied by Carolina madtoms, and unoccupied artificial cover units in the Tar and Neuse River basins, North Carolina (CI = confidence interval).

Variable	*N*	Mean or mode	95% CI	Range
Instream cover				
Depth (m)	120	0.42	0.38–0.46	0.01–0.43
Bottom velocity (m/s)	120	0.14	0.12–0.16	0–0.43
Mean column velocity (m/s)	120	0.12	0.10–0.14	0–0.58
Substrate	120	Sand		
Occupied artificial cover units				
Depth (m)	139	0.34	0.30–0.38	0.06–0.94
Bottom velocity (m/s)	139	0.12	0.10–0.14	0–0.53
Mean column velocity (m/s)	139	0.19	0.17–0.21	0–0.53
Substrate	139	Sand		
Unoccupied artificial cover units				
Depth (m)	466	0.36	0.34–0.38	0–1.04
Bottom velocity (m/s)	466	0.06	0.05–0.07	0–0.41
Mean column velocity (m/s)	466	0.12	0.11–0.13	0–0.61
Substrate	466	Silt		

Occupancy rates by other species were 15.7% for margined madtoms *N. insignis*, 1.7% for channel catfish *Ictalurus punctatus*, 1.3% for sunfishes *Lepomis* spp., 1.3% for decapod crayfish, and 1.2% for American eels *Anguilla rostrata*. The BACI analysis showed that within the four reaches occupied by Carolina madtoms, the species was more abundant in reach halves where artificial cover units were deployed (Table 1). After the treatment was applied (i.e., deployment of artificial cover units in one-half of the reach), all treated areas showed an increase in fish abundance (mean increase of 6.2 fish), while overall reach abundances also increased. Tar 2 showed the greatest increases in abundance, averaging 13 fish in the treated reach. Tar 1 also showed a large increase in abundance, while Tar 3 and Neuse 1 increased at a smaller rate. Three of four control reaches showed a slight increase in abundance after the treatment, but these increases were small in comparison with the treatment reach increases. This finding provides clear experimental evidence that artificial cover units significantly (t = 2.62, df = 3, P = 0.04) increased the number of Carolina madtoms in the treated area relative to control reaches. Artificial cover units deployed at Neuse 2 (N = 24 units) and Neuse 3 (N = 15 units) attracted no Carolina madtoms after the full treatment period.

We were also interested in looking at the similarities and differences in microhabitat variables among occupied and unoccupied artificial cover units and instream fish locations (Table 6). For instream microhabitat use and occupied artificial cover units, mean bottom velocities overlapped with 95% CIs, and sand was the most used substrate for both. Also, unoccupied artificial cover units were most commonly located over silt substrate, which was previously shown to be the most suboptimal substrate category.

Discussion

Carolina madtoms are found under cover in moderately flowing, sand and gravel-lined streams and rivers in the Tar and Neuse River basins of North Carolina. We found cobble to be the most frequently used cover structure for the species, although woody debris was also employed when rock cover was limited or unavailable. The streams in the native range of this fish contain very few boulders, but Carolina madtoms demonstrated a tendency to use them as cover objects if the boulders were small enough to exclude larger, predatory species from inhabiting them. Carolina madtoms also occupied microhabitats with a moderate amount of bottom velocity; however, the velocities of the occupied interstitial spaces may have varied widely. We also found that Carolina madtoms did not use stream habitat randomly but rather selected a narrow suite of instream conditions. Results of our multivariate analysis identified these conditions as riffle or thalweg macrohabitats.

Our work is the first to describe instream habitat suitability criteria for this species. Suitability functions are the only biological input in most streamflow models and are useful tools for stream managers to implement flow regimes or to otherwise manage a desired condition (Bovee 1986; Annear et al. 2004). Such indices are also important in impacted basins; the Neuse River basin has been modified with numerous impoundments and is experiencing rapid human population growth and associated land development, which makes it prone to quickly developing drought conditions and widely fluctuating flows.

One of our most relevant but counterintuitive findings was the Neuse River basin's relative abundance of suitable habitat yet lack of Carolina madtoms. Recent work by NCWRC biologists found Carolina madtom abundance in the Neuse River basin to be much lower than historical records indicate, even suggesting extirpation of some populations. The Tar River basin, conversely, has retained nearly all of its populations (Wood and Nichols 2008). One possible assumption regarding the basinwide population decline in the Neuse River basin was degradation of suitable habitat as instream habitat has been both degraded and lost by deforestation, urban and residential development, impoundments, and wastewater treatment plant effluents (NCDENR 2008). Because we demonstrated that suitable habitat existed in the Neuse River basin during our study at base flow conditions—with twice the frequency as in the Tar River basin for some variables—the next steps in Carolina madtom research are to investigate other influential factors. Our results suggest that instream physical habitat may not limit juvenile and adult Carolina madtom populations during spring and summer, but habitat quality or quantity during other seasons or for early life stages could be limiting factors that were not addressed in our study.

A study of historical and present water quality in the impacted basin should be carried out in the framework of Carolina madtom tolerance. In addition to once-minimally regulated agricultural and farming practices in the basin, the catchment has seen considerable development recently, and the report of 8% urban land use in 2002 (Whitall et al. 2003) is probably an underestimate for current conditions. The Neuse River basin averages 53 more humans per square kilometer than the Tar River basin, and this human population density is also a source of considerable impact for area water use (NCDENR 2004, 2008).

Though not quantified in our study, a second potential cause of Carolina madtom decline in the Neuse River basin is the recent introduction of flathead catfish *Pylodictis olivaris*. The NCWRC biologists working in these systems have noted Carolina madtom declines in the basin's larger river segments that historically held populations. The flathead catfish is known to occur in main-stem reaches of the Tar River but is not widespread within that basin (T.J.K., unpublished data). Flathead catfish typically inhabit these large rivers and have been documented to forage on madtoms (Guier et al. 1981; Brewster 2007); in some cases, near eradication of native ictalurid species has been recorded (Thomas 1995). Further, simulation modeling suggests that flathead catfish suppress native fish abundance in streams by 5–50% through predatory and competitive interactions (Pine et al. 2007).

We found visual snorkel surveying to be an effective method of Carolina madtom instream detection, and we recommend it for similar studies of cover-associated benthic fishes where conditions are suitable. Although there are drawbacks inherent to visual snorkel surveying (Ensign et al. 1995; Thompson 2003), similar studies of benthic species have suggested visual detection to be as good as traditional methods (Hankin and Reeves 1988) and preferable for use with threatened and endangered species (Jordan et al. 2008). Burr et al. (1989) employed kick seining to sample Carolina madtoms—a viable method but one that would have prevented us from identifying microhabitat occupancy. Other traditional fish sampling methods (e.g., electrofishing or other netting gears) would have posed similar problems. Past and present work with Carolina madtoms by biologists at the NCWRC suggested that visual snorkeling was the most effective method; after familiarizing ourselves with a reach, we were able to thoroughly and confidently survey the entire delineated area. Concurrent snorkel surveys in 2007 by NCWRC biologists found Carolina madtom abundances similar to those documented in our study, further illustrating the accuracy of the method. Limitations to the technique were almost exclusively imposed when streams quickly increased in flow and turbidity, as is typical in low-gradient, impacted streams. Other factors potentially affecting detectability are water depth, observer skill and bias, diel patterns of fish behavior, and habitat complexity. Although the presence of cover may impede detection of some fish species, we found that Carolina madtoms closely associated with instream cover, which enhanced the fish's detectability by focusing our effort accordingly. Additional study of detectability and bias of snorkeling techniques to assess abundance of the Carolina madtom and other stream fishes is warranted.

Management Implications

The Carolina madtom recently received a change in state-protected status from "special concern" to "threatened" in North Carolina (LeGrand et al. 2008). With apparently declining populations in approximately half of the species' native range and with general life history questions still unanswered, additional conservation measures may be necessary in the near future to ensure the long-term existence of the Carolina madtom.

Our design and deployment of an artificial cover unit significantly increased the abundance of fish in a treatment area; however, the ecological implications of this result are unclear. The increased abundance that we demonstrated may reflect a simple attraction effect for fish in the area or could ultimately enhance population numbers. Because we did not quantify reproductive behaviors, we cannot comment on the ability of artificial cover units to serve as reproductive structures beyond anecdotal observations. We did note occasional Carolina madtom egg guarding and occurrence of madtom young of the year within the artificial cover units. Between sampling years, eastern North Carolina rivers experienced no catastrophic flooding or serious rainfall events (e.g., hurricanes), so we cannot unequivocally predict the retention of these units under extreme flows. Perhaps the most pragmatic aspect of the artificial cover units we designed is that they are quickly and inexpensively produced; an individual unit can be assembled in less than 2 h with approximately US$2 in materials.

Uniform placement of artificial cover units in our study allowed identification of the most effective instream locations for possible application of the units on a larger scale. Microhabitat parameters associated with occupied artificial cover units closely resembled those of fish occupying natural instream habitat. Because bottom velocity and substrate were particularly important microhabitat parameters for occupancy of Carolina madtoms, we suggest that an artificial cover unit distribution concentrated in areas of most suitable natural instream habitat, focusing specifically on both velocity and substrate, would be most effective. While stream restoration is a much larger and more expensive undertaking than the addition of cover units or fish aggregation devices, these cover units show promise as a cost-effective, short-term, spatially restricted component of improvements designed to restore stream cover and support viable Carolina madtom populations.

The Carolina madtom plays an important role in stream ecosystems, whether in more traditional ecological roles or as part of the suite of Tar–Neuse River endemics that make these rivers biologically diverse and distinct. The Swift Creek (Tar 2) and Fishing Creek (Tar 3) tributaries within the Tar River basin are among the most biologically diverse watersheds in the state (NCNHP 1997), and Swift Creek may be the most significant lotic ecosystem remaining along the Atlantic Seaboard (Alderman et al. 1993). In addition, the Swift Creek (Tar 2) watershed has been supplementally classified as one of the Outstanding Resource Waters by the North Carolina Division of Water Quality, and the Fishing Creek watershed is also eligible for Outstanding Resource Waters reclassification. Due to the specific microhabitat requirements and ecological sensitivity of Carolina madtoms, the possibility exists to use them as an indicator of overall stream health. Urban land use can severely degrade stream ecosystems (Booth and Jackson 1997; Wang et al. 2000; Roy et al. 2003; Brown et al. 2005), and it is likely that Carolina madtom abundances will be negatively influenced as stream degradation increases, both on basinwide and stream-reach scales. Another possible ecological role for the Carolina madtom is in a symbiotic or commensal relationship with a rare mussel species found in the Tar River basin (i.e., the federally endangered Tar River spinymussel *Elliptio steinstansana*). Mussel glochidium-stage larvae are known to use fish hosts for part of their lives (Neves et al. 1985; Yeager and Saylor 1995). Because habitat requirements for Carolina madtoms and rare mussel species are probably similar, protecting and enhancing Carolina madtom populations could yield positive effects on sympatric freshwater mussels, another imperiled group that is actively managed. The application of our results in a management framework will allow informed actions to protect and enhance the instream habitat of this imperiled endemic fish.

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References

Aadland, L. P. 1993. Stream habitat types: their fish assemblages and relationship to flow. North American Journal of Fisheries Management 13:790–806.

Alderman, J. M., A. L. Braswell, S. P. Hall, A. W. Kelly, and C. McGrath. 1993. Biological inventory: Swift Creek subbasin. North Carolina Wildlife Resources Commission, North Carolina Natural Heritage Program, North Carolina State Museum of Natural History, Raleigh.

American Rivers Foundation. 2007. Report on the 20 most threatened American rivers. American River Foundation, New York.

Angermeier, P. L. 1995. Ecological attributes of extinction-prone species: loss of freshwater fishes of Virginia. Conservation Biology 9:143–158.

Annear, T., I. Chisholm, H. Beecher, A. Locke, P. Aarrestad, C. Coomer, C. Estes, J. Hunt, R. Jacobson, G. Jöbsis, J. Kauffman, J. Marshall, K. Mayes, G. Smith, R. Wentworth, and C. Stalnaker. 2004. Instream flows for riverine resource stewardship, revised edition. Instream Flow Council, Cheyenne, Wyoming.

Baillie, J. E. M., C. Hilton-Taylor, and S. Stuart. 2004. IUCN red list of threatened species: a global species assessment. International Union for the Conservation of Nature, Gland, Switzerland.

Bain, M. B., and N. J. Stevenson, editors. 1999. Aquatic habitat assessment: common methods. American Fisheries Society, Bethesda, Maryland.

Booth, D. B., and C. R. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. Journal of the American Water Resources Association 33:1077–1090.

Bovee, K. D. 1986. Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. U.S. Fish and Wildlife Service, Biological Report 86(7), Washington, D.C.

Bovee, K. D., and R. Milhous. 1978. Hydraulic simulation in instream flow studies: theory and techniques. U.S. Fish and Wildlife Service, Instream Flow Information Paper Number 5, FWS/OBS-78/33, Fort Collins, Colorado.

Brewster, J. R. 2007. Trophic relations of introduced flathead catfish in a North Carolina Piedmont river. Master's thesis. North Carolina State University, Raleigh.

Brown, L.R., R. H. Gray, R. H. Hughes, and M. R. Meador, editors. 2005. Effects of urbanization on stream ecosystems. American Fisheries Society, Symposium 47, Bethesda, Maryland.

Bulger, A. G., and D. R. Edds. 2001. Population structure and habitat use in Neosho madtom (*Noturus placidus*). Southwestern Naturalist 46:8–15.

Burkhead, N. M., S. J. Walsh, B. J. Freeman, and J. D. Williams. 1997. Status and restoration of the Etowah River, an imperiled southern Appalachian ecosystem. Pages 375–444 *in* G. W. Benz and D. E. Collins, editors. Aquatic fauna in peril: the southeastern perspective. Southeast Aquatic Research Institute, Lenz Design and Communications, Decatur, Georgia.

Burr, B. M., B. R. Kuhajda, W. W. Dimmick, and J. M. Grady. 1989. Distribution, biology, and conservation status of the Carolina madtom, *Noturus furiosus*, an endemic North Carolina catfish. Brimleyana 15:57–86.

Burr, B. M., and J. N. Stoeckel. 1999. The natural history of madtoms (genus *Noturus*), North America's diminutive catfishes. Pages 51–101 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. J. Schramm, and T. Coon, editors. Catfish 2000: proceedings of the international ictalurid symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Burr, B. M., D. J. Eisenhour, and J. M. Grady. 2005. Two new species of *Noturus* (Siluriformes: Ictaluridae) from the Tennessee River drainage: description, distribution, and conservation status. Copeia 2005:783–802.

Ensign, W. E., P. L. Angermeier, and C. A. Dolloff. 1995. Use of line transect method to estimate abundance of benthic stream fishes. Canadian Journal of Fisheries and Aquatic Sciences 52:213–222.

Etnier, D. A. 1997. Jeopardized southeastern freshwater fishes: a search for causes. Pages 87–104 *in* G. W. Benz and D. E. Collins, editors. Aquatic fauna in peril: the southeastern perspective. Southeast Aquatic Research Institute, Lenz Design and Communications, Decatur, Georgia.

Etnier, D. A., and W. C. Starnes. 1991. An analysis of Tennessee's jeopardized fish taxa. Journal of the Tennessee Academy of Science 66:129–134.

Fries, J. S., G. W. Characklis, and R. T. Noble. 2008. Sediment–water exchange of *Vibrio* sp. and fecal indicator bacteria: implications for persistence and transport in the Neuse River estuary, North Carolina, USA. Water Research 42:941–950.

Fuselier, L., and D. Edds. 1994. Seasonal variation in habitat use by the Neosho madtom (Teleostei: Ictaluridae: *Noturus placidus*). Southwestern Naturalist 39:217–223.

Gagen, C. J., R. W. Standage, and J. N. Stoeckel. 1998. Ouachita madtom (*Noturus lachneri*) metapopulation dynamics in intermittent Ouachita Mountain streams. Copeia 1998:874–882.

Gorman, O. T., and J. R. Karr. 1978. Habitat structure and stream fish communities. Ecology 59:507–515.

Gowan, C., and K. D. Fausch. 1996. Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. Ecological Applications 6:931–946.

Guier, R. C., L. E. Nichols, and R. T. Rachels. 1981. Biological investigation of flathead catfish in the Cape Fear River. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 35:607–621.

Hankin, D. G., and G. H. Reeves. 1988. Estimating total fish abundance and habitat area in small streams based on visual estimation methods. Canadian Journal of Fisheries and Aquatic Sciences 45:834–844.

Hubert, W. A., and F. J. Rahel. 1989. Relations of physical habitat to abundance of four nongame fishes in high-plains streams: a test of habitat suitability index models. North American Journal of Fisheries Management 9:332–340.

Jelks, H. L., S. J. Walsh, N. M. Burkhead, S. Contreras-Balderas, E. Díaz-Pardo, D. A. Hendrickson, J. Lyons, N. E. Mandrak, F. McCormick, J. S. Nelson, S. P. Platania, B. A. Porter, C. B. Renaud, J. J. Schmitter-Soto, E. B. Taylor, and M. L. Warren Jr. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. Fisheries 33(8):372–407.

Jordan, F., H. L. Jelks, S. A. Bortone, and R. M. Dorazio. 2008. Comparison of visual survey and seining methods for estimating abundance of an endangered, benthic stream fish. Environmental Biology of Fishes 81:313–319.

Kottcamp, G. M., and P. B. Moyle. 1972. Use of disposable beverage cans by fish in the San Joaquin Valley. Transactions of the American Fisheries Society 101:566–567.

Kwak, T. J., and J. T. Peterson. 2007. Community indices, parameters, and comparisons. Pages 677–763 *in* C. S. Guy and M. L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

LeGrand, H. E., Jr., S. E. McRae, S. P. Hall, and J. T. Finnegan. 2008. Natural Heritage Program list of the rare animal species of North Carolina. North Carolina Department of Environment and Natural Resources, Division of Natural Resource Planning and Conservation, North Carolina Natural Heritage Program, Raleigh.

Lydeard, C., and R. L. Mayden. 1995. A diverse and endangered aquatic ecosystem of the southeast United States. Conservation Biology 9:800–805.

Mayden, R. L., B. M. Burr, and S. L. Dewey. 1980. Aspects of the life history of the Ozark madtom, *Noturus albater*, in southeastern Missouri (Pisces: Ictaluridae). American Midland Naturalist 104:335–340.

Mayden, R. L., and S. J. Walsh. 1984. Life history of the least madtom *Noturus hildebrandi* (Siluriformes: Ictaluridae), with comparisons to related species. American Midland Naturalist 112:349–368.

Meffe, G. K., and A. L. Sheldon. 1988. The influence of habitat structure on fish assemblage composition in southeastern blackwater streams. American Midland Naturalist 120:225–240.

Midway, S. R. 2008. Habitat ecology of the Carolina madtom, *Noturus furiosus*, an imperiled endemic stream fish. Master's thesis. North Carolina State University, Raleigh.

Neves, R., L. R. Weaver, and A. V. Zale. 1985. An evaluation of host fish suitability for glochidia of *Villosa vanuxemi* and *V. nebulosa* (Pelecypoda: Unionidae). American Midland Naturalist 113:1–13.

NCDENR (North Carolina Department of Environment and Natural Resources). 2004. Tar Pamlico River basinwide water quality plan. NCDENR, Raleigh.

NCDENR. 2008. Neuse River basinwide water quality plan. NCDENR, Raleigh.

NCNHP (North Carolina Natural Heritage Program). 1997. The upper Tar River basin: Swift Creek and Fishing Creek subbasins biological conservation database. NCNHP, Raleigh.

Orth, D. J., and O. E. Maughan. 1982. Evaluation of the incremental methodology for recommending instream flows for fishes. Transactions of the American Fisheries Society 111:413–445.

Paerl, H. W., J. L. Pinckney, J. M. Fear, and B. L. Peierls. 1998. Ecosystem responses to internal and watershed organic matter loading: consequences for hypoxia in the eutrophying Neuse River estuary, North Carolina, USA. Marine Ecology Progress Series 166:17–25.

Pajak, P., and R. J. Neves. 1987. Habitat suitability and fish production: a model evaluation for rock bass in two Virginia streams. Transactions of the American Fisheries Society 116:839–850.

Pinckney, J. L., D. F. Millie, B. T. Vinyard, and H. W. Paerl. 1997. Environmental controls of phytoplankton bloom dynamics in the Neuse River estuary, North Carolina, USA. Canadian Journal of Aquatic Science 54:2491–2501.

Pine, W. E. III, T. J. Kwak, and J. A. Rice. 2007. Modeling management scenarios and the effects of an introduced apex predator on a coastal riverine fish community. Transactions of the American Fisheries Society 136:105–120.

Powers, S. E., C. H. Peterson, R. R. Christian, E. Sullivan, M. J. Powers, M. J. Bishop, and C. P. Buzzelli. 2005. Effects of eutrophication on bottom habitat and prey resources of demersal fishes. Marine Ecological Progress Series 302:233–243.

Reeves, G. H., F. H. Everest, and J. R. Sedell. 1993. Diversity of juvenile anadromous salmonid assemblages in coastal Oregon basins with different levels of timber harvest. Transactions of the American Fisheries Society 122:309–317.

Ricciardi, A., and J. B. Rasmussen. 1999. Extinction rates of North American freshwater fauna. Conservation Biology 13:1220–1222.

Robison, H. W., and G. L. Harp. 1985. Distribution, habitat, and food of the Ouachita madtom, *Noturus lachneri*, an Ouachita River drainage endemic. Copeia 1985:216–220.

Roy, A. H., A. D. Rosemond, M. J. Paul, D. S. Leigh, and J. B. Wallace. 2003. Stream macroinvertebrate response to catchment urbanization (Georgia, USA). Freshwater Biology 48:329–346.

Schlosser, I. J. 1982. Fish community structure and function along two habitat gradients in a headwater stream. Ecological Monographs 52:395–414.

Simonson, T. D., and R. J. Neves. 1992. Habitat suitability and reproductive traits of the orangefin madtom *Noturus gilberti* (Pisces: Ictaluridae). American Midland Naturalist 127:115–124.

Starnes, L. B., and W. C. Starnes. 1985. Ecology and life history of the mountain madtom, *Noturus eleutherus* (Pisces: Ictaluridae). American Midland Naturalist 114:331–341.

Taylor, W. R. 1969. A revision of the catfish genus *Noturus* Rafinesque with an analysis of higher groups in the Ictaluridae. U.S. National Museum Bulletin 282.

Thomas, M. E. 1995. Monitoring the effects of introduced flathead catfish on sport fish populations in the Altamaha River, Georgia. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 47(1993):531–538.

Thompson, W. L. 2003. Hankin and Reeves' approach to estimating fish abundance in small streams: limitations and alternatives. Transactions of the American Fisheries Society 132:69–75.

Underwood, A. J. 1994. On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological Applications 4:3–15.

Vadas, R. L. Jr., and D. J. Orth. 2000. Habitat use of fish communities in a Virginia stream system. Environmental Biology of Fishes 59:253–269.

Wang, L., J. Lyons, P. Kanehl, R. Bannerman, and E. Emmons. 2000. Watershed urbanization and changes in fish communities in southeastern Wisconsin streams. Journal of the American Water Resources Association 36:1173–1175.

Warren, M. L. Jr., P. L. Angermeier, B. M. Burr, and W. R. Haag. 1997. Decline of a diverse fish fauna: patterns of imperilment and protection in the southeastern United States. Pages 105–164 *in* G. W. Benz and D. E. Collins, editors. Aquatic fauna in peril: the southeastern perspective. Southeast Aquatic Research Institute, Lenz Design and Communications, Decatur, Georgia.

Warren, M. L. Jr., and B. M. Burr. 1994. Status of freshwater fishes of the United States: overview of an imperiled fauna. Fisheries 19(1):6–18.

Whitall, D., B. Hendrickson, and H. Paerl. 2003. Importance of atmospherically deposited nitrogen to the annual nitrogen budget of the Neuse River estuary, North Carolina. Environment International 29:393–399.

Wilcove, D. S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos. 1998. Quantifying threats to imperiled species in the United States. BioScience 48:607–615.

Wildhaber, M. L., A. L. Allert, C. J. Schmitt, V. M. Tabor, D. Mulhern, K. L. Powell, and S. P. Sowa. 2000. Natural and anthropogenic influences on the distribution of the threatened Neosho madtom in a midwestern warmwater stream. Transactions of the American Fisheries Society 129:423–261.

Wood, C., and R. Nichols. 2008. Status assessment of the Carolina madtom. North Carolina Wildlife Resources Commission, Final Report, Raleigh.

Yeager, B. L., and C. F. Saylor. 1995. Fish hosts for four species of freshwater mussels (Pelecypoda: Unionidae) in the upper Tennessee River drainage. American Midland Naturalist 133:1–6.