

## Abstract

MALINDZAK, EDWARD GEORGE. Behavior and habitat use of introduced flathead catfish in a North Carolina Piedmont river. (Under the direction of Dr. Thomas J. Kwak.)

The flathead catfish *Pylodictis olivaris* is a large piscivorous carnivore that has been widely introduced beyond its native range. I studied the behavior of a flathead catfish population that has recently inhabited a section of the Deep River, North Carolina (in the upper Cape Fear River basin), and currently coexists with the federally endangered Cape Fear shiner *Notropis mekistocholas*. This coexistence raises concerns of predation risks of the flathead catfish on the Cape Fear shiner. I radio-tagged 24 adult flathead catfish in the Deep River between Carbonton and Highfalls dams and monitored their behavior from June 2004 to August 2005. Fish were tracked weekly to determine seasonal patterns, and subsets of those were tracked once per hour for a 24-hour period to determine diel patterns. Eight of the fish were captured, tagged, and released in the upstream, shallow section of the river, and 16 in the deep, downstream, impounded section. A majority of the tagged fish either quickly moved into or stayed in the downstream, impounded section for the entire study period. Flathead catfish selected microhabitats non-randomly annually and within three functional seasons (spawning, growth, and winter). Flathead catfish were usually associated with habitats that were relatively deep (3-6 m), slow in velocity, over bedrock substrates, and nearly always in or adjacent to coarse woody debris or associated with no cover. Among seasons, these fish utilized different habitats, with faster bottom velocities during the spawning season, silt/clay substrates and faster mean column velocities in the growth season, and in the winter season, they occupied the deepest water available and most frequently, not

associated with any cover type. I calculated estimates of seasonal home range as linear home range and kernel density estimates (99%, 95%, 90% and 50%). Flathead catfish mean linear home ranges were greater than 16 km annually, and mean seasonal ranges were 13.1 km during spawning, 10.1 km during growth, and 3.8 km in winter. Mean kernel density estimates of home range at 95% level were approximately half the linear estimate of home range annually and for each season. Mean kernel density estimates of home range at 50% (or core use) level were one-tenth of respective linear home ranges. On a diel scale, flathead catfish were generally more active and occupied deeper water at night. My findings on habitat use of adult flathead catfish at multiple spatial and temporal scales suggest the predation risk to Cape Fear shiners may be minimal, based on limited overlap. Furthermore, my results support other recent research describing flathead catfish as a highly mobile fish. These results add to our ecological understanding of this species in its introduced range and offer implications for improved management.

**BEHAVIOR AND HABITAT USE OF INTRODUCED  
FLATHEAD CATFISH IN A NORTH CAROLINA PIEDMONT RIVER**

by

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## **Biography**

Edward George Malindzak was born in Winston Salem, North Carolina, on the 30th of March, 1968, to Marianne and George Malindzak. His family moved to Chapel Hill, North Carolina, in 1973, and then to Kent, Ohio, in 1976. He graduated from Theodore Roosevelt High School in 1986 and moved to Ruston, Louisiana, to attend Louisiana Tech University. In 1988, he returned to Kent, Ohio, to attend Kent State University and eventually received an Associate of Science Degree in Criminal Justice Technology from the University of Akron, Ohio, in 1995. He promptly moved to Columbus, Ohio, and in 1998 returned to Raleigh, North Carolina. Dissatisfied with his lot in life, Ed enrolled in North Carolina State University in the spring of 1999 in an effort to gain that ever-elusive Bachelor's Degree.

The following two semesters at North Carolina State University brought encounters with two influential professors that opened Ed's eyes to the world of Fisheries and Wildlife Sciences. The first, Dr. Peter Bromley, was able to convince Ed that studying Fisheries and Wildlife Sciences was both intellectually interesting and had a potential future. The second, Dr. Richard Noble, convinced him that a concentration in fisheries was a good idea.

In the spring of 2000, Ed applied for a position as a technician for the North Carolina Cooperative Fish and Wildlife Research Unit and worked on a project studying flathead catfish ecology in three coastal North Carolina rivers. For the first time in his life, Ed was excited about what he was doing and inspired to strive for excellence. Working under Dr. Thomas Kwak, William Pine, and Scott Waters gave

him exposure to the inner workings of graduate school and fisheries research, quickly making it clear that a Master of Science Degree in Fisheries and Wildlife Sciences was what he wanted.

Ed graduated with a Bachelor of Science in Fisheries and Wildlife Sciences in August of 2003. That same month he accepted a position with Dr. Thomas Kwak as a Master of Science student. The following pages describe in detail his activities for the next three years.

## **Acknowledgments**

I would like to thank Dr. Tom Kwak for his guidance and mentorship for the past 5 years; I am truly a different and better person for it. Dr. Ken Pollock and Dr. Wayne Starnes were crucial in the design of this study and also offered helpful suggestions for improving the scope and direction of my research. This research was funded by the North Carolina Wildlife Resources Commission through Federal Aid in Sport Fish Restoration funds (Project F-68).

I am grateful to many people within North Carolina State University and state and federal agencies that provided logistical support, resources, and information toward the completion of this project. Special thanks to Wendy Moore for administrative and logistical support, Dr. Joe Hightower and the biologists at Progress Energy for the temporary use of field equipment when ours failed, and Keith Ashley and Christian Waters for guidance while initiating this research.

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My father George has been a tremendous asset, performing mid-winter fieldwork when nobody else was available and reviewing a draft of this document. My mother Marianne has been supportive by serving as a live-in babysitter while the final edits of this document were completed.

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## Introduction

The flathead catfish *Pylodictis olivaris* was originally found in the Mississippi, Mobile, and Rio Grande river drainages (Lee and Terrell 1987). Its native range extends north to South Dakota and western Pennsylvania and south to northeastern Mexico (Minckley and Deacon 1959; Lee and Terrell 1987). In its native range, it is considered a big game fish, also is exploited as a commercial fishery, and often is considered great table fare (Jackson 1999). This species has acquired many colloquial names including shovel-headed cat, mud cat, appaloosa cat, and yellow cat (Jackson 1999).

The flathead catfish has been introduced outside of its native range throughout much of the United States and Canada (Jackson 1999). Along the Atlantic and Gulf slopes, the flathead catfish has been introduced into many rivers, natural lakes, and reservoirs by local biologists and anglers in efforts to create new fisheries where none had existed previously. Presently, the introduced range of this species in the eastern United States extends from Florida to eastern Pennsylvania (Jackson 1999; Brown et al. 2005).

Flathead catfish were first introduced to the waters of North Carolina in 1966 via an unauthorized introduction. This initial introduction occurred in the Cape Fear River near Fayetteville, North Carolina, and consisted of 11 adult fish weighing a total of 107 kg (Ashley and Buff 1987). By 1979, the flathead catfish population in the Cape Fear River had expanded to >10% of fish collected by number and >64% by total weight (Guier et al. 1981).

The rapid expansion of flathead catfish in its introduced range and the effect of this expansion on native fishes are causes of concern by resource managers, biologists, and anglers alike. Once introduced, flathead catfish may grow into a population of significant size in approximately 10 years (Guier et al. 1981; Thomas 1993). Several studies evaluating the effects of introduced populations on native fauna have suggested that introduced flathead catfish pose no substantial threat to native fish populations (Ashley and Buff 1987; Quinn 1987). Other studies, however, indicated flathead catfish introductions have severe and negative impacts on traditional fisheries (Guier et al. 1981; Thomas 1993; Jackson 1999). Kwak et al. (2004) suggest introduced flathead catfish may have the greatest impact on native fish communities shortly after their initial introduction and subsequent population growth. The rapid dispersal and growth rates of introduced flathead catfish have allowed these fish to occupy and dominate many waters where they had previously not been found.

The carnivorous feeding habits of the flathead catfish are the primary ecological concern in waters where they are introduced. Unlike other catfish species, the flathead catfish is exclusively predaceous, feeding on live prey throughout its entire life (Jackson 1999). Juvenile flathead catfish typically prey on invertebrates and gradually shift prey selection to fishes as they mature (Minckley and Deacon 1959; Quinn 1987; Pine et al. 2005). Fish and crayfish are the most common food items found in adult flathead catfish stomachs (Minckley and Deacon 1959; Layher and Boles 1980; Guier et al. 1981; Ashley and Buff 1987; Quinn 1987; Haas et al. 2001; Pine et al. 2005). Declines in native centrarchids and ictalurids have been

attributed to flathead catfish introductions in the Altamaha River, Georgia (Thomas 1993). Flathead catfish are suspected of causing declines in several important native North Carolina game fishes, including the redbreast sunfish *Lepomis auritus* (Guier et al. 1981; Ashley and Rachels 1998) and native bullheads *Ameiurus* spp. (Guier et al. 1981; Moser and Roberts 1999). However, Quinn (1987) suggests it is unlikely that flathead catfish will have an adverse impact on river fisheries, a position supported by Ashley and Buff (1987), who concluded, “There was no evidence... that flathead catfish may be responsible for the reputed decline in sunfish populations within the Cape Fear River.”

Surveys performed by the North Carolina Wildlife Resource Commission (NCWRC) and the North Carolina Museum of Natural Sciences indicated that flathead catfish had become established upstream of the Carbonton Dam on the Deep River, a major tributary to the Cape Fear River in central North Carolina. Carbonton Dam was a low-head dam previously thought to serve as a migration barrier and the upstream extent of the flathead catfish distribution in the Cape Fear River system. The dam impounded approximately 15 km of the Deep River between Highfalls and Carbonton dams forming deep-water habitats well suited for flathead catfish. While effects on native fishes were unknown, there was concern that the flathead catfish may negatively impact the federally endangered Cape Fear shiner *Notropis mekistocholas* (Howard 2003). In an effort to enhance habitat and population connectivity for the Cape Fear shiner, removal of Carbonton Dam commenced in October 2005 and was completed in February 2006. Another imperiled species, the



Carolina Redhorse *Moxostoma sp.*, a federal species of concern also occurs in this reach of the Deep River (Starnes et al. 2005)

An understanding of interactions and the potential impact of flathead catfish on the Cape Fear shiner is required to develop useful and effective fish and river management plans to minimize the potential effects of introduced flathead catfish and preserve this rare fish species. A thorough scientific understanding of the movement behaviors and habitat use of flathead catfish is the first step in understanding the interactions of these two species and this is what my research involved.

Conflicting paradigms exist in the literature regarding the movement behavior of stream fishes. It was proposed by Gerking (1953) that adult stream fishes exhibit non-migratory or restricted movement patterns, and many published studies since then support this restricted movement paradigm (Gowan et al. 1994). Flathead catfish have been reported to be semi-mobile to sedentary in their native range (Funk 1957; Quinn 1988; Skains and Jackson 1993; Dobbins et al. 1999; Pugh and Schramm 1999). Several studies in the Mississippi River drainage have concluded that flathead catfish movements are minimal and suggest management units for flathead catfish to be small sections of river. Often in these studies there is a small percentage of fish that exhibit large migrations and are usually reported as anomalies.

Dames et al. (1989) used mark-recapture techniques to study movement behavior of flathead catfish in the Missouri River and a tributary, Perche Creek. They anchor-tagged 180 flathead catfish, and 16 tags were returned (8.9%), 14 were angler returns. They reported that movements of a majority of their returned flathead catfish

tags were less than 14 km, with two fish moving 100 km and 300 km. They recommended a localized spatial scale for a flathead management plan. Also in the Missouri River, Travnichuk (2004) tagged 2,939 flathead catfish and reported movements based on 370 returned tags (13%), 277 of which were angler returns (9%), and 93 tags were collected by the Missouri Department of Conservation (3%). He found the mean distance traveled was 6.5 km.

Skains and Jackson (1993) used mark-recapture and radio telemetry techniques to monitor linear ranges of adult flathead catfish (greater than 510 mm total length) in two Mississippi streams. Linear ranges of radio tagged fish averaged 0.75 km in the Big Black River and 1.04 km in the Tallahatchie River. They marked 116 fish with Floy tags in the Big Black River and recaptured 6 (5.2%), all less than 2 km from the release site. They marked 103 fish in the Tallahatchie River with 5 recaptures (4.9%); all but one recaptured fish was less than 1 km from the release site. They recommended a stream-reach specific approach in 2-km increments to manage for large flathead catfish.

Recent advances in technology and methods for monitoring fish movements and additional studies have brought these restricted movement beliefs into question (Lucas and Baras 2001). Vokoun and Rabeni (2005a) examined the movements of flathead catfish in two large river systems in Missouri and found mean annual movements of native flathead catfish in the Grande River to be 63.4 km, while mean annual movements were 22.5 km in the Cuivre River.

A previous study examined movements of flathead catfish in their introduced range in three Coastal Plain rivers in North Carolina, the Lumber River, Cape Fear River, and Contentnea Creek, and found mean linear home ranges to be 20.0 km, 13.4 km, and 25.0 km, respectively (Kwak et al. 2004). Kwak et al. (2004) demonstrated that North Carolina Coastal Plain populations of introduced flathead catfish are highly mobile and recommended that management for introduced flathead catfish populations be approached from a watershed scale.

In early research, Funk (1957) proposed the concept that a population of stream fish may be composed of two subpopulations, one of sedentary fish and one of mobile fish. He categorized 14 species of warmwater stream fish with both sedentary and mobile components to their populations. He found that sedentary fish stayed at or very near the point of release after tagging, and that mobile fish tended to roam freely. The literature is rich with examples of flathead catfish studies indicating this species is sedentary, yet commonly, studies may describe individual fish that traveled much farther than expected (Dames et al. 1989; Travnichek 2004), after being located intermittently over time (Coon and Dames 1989; Vokoun 2003a; Kwak et al. 2004) or fish that were never relocated while tracking (Skains and Jackson 1993; Kwak et al. 2004; Daugherty and Sutton 2005a). These fish are generally considered anomalies or, in the case of fish with unknown whereabouts and behavior, cannot be included in analyses and are omitted from consideration. When telemetry is used as the method for monitoring fish movements in a largely unrestricted river system, it is easy to perceive a flathead catfish moving completely outside of the routine tracking area.

Should this occur, the resulting flathead catfish movement estimates based on the remaining individuals would be biased low.

To understand and successfully manage the current and future effects of introduced flathead catfish populations, the habitat requirements for all life stages must be recognized and considered, and essential habitat for any life history stage must be identified (Langton et al. 1996). Langton et al. (1996) defined essential habitat as being physically discrete and indispensable for the survival of at least one life stage of the target species. Identification of the sum of essential habitats necessary to sustain all life stages is crucial when considering managing a population for growth or decline.

It has been proposed that introduced flathead catfish may represent a physical threat to the endangered Cape Fear River shiner (Howard 2003). The literature remains unresolved regarding the mobility of the flathead catfish; some reports support the postulate that flathead catfish are sedentary (Quinn 1988; Skains and Jackson 1993); some report they are mobile (Vokoun 2003a; Kwak et al. 2004); others propose that there may be both subpopulation types within a flathead catfish population (Funk 1957). Additional research in the area where introduced flathead catfish coexist with Cape Fear shiners would provide important findings to better understand species behavior and interactions.

## **Objectives**

This research is a component of a larger study on introduced flathead catfish in Piedmont North Carolina Rivers. The current component will focus on movement behavior and habitat use of flathead catfish in the Deep River, North Carolina. Concurrent studies, not included as part of this current project, will estimate flathead catfish population density, biomass, and predator-prey interactions within this river system.

The goal of my research is to undertake a scientific study of movement behavior and habitat selection of a flathead catfish population in an effort to better understand the biology and ecology of this species within its introduced Piedmont North Carolina range. A better understanding of movement behavior and habitat selection of this species will permit the prediction of the ecological impact of future introductions of this fish on native species of aquatic organisms and provide a scientific basis for more effective management options. This research represents a natural extension of a previous study with similar objectives on three North Carolina Coastal Plain rivers completed in January 2004 (Kwak et al. 2004).

I proposed to determine diel and seasonal movement patterns and habitat use of flathead catfish greater than 800 g in the Deep River, North Carolina, between Highfalls Dam and Carbonton Dam. My specific objectives were to use radio telemetry techniques to quantify annual, seasonal, and diel movement patterns of flathead catfish by calculating linear home range and kernel density estimates of

home range; and determine habitat use of adult flathead catfish and compare it to habitat availability to yield suitability of habitat within two reaches in the study site on the Deep River (a shallow riffle/pool area and an impounded deep water area).

This information will then be analyzed for comparison of habitat use and suitability of the endangered Cape Fear shiner to determine the extent of overlap in habitat use of flathead catfish and Cape Fear shiner, based on the findings of Howard (2003).

## **Methods**

### *Site Description*

My research was conducted in a 35-km section of the Deep River, North Carolina, a medium-sized river in the upper Cape Fear drainage, between Highfalls and Carbonton dams near the Lee and Moore County line. The study site was divided into two distinct reaches, each of which is approximately 17 km in length (Figure 1). The upstream (upper) reach of the site (between Highfalls Dam and the Glendon-Carthage Road Bridge) was characterized by fast to moderate-flowing, shallow water in a series of riffles and pools. The downstream (lower) reach of the site (between the Glendon-Carthage Road Bridge and Carbonton Dam) was impounded by Carbonton Dam, with water depths exceeding 6 meters (personal observation). The site was approximately 25 km west of Sanford, North Carolina, and approximately 220 km from the mouth of the Cape Fear River, where it discharges into the Atlantic Ocean. Exploratory sampling within the two reaches and communication with North Carolina Wildlife Resources Commission (NCWRC) biologists indicated that flathead catfish

may have recently dispersed upstream over Carbonton Dam during exceedingly high flow periods when the dam was submerged or were intentionally introduced into this section of the Deep River.

### *Radio Telemetry*

Twenty-four flathead catfish were implanted with Advanced Telemetry Systems model F1835 radio transmitters during May and June 2004. Flathead catfish were captured using a boat-mounted Smith-Root 2.5 GPP electrofishing unit in the upstream site and a Smith-Root 5.0 GPP electrofishing unit in the lower site. All fish were captured using low-frequency pulsed-DC current (15-30 Hz) operating between 1.5 and 2.0 A. Sixteen of the transmitters were implanted in fish collected in the downstream reach of the site, and eight were implanted in fish collected in the upstream reach of the site (Figure 1).

Transmitters implanted in fish weighing over 800 g did not exceed 2% of the fish's total body weight (Winter 1996). Each implanted transmitter operated at a unique and identifiable frequency between 49.0 and 50.0 MHz and had a mean weight of 15.38 grams (SD 0.24 g) in air. Each radio transmitter was programmed to operate at 37 pulses per minute, extending the guaranteed battery life to 370 days and expected battery life to 640 days. This ensured that transmitters would continue to operate for the duration of the study.

Flathead catfish transmitter implantation surgeries were performed in the field, and fish were released in the general area of initial capture. Fish captured for transmitter implantation were anesthetized in a 2.6-mg/L concentration of 1.0 g/30

mL of Benzocaine/ethyl alcohol solution until oriented ventral side up and showing minimal opercular movements (mean 6.2 minutes, SD 1.7 minutes). Transmitters were implanted intra-peritoneally through a 2.5-cm incision anterior to the pelvic girdle and to the left of the ventral midline. All incisions were closed using coated, braided, nylon suture material with 4-5 interrupted sutures. Mean total surgery time was 10.7 minutes (SD 2.4 minutes). We requested the manufacturer strip the tip of each transmitter antenna and dip it in 3M Scotchcast Electrical Resin 5 (5235) to minimize peritoneal perforations caused by inserting the wire antenna into the fish; the antenna was coiled manually and completely contained within the peritoneal cavity. Fish were placed in a recovery tank after completion of the surgery and observed until they had recovered from anesthesia based on visual inspection of their mobility (mean 10.6 minutes, SD 6.1 minutes).

Fish relocation (tracking) occurred approximately weekly from 24 May 2004 to 29 August 2005 to identify seasonal patterns. All data analyzed for this study were collected no fewer than 12 days after transmitter implantation to allow a reasonable period for fish to return to normal behavior patterns. Fish were located using an ATS Model R2100 receiver, a handheld loop antenna, and a suitable watercraft. Each fish's location was recorded using a handheld Global Positioning System (GPS, Garmin Model GPS III +, Garmin Model GPS V). Microhabitat use measurements were collected at the site of each fish's relocation for analysis (see below). Fish were tracked for 63 weeks with 929 total fish locations. During each of the 63 tracking events approximately 15 of the 16 (92 %) transmitter-implanted fish were located.



Not all fish were located every week due to various technical conditions, such as malfunctioning equipment, angler induced mortality, and possible signal attenuation due to water depth and heightened water conductivity (Freund and Hartman 2002). Tracking was rescheduled for later in the week when water conditions were excessively high and deemed unsafe; however, no tracking was completed the week of 12 July 2004 or the week of 27 December 2004.

Flathead catfish are presumed to be more active at night than during the daylight hours (Minckley and Deacon 1959; Skains 1992). In an effort to evaluate this observation, a diel tracking component was incorporated as part of this study. During a weekly tracking event a suitable river section typically containing 4-5 fish within proximity to one another was identified and located for diel tracking. During that same week each fish in the subset was located every hour for 24 hours during 2-12 hour diel tracking periods. Finding suitable areas to track multiple fish over a 24-hour period was difficult, and several areas were used multiple times between and within seasons. Diel tracking was performed twice during August 2004 and December 2004, corresponding with the growth and winter seasons, respectively, and twice in March 2005 and May-June 2005 corresponding to early and late spawning seasons, respectively. Tracking for each daytime tracking period commenced at 07:00 and tracking for nighttime commenced at 19:00. GPS coordinates for each fish were recorded at the time of relocation.

### *Microhabitat Use and Availability*

Measurements of microhabitats used by radio-tagged flathead catfish were collected following each fish location, and microhabitat availability data were collected during a cross-sectional survey. The microhabitat availability survey was conducted June-July 2004 along the entire site using the line-transect method. The transect method was employed because it has been shown to minimize measurement error (McMahon et al. 1996). Specific microhabitat variables measured were depth (m), bottom velocity (m/s), mean column velocity (m/s), substrate composition, and cover type. The upper and lower river reaches were evenly divided into four subreaches. Five transects were surveyed within each subreach, with the location of the first transect selected randomly. Transects were spaced two mean river widths apart within each subreach, yielding 20 transects per reach and 40 transects for the entire site. Bank width was calculated by measuring the horizontal distance along each transect from bank to bank at the bankfull stage (Armantrout 1998). Mean bank width in the lower reach (50 m) was used for all transects; thus, the microhabitat availability survey covered 4,000 m of river length, or greater than 10% of the entire site. Microhabitat data were collected at the water-bank interface and then every 3 m along each transect to the opposite bank. Mean number of survey points along each transect was 18.0 (SD 3.7), and each subreach of transects included a mean of 89.9 (SD 12.6) survey points. The microhabitat availability survey was performed at base-flow conditions, when water levels in the river were approximately equal to the U.S. Geological Survey (USGS) multi-year average for the Deep River at the Moncure

gauging station (USGS 2005); located approximately 39 km downstream of the study reach.

River depth was measured to the nearest centimeter using a top-set wading rod in the upper reach, or a boat mounted winch with a suspended 6.8 kg lead torpedo weight in the lower reach. Marsh-McBirney flow meters (models 2000 and 201D) were used in conjunction with the top-set wading rod or suspended weight to measure current velocities. In water depths of 0.75 meters or less, mean column velocity was measured at 60% of the total depth from the surface. In water depths greater than 0.75 meters, velocities were measured at 20% and 80% of the total depth from the surface and averaged to yield mean column velocity. Substrate samples were collected using a Petit Ponar dredge device and visually classified using a Modified Wentworth Classification (Table 1, Lee and Terrel 1987). This scale classifies substrate by particle size from smallest to largest and originally was used to classify substrate for benthic invertebrates (Cummins 1962). The original scale contained several particle size classifications within each particle group which were pooled into one category each to yield the following classifications: silt/clay, sand, gravel, cobble, and boulder (Table 1).

Cover type was determined visually when practical and by contact with the Petit Ponar and the suspended weight. Cover types were listed as one of the following: coarse woody debris, fine woody debris, boulder, rootwad, undercut bank, emergent vegetation, and submerged vegetation. Published results suggest that radio telemetry location accuracy is 3 m (Vokoun 2003a; Daugherty and Sutton 2005a);

therefore, cover types that were 3 m or less from a fish location were considered associated with the fish and included in analyses.

Water temperature data were collected using Optic StowAway temperature loggers (Onset Computer Corporation) anchored on the river bottom. Temperature loggers were deployed in two locations in the upstream reach and one location in the downstream reach. Data from the temperature loggers were extracted seasonally. Attempts to compile a complete data record were hampered by one temperature logger failure and two missing loggers, presumably due to vandalism or high water events.

### *Statistical Analysis*

Home Range. Linear home range was calculated as the distance between the most upstream and downstream location points. Kernel density estimates of flathead catfish movements were calculated annually and for each season using a procedure described by Vokoun (2003b). Fish location coordinates were imported into the ArcView geographic information system software. Within ArcView, a midline was delineated along the entire length of the river section studied. A shareware program was used to add a reference point every 10 m along the river midline (Lead 2002). Reference points started at Carbonton Dam, the downstream edge of the study section with a corresponding distance of zero meters, and ended at Highfalls Dam, the upstream edge of the study section with a corresponding distance of 35,750 m. Shareware program “Nearest Neighbor 3.1” (Weigel 2002) was then used to determine which 10-m reference point each fish location was closest, indicating

distance from Carbonton Dam (0 m). Net weekly movement was determined by calculating the absolute value of weekly directional movements for each fish and then averaging them.

The output from ArcView was imported into the SAS/STAT 9.1 statistical software program, and linear home range and kernel density estimates of home range were calculated using PROC KDE (SAS Institute Inc., 2004). Kernel density estimates were calculated at the 99%, 95%, 90%, and 50% levels. A univariate distribution of the relocation points was used to calculate a univariate kernel density estimate. The univariate kernel density estimate is defined as

$$\hat{f}(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - X_i}{h}\right),$$

where  $n$  is the number of data points,  $x$  is the grid point being evaluated,  $X_i$  is the grid point associated with each data point,  $h$  is the bandwidth, and  $K$  is the Gaussian kernel function. The Sheather-Jones plug-in bandwidth procedure (SAS default) has produced acceptable results and was used to determine the amount of smoothing (Jones et al. 1996; Vokoun 2003b). Grid points corresponded to the 10-m reference points on the midline.

Calculated kernel densities and associated 10-m reference points were used to determine the corresponding section(s) of river used at each KDE level for each fish. Counting the number of 10-m reference points within the identified river section(s) and multiplying them by 10 enabled calculation of the linear distance for each fish at each KDE level. Note that these river sections of use are not necessarily contiguous. River section(s) used by each fish were delineated annually and by functional season.

Diel movement analysis consisted of calculating a daily linear range for all dielily-tracked fish for a 24-hour period and hourly for each functional season. Daily linear range is defined here as the linear distance between the uppermost fish location and the lower most fish location for one fish in a 24-hour period. Means of distances moved were not normally distributed (Shapiro-Wilk test) and a natural logarithm  $\text{Log}_e(x+1)$  transformation did not remedy the situation. The non-normal distribution of data was likely caused by the large number of observations with zero distance moved (>88%). Thus, a non-parametric Wilcoxon test was used to compare daytime to nighttime movements.

Microhabitat. Principal Component Analysis (PCA) was used to analyze habitat data of all continuous variables measured to determine the most suitable microhabitats for flathead catfish. PCA is a technique for analyzing multiple quantitative variables and produces orthogonal linear combination of variables, referred to as components, accounting for the maximum amount of variance. The first component accounts for the maximum amount of variance, the second component accounts for the next highest amount of variance, etc. Habitat availability data for continuous variables (depth, bottom velocity, mean column velocity, and substrate) were included in the PCA; cover data were omitted from PCA due to their non-continuous nature. Stevens (1996) recommended retaining components with eigenvalues greater than 1.0; I retained those with values greater than 0.98. Principal component scores for habitat use data were then calculated using scoring coefficients from the habitat availability analysis.

Microhabitat use data were also summarized and compared on annual, seasonal, and diel scales for continuous variables (depth, bottom velocity, mean column velocity, and substrate). I used a Kolmogorov-Smirnov two-sample test (K-S test, Sokal and Rohlf 1981) to test for nonrandom microhabitat use between available microhabitat and that used by flathead catfish. The K-S test compares the frequency distribution of microhabitats used by all fish to the frequency distribution of the availability of that microhabitat variable. Substrate was considered a continuous variable with bedrock being the finest particle size and boulder being the largest particle size. Each substrate category from bedrock to boulder was assigned a sequential number from one to six for analysis (Table 1). An analogous likelihood ratio test (G-test) was performed on the cover data due to their non-continuous categorical nature. Microhabitat use between seasons and diel microhabitat use between daytime and nighttime were also analyzed using the K-S test to examine temporal differences. All statistical analyses were performed using the statistical software package SAS/STAT 9.1 (SAS Institute Inc., 2004)

Microhabitat suitability describes the importance of a microhabitat to flathead catfish by comparing frequency of use for each particular microhabitat to the overall frequency of availability of that microhabitat (Bovee 1986, Lee and Terrel 1987). For example, water depths greater than 5 m were not frequently available in the habitat availability survey (<1%), yet flathead catfish utilized these depths frequently (>49%, Figure 6d), suggesting deep-water habitats are important to the fish. Microhabitat suitability ranges from a value of zero for unsuitable habitat to 1.0 for optimal ranges

of habitat (Bovee 1986). Microhabitat suitability was calculated for the variables depth, bottom velocity, mean column velocity, and substrate. Habitat suitability was determined by using the formula

$$\text{Unnormalized habitat suitability} = \% \text{ used} / \% \text{ available},$$

for each interval of the variables' frequency distribution. Then the unnormalized suitability values for each interval were normalized to a maximum of 1.0 by dividing the value of each interval by the maximum value of any interval. Microhabitat suitabilities for flathead catfish were compared to those for the Cape Fear shiner (Howard 2003) to determine the amount of microhabitat overlap between the species.

## **Results**

Twenty-four fish with a mean total length of 579 mm (SD 156 mm) and a mean weight of 3,301 g (SD 4,000 g) were implanted with radio transmitters between 12 May and 3 June 2004 (Table 2). Eight fish were collected and implanted in the upstream reach and 16 were collected and implanted in the downstream reach. Eight fish mortalities occurred within 3 months of the surgical implants; one was angler induced mortality, and seven fish likely died due to surgical stress or complications. Each of these seven fish exhibited minimal movement immediately after the surgical implantation. Three of the seven surgical mortalities were fish implanted with transmitters in the upstream reach and four were from the downstream reach. No



data from these eight fish were included in this study. All five remaining upstream implanted fish moved into the downstream reach within 3 weeks after transmitter implantation. Fish that survived surgery tended to be larger (mean weight 3,839 g, SE 1,117g) than the fish that perished soon after the surgeries (mean weight 1,995g, SE 528g). No other natural mortalities occurred during the duration of the study (15 months).

During subsequent sampling, two fish that had recently been implanted with transmitters were recaptured. One of these was recaptured 9 days after surgery and showed favorable signs of healing, although several sutures had pulled through the flesh and were replaced. The second fish was recaptured 19 days after transmitter implantation and appeared to have a nearly completely healed incision. Both of these fish survived for the duration of the study.

I found distinct movement and migratory patterns in flathead catfish of the Deep River, which I stratified into three distinct “functional seasons” (Figure 2). These functional seasons were formed by examination of movement patterns as mean weekly movement, comparing results of similar studies in the literature (Coon and Dames 1989; Kwak et al. 2004; Daugherty and Sutton 2005a; Vokoun and Rabeni 2005a), and direct observation of gravid females during transmitter implantation (spawning season). In general, mean linear movement was greatest during the spawning season, which was 21 March to 27 June (Figure 2); mean linear movements during the growth season were moderate and spanned 5 July to 18 October; mean linear winter movements were minimal and spanned 25 October to 14 March.

### *Migration, Behavior, and Home Range*

Linear range (distance between uppermost and lower most locations) of flathead catfish varied widely among individual fish and seasons. Annual linear ranges averaged 16.2 km (SD 9.7 km, Table 3). Mean spawning season linear range was 13.1 km (SD 11.4 km, Table 3). However, four fish (25%) showed mean spawning movements less than 1.2 km. Three fish (19%) had linear spawning ranges greater than 28 km, suggesting these fish utilized at least 76% of the available river section. These results illustrate wide variation in spawning migration behavior over the study period.

Mean growth season linear range was 10.1 km (SD 7.7, Table 3). One fish spanned a linear range of 27.7 km during the growth season, the result of returning from a long upstream migration to the downstream reach in July 2005, after the spawning season. Another fish had identical linear ranges of 22.9 km during both the spawning and growth seasons in 2005. This was likely caused by the fish moving into the upstream reach late in the spawning season and remaining there until the conclusion of the study in August 2005.

Mean winter season linear range was 3.9 km (SD 2.5 km, Table 3). The greatest movement in winter was a 9.0-km downstream movement in late November. This movement was also the extent of that fish's annual linear home range. The smallest winter range was 0.13 km and was attributed to one fish initially captured and implanted with a transmitter in the upstream reach of the study site and subsequently moved into deep water near the downstream dam during winter.

We found that flathead catfish movements varied with fluctuating water temperatures (Figure 3). Although we did not collect a continuous record of water temperature in the Deep River, patterns in the data collected are evident. In late-June through August 2004, relatively soon after transmitter implantation, water temperatures were at their peak (26 - 29 °C) and flathead catfish movements were moderate. As temperatures began to drop in late August, fish movements increased until mid-November 2004, when temperatures reached 17 °C, corresponding with the onset of winter. During winter, from November 2004 to mid-March 2005, when water temperatures were presumed lowest, movements were minimal. Fish movements increased as water temperatures rose above 10 °C in mid-March, corresponding with spawning season. When water temperatures increased to 16 - 17 °C in late April, fish began long upstream migrations, presumably to their spawning grounds. These movement patterns continued until temperatures approached 25 °C, approximately mid-June, when water temperatures were at their highest and fish movements were moderate.

Annually, mean daily linear range was 509 m with the greatest diel movements during the spawning season and the most restricted movement during the winter season (Table 4). Movement behavior was significantly greater during the nighttime hours annually and for spawning and growth seasons, but not during winter (Table 5, Figure 4).

Kernel density estimates of home range were calculated for all fish annually and for each functional season. Estimates were calculated at the 99%, 95%, 90%, and

50% levels. Kernel estimates at the 99%, 95%, and 90% levels represent use levels at the extremities of the fish's range. Kernel estimates at the 50% level represent the length of river in which the fish spent 50% of their time and is considered the core area (Vokoun 2003b). These kernel estimates may be interpreted as the proportion of time each fish spent in the river section represented by the respective levels or the probability (e.g., 50%) of locating the fish in that river section within the corresponding time period (Vokoun 2003b, Table 3).

The 99% kernel density estimates were smaller than the linear home ranges annually and seasonally for all fish with two exceptions (Table 3). For one fish, this occurred in the annual analysis, where the kernel density estimate exceeded the linear home range by 130 m. The other instance occurred in the winter season and involved one fish moving upstream greater than 6 km in mid-November. This fish had returned to within 70 m of its original location the following week. Kernel density estimates of home range at the 95%, 90%, and 50% levels were all smaller than linear home range estimates.

Mean kernel density estimates of home range at the 99% and 95% levels were nearly 50% of the linear range annually and for each season (Table 3). Mean 99% kernel density estimate of winter range was 44% of the winter linear range. The difference between 99% and 95% estimation levels annually was 1,630 m. Variation between 99% and 95% levels within seasons differed by as little as 56 m during the spawning season and by as much as 766 m during the growth season. Mean kernel density estimates at the 90% level were at least 50% of the linear range annually and

for each season. Mean kernel density estimates of home range at the 50% level were approximately 10% of the linear range annually and for each season.

#### *Microhabitat Use and Suitability*

Principal Component Analysis (PCA) revealed habitat gradients generally describing downstream impounded water to upstream, unimpounded water (component 1) and from the river bank to the mid-channel (thalweg) of the river (component 2, Table 6). Component 1 (49%) and component 2 (25%) combined to explain 74% of the variation in the microhabitat availability (Table 6). Component 1 (impounded pool-unimpounded riffle) was interpreted as describing a gradient from impounded to unimpounded habitats due to its positive velocity and substrate loadings and negative depth loading (Figure 5, Table 6). The downstream, impounded section of the Deep River was characterized by deep water (mean 2.9 m, SD 1.4 m) with lower velocities (bottom velocity mean 0.05 m/s, SD 0.07 m/s; mean column velocity mean 0.09 m/s, SD 0.10 m/s) and finer substrates (bedrock and silt/clay). The upstream, unimpounded section of the Deep River was characterized by shallow (mean 0.58 m, SD 0.03 m), faster moving water (bottom velocity mean 0.07 m/s, SD 0.11 m/s; mean column velocity mean 0.15 m/s, SD 0.17 m/s) with coarse substrates (gravel, cobble, boulder). Component 2 (bank-channel) was interpreted as a gradient from river bank to mid-channel areas, due to its positive correlation with depth and velocities and negative correlation with substrate. I found flathead catfish most often associated with slower, deeper water over bedrock or silt/clay substrate types (low component 1 scores, Figure 5a), consistent with

impounded pool habitat, and they were only rarely found in shallow, unimpounded riffle habitats (high component 1 scores), suggesting that microhabitats were used non-randomly. Seasonally, flathead catfish utilized impounded pool habitats more frequently than unimpounded riffle type habitats; unimpounded riffle habitats were seldom used in the winter season and were used slightly more during the spawning and growth seasons (Figure 5b-d). Flathead catfish used mid-channel habitats (high component 2 scores) more frequently than riverbank habitats for all seasons, although riverbank habitats were commonly used (Figure 5b-d).

Univariate frequency distributions of microhabitat use and habitat availability were significantly different for all variables, both annually and seasonally ( $P < 0.005$ , Table 7, Figures 6-10), indicating that flathead catfish select and use microhabitat non-randomly. Table 7 also shows a great difference between the available mean depth (1.69 m) and that actually used (4.06 m) annually. Variation in mean depth among seasons was minimal between spawning and growth seasons; however, winter season mean depth was greater compared to spawning and growth seasons (spawning = 3.64 m, growth = 3.62 m, and winter = 4.91 m). Available mean velocities were approximately 2-3 times greater than annual and seasonal use velocities (Table 7).

Microhabitats selected by flathead catfish varied by season. Distributions of depths in microhabitats occupied by flathead catfish were not significantly different between spawning and growth seasons (Table 8), and fish occupied deeper water more frequently in winter when compared to spawning and growth seasons (Figure 6b-d). Bottom velocity comparisons between growth and winter seasons were not

significantly different (Table 8) but were slightly faster during the spawning season, compared to winter or growth seasons (Figure 7b-d). Mean column velocities were significantly different during the growth season when compared to spawning and winter seasons (Table 8). Flathead catfish were associated with higher mean column velocities more frequently during the growth season than during spawning or winter seasons (Figure 8b-d). Substrates of occupied microhabitats were highly significantly different between growth and winter seasons, marginally different between spawning and growth seasons, and not significantly different between winter and spawning seasons (Table 8). Substrates most frequently occupied were silt/clay during the growth season and bedrock during spawning and winter seasons (Figure 9b-d). Comparisons between seasonal cover type associations (Table 8) indicate that cover use in winter is significantly different than during spawning or growth seasons, and flathead catfish are found associated with coarse woody debris more frequently during spawning and growth seasons than during winter season (Figure 10b-d).

Flathead catfish microhabitat suitabilities are optimal for deep, slow water, except during the spawning season, when the suitability is highest for shallower, faster water (Figures 11-15). The most suitable substrate category was silt/clay, except in winter, when suitabilities for bedrock and silt/clay were equally high (Figure 14). The most suitable cover type among those used was root wad (Figure 15). Root wad cover appeared in our habitat availability survey on only one occasion and was associated with the location of a single fish eight times. The next most suitable cover type was coarse woody debris followed by fine woody debris.

Comparing the microhabitat suitability of flathead catfish and the Cape Fear shiner (Howard 2003) suggests minimal microhabitat overlap between the species (Figure 16). Flathead catfish most suitable habitat in the Deep River was the deepest water available, and conversely, Cape Fear shiners were rarely found in water deeper than 0.5 m (Figure 16a). A comparison of bottom velocity suitability between the species indicates that flathead catfish select the slowest available bottom velocities, and Cape Fear shiners select moderate water velocities (Figure 16b). However, during the spawning season, flathead catfish select bottom velocities that are significantly faster than during the rest of the year (Table 8, Figure 7), which could account for the bottom velocity suitability overlap between the two species. A comparison of mean column velocity suitabilities indicates flathead catfish select the slowest column velocities and Cape Fear shiner select moderate column velocities, indicating moderate microhabitat overlap between the species (Figure 16c). A comparison of substrate suitability between species shows that flathead catfish select bedrock and silt/clay substrates, while the Cape Fear shiner selected rock substrates of gravel, cobble, and boulders (Figure 16d). This overlap could be explained by the flathead catfishes selection for faster waters during the spawning season.

Depths of microhabitats occupied annually and for all seasons were significantly different between night and day, except during the winter season (Table 9). These differences reflected that hourly mean depth of habitats utilized by flathead catfish was generally deeper and more varied at night than during the day, except in the winter season (Figure 17). A comparison of daytime and nighttime bottom



velocity selection was highly significant during the spawning season and marginally significant annually, but not significantly different for growth or winter seasons (Table 10). Hourly mean bottom velocity trends indicate that selected velocities were slightly higher during the night than during the day in all seasons except winter (Figure 18). Mean column velocity was significantly different between daytime and nighttime hours annually and for all seasons, though marginally so during the spawning season (Table 11). Hourly mean column velocity was generally greater during the day than at night for all seasons except winter (Figure 19). Substrate of occupied habitats was not significantly different between day and night for any season except winter, which was marginally significant (Table 12, Figure 20). Cover associations were significantly different between day and night annually and for all seasons, though marginally so during the spawning season (Table 13, Figure 21). Differences between daytime and nighttime microhabitat use could be influenced by discharge fluctuations experienced during and between tracking intervals; however, effort was made to ensure that diel tracking events were conducted under conditions that would minimize this effect.

## **Discussion**

I am confident with the accuracy and validity of results presented here, from the standpoint of consistency of operation of the equipment. From observations of flathead catfish shortly after the transmitter implants and subsequent fish behavior, it is clear that those fish that survived the initial surgical implantation, survived the

entire study period, with the exception of one angler induced mortality, and there were no natural mortalities. In addition, during each of the 63 tracking sessions, a mean of 14.7 of the 16 surviving radio-tagged flathead catfish (92%) were located. This is a favorable result when compared to previous telemetry studies in which fish moved out of primary study areas to return later or never to be located again (Coon and Dames 1989; Skains and Jackson 1993; Kwak et al 2004; Daugherty and Sutton 2005a; Vokoun and Rabeni 2005a).

The occurrence of lost fish with unknown whereabouts or fate in telemetry studies certainly brings into question associated reported movement estimates with the possibility of a bias towards underestimating ranges. All of the previously mentioned studies were in river systems with long, unobstructed river sections allowing unimpeded movement by the flathead catfish. Our study was conducted in a relatively small, closed system, and even in this closed system where fish could not move out of the study site, our success rate at locating every fish while tracking was less than perfect (92%). All fish were located in the lower reach of the site for most of the study period. It was unfortunate that eight of the initial 24 preparations of radio tagged fish (33%) were lost early in the study; an attrition rate of 33% is higher than such rates reported in previous studies (<10%, Kwak et al. 2004; Vokoun 2003a), one with the same investigators performing surgeries. The higher attrition rate was almost certainly due to mortality resulting from surgical complications, which may be affected by environmental conditions after release.

In the case of radio telemetry with flathead catfish, researchers are faced with a timing dilemma. Surgery survival is generally higher when performed in cool waters (Winter 1996), but flathead catfish are not vulnerable to electrofishing until waters exceed 18 °C (Kwak et al. 2004). Thus, initial surgery mortalities may be related to water temperatures as high as approximately 25 °C during surgery (Figure 3, Winter 1996).

My results are in accord with findings of previous studies (Kwak et al. 2004; Vokoun and Rabeni 2005b). Kwak et al. (2004) suggested that temperature played a crucial role in determining when spring spawning migrations commence in Coastal Plain river populations of flathead catfish, indicating similar seasonal movement patterns among rivers, and my findings support this. Flathead catfish move into the littoral zone of lakes and reservoirs as water temperatures warm. When water temperatures rise to 19-25 °C, they move to spawning areas, which are typically hollow logs or cavities in river systems, or rock revetment areas in reservoir systems (Lee and Terrell 1987; Weller and Winter 1999). Habitat variables such as cover and prey availability may be more important than temperature in overall habitat selection (Weller and Winter 1999). However, I suggest that such causal factors interact to influence flathead catfish habitat use.

#### *Migration, Behavior, and Home Range*

A key to understanding and successfully managing the current and future effects of introduced flathead catfish populations is to identify the fish's home range. Home range is defined as "the area over which the animal normally travels" (Gerking

1953). Quantifying and characterizing an animal's home range is essential to understanding its ecology and behavior. Successful management of a fishery requires thorough understanding of how much of an area the species of interest occupies, the seasonal patterns of movement, and the amount of time a fish occupies an area during any particular season.

Linear range is the most common method of reporting the home range for riverine fishes and represents the length of river section occupied by each fish on any time scale. Linear range is the distance between the uppermost and lowermost location points and was calculated for each individual fish. Weekly mean linear ranges were plotted and used to delineate different functional seasons based on changes in movement distances and results of previous studies (Figure 2). Then I calculated the mean linear home ranges annually and seasonally to allow comparison of movement patterns among seasons. Seasonal linear range is the average linear home range of all fish for each respective functional season. Quantifying animal behavior characteristics based on a biological calendar rather than a lunar calendar will provide more accurate results and ultimately better management practices.

In my study, linear home ranges of flathead catfish varied among seasons and annually. Mean annual linear home range was greater than 16 km and included relatively large migrations by 25% of tagged fish. These results are similar to those of Kwak et al. (2004) in their study of introduced flathead catfish in North Carolina and Vokoun and Rabeni (2005a) in their study of native flathead catfish in Missouri. They reported large-scale migrations and relatively large linear ranges by a majority

of the population (Table 14, Kwak et al 2004; Vokoun and Rabeni 2005a); conversely, several studies have concluded native flathead catfish have minimal linear range (Skains and Jackson 1993; Dobbins et al. 1999; Pugh and Schramm 1999).

Differences in between-season mean linear home ranges in my research were significant. Ranges were greatest during the spawning season and least during winter. These results correspond well with those of a study on the Grande and Cuivre Rivers, Missouri (Vokoun and Rabeni 2005a), and indicate that although the annual linear ranges between river systems vary, the seasonal ranges are remarkably similar (Table 15). Another study of seasonal movement behaviors of flathead catfish in the St. Joseph River, Michigan, reported similar temporal movement patterns; however, mean seasonal movements were spatially smaller than in the two previously mentioned studies (Daugherty and Sutton 2005a). Significant differences in seasonal home range were reported in all three studies comparing seasonal movements, as well as similar trends in home range compared to season (e.g., spawning was largest, winter was smallest), suggesting differences in annual linear home ranges may be related to distance fish must travel to reach their seasonal habitats and not activities of the fish during that particular season.

Flathead catfish in the Deep River, North Carolina, were significantly more mobile during the nighttime than during the daytime. This is similar to the findings of four previous studies examining diel movements of flathead catfish in their native range (Minckley and Deacon 1959; Skains 1992; Daugherty and Sutton 2005b;

Vokoun and Rabeni 2006). Minckley and Deacon (1959) observed higher catches per hour during nighttime than during the daytime and assumed that this was due to higher nighttime mobility. Skains (1992) reported that all but one recorded incidence of flathead catfish movement was during the nighttime. Vokoun and Rabeni (2006) tracked six flathead catfish every 15 minutes for 24-hours from July-September, which corresponds with our growth season. They reported mean daily movements of 712 m, not remarkably different than our finding of daily movement of 385 m during August (growth season). Daugherty and Sutton (2005b) tracked seven fish and reported a median diel range of flathead catfish during July and August to be 44 m, a considerably smaller range when compared to median range of 360m during August for flathead catfish in the Deep River. Within the Deep River, there were several areas in the lower reach where fish were frequently located; thus, I conducted diel tracking near these areas for efficiency in an effort to increase sample sizes. Bias among individuals may be included in my diel movements results, since the same fish were commonly tracked among seasons and even several times within a season, but no fish was dielly tracked during all three seasons. Diel ranges may be underestimates, as fish moving great distances could not be tracked. Seven additional fish were initially tracked for the purpose of determining diel movements, but moved out of the area and could not be tracked due to logistic constraints to continue tracking other fish concurrently. Nonetheless, the relative activity patterns (i.e., more active at night) discerned by diel tracking in my study remain valid.

Movement behaviors of stream fishes have been studied extensively. The concept of restricted movement in stream fishes has been greatly influenced by the early writings of Gerking (1959; see also Gowan et al. 1994), who used mark-recapture techniques to study stream fish movements. Gerking (1953, 1959) reported that many stream fishes exhibit limited mobility behaviors, and once established would remain relatively immobile indefinitely. Gowan et al. (1994) reviewed literature that supports the restricted movement paradigm in stream salmonids. Additionally, Gerking (1953) concluded that in a riffle-pool stream system, each pool could be considered an individual habitat unit hosting a population of fish.

Flathead catfish have been variably reported to be sedentary or exhibit limited movements and utilize relatively small river sections (Funk 1957; Dames et al. 1989, Quinn 1988; Skains and Jackson 1993). It is common practice in these and other studies to disregard or minimize the importance of the tagged population not recaptured (Gowan et al. 1994; Gowan and Fausch 1996). Reported numbers of errant fish are frequently >90% in studies using passive tags (Kwak et al. 2004) and 10% - 20% in telemetry studies (Skains and Jackson 1993; Kwak et al. 2004; (Daugherty and Sutton 2005a). This brings into question the whereabouts of a significant portion of the marked population unaccounted for and whether those fish have left the study site (Gowan et al. 1994) or were simply not able to be recaptured.

Confounding these results may be the timing of the tag or transmitter implantation or the time period during which the study was conducted. If flathead catfish are universally most mobile during the spawning season, less mobile during

the growth season, and minimally so during the winter, studies that implant transmitters during the spawning season and do not encompass an entire year will bias the results accordingly. Travnichek (2004) performed all of his sampling and tagged all fish in the Missouri River during the first two weeks of June, corresponding with the pre-spawn/spawning period in the Missouri River (Vokoun and Rabeni 2005a), when fish are most mobile. Tagging and recapture studies completed during this time will tend to sample transient fish more frequently, possibly reducing recapture rates in mark-recapture studies. Skains and Jackson (1993) used radio telemetry and mark-recapture techniques to calculate linear ranges of native flathead catfish in two Mississippi rivers from June until January, a time period that is largely represented by periods of restricted movement in studies of native and introduced populations (Daugherty and Sutton 2005a; Vokoun and Rabeni 2005a; present study). Drawing conclusions about the range of a fish based on a limited number of recaptures or without including an assessment of all functional periods leaves open the possibility of erroneously estimating a fish's range and misinterpreting the significance of fish movements.

Funk (1957) suggested that stream fish populations may be composed of two subpopulations, sedentary and mobile groups, and my findings support this theory for flathead catfish in the Deep River. The closed system of the Deep River was an ideal location to study the possibility of the existence of two subpopulations of flathead catfish, a sedentary and a mobile component. I attempted to study fish representative of the entire population by collecting fish throughout the entire site during late



spawning season. During the spawning season of 2005, four of five fish (80%) initially captured and tagged in the upstream reach in 2004 made at least one long-distance upstream movement greater than 25 km, returning the same locations in which they were initially captured. These movements were most frequently completed between my weekly tracking intervals, and the amount of time fish remained in these upstream locations varied from one to five weeks. One of these fish completed six substantial upstream-downstream movements during spawning season of 2005. Four of these movements were greater than 17 km and occurred in consecutive weeks, first moving upstream, then back downstream (March-April), reusing the same upstream and downstream locations with each successive movement. Later in the spawning season, the same fish made two additional forays over 25 km (May-June), first moving upstream to the initial capture area and then back downstream. Several studies have concluded that their results support Funk's (1957) theory of two subpopulations (Heggenes et al. 1991; Freeman 1995; Smithson and Johnston 1999). Smithson and Johnston (1999) found stream fishes in Little Glazypeau Creek, Arkansas, that made regular exploratory trips outside of their home pools; the percentage of marked fish following this trend ranged from 12-33%. Based on their findings, critical habitat requirements for stream fish may be underestimated.

Home range has been studied in lotic systems for many fish species and typically is reported as linear home range. While this is informative in that it provides an upper and lower boundary of where a fish is likely to be found, it does not account for the variable amount of time a fish may spend in a particular area.

Furthermore, highly mobile fish species will yield a large area that could include unusual observations outside the normal home range of the fish, thereby producing ecologically irrelevant results. Other methods for calculating home range, such as minimum convex polygon, are incapable of handling the boundaries of a stream as they include the terrestrial environment (Worton 1987; Vokoun 2003b). Thus, a more informative approach to estimating animal home ranges is by calculating univariate kernel density estimates of home range. Kernel density estimators are commonly applied to the study of home range in terrestrial animals (Worton 1989; Seaman and Powell 1996). Kernel density estimation is a nonparametric technique in which a known density function (or kernel) is averaged across the observed data points to create a smooth approximation (SAS Institute Inc. 2004). The kernel home range estimates can then be interpreted as utilization distributions (Van Winkle 1975), which incorporates the linear home range with an estimate of amount of time an animal spends in a given area of its home range (Vokoun 2003b). The delineation of time spent in each area is broken down to percentages of use, for example, 95% level is the area(s) where the animal spent 95% of its time. Since kernel home range estimates are calculated from observed data, an estimate may be broken into two or more discrete river sections, giving a more concise estimate of actual utilized range without including relatively unused areas in between.

I calculated kernel density estimates of home range for flathead catfish in the Deep River, annually and for each of three functional seasons, at 99%, 95%, 90%, and 50% levels. It is difficult to compare kernel density estimates of home range of

flathead catfish since only one previous study has calculated them. That study was conducted on native flathead catfish in two Missouri rivers and occurred in a time period corresponding to the growth season in my study. In the Deep River, growth season linear range was greater than the 99% kernel estimate for 13 flathead catfish (81%); all 13 fish had two or more discontinuous use areas at the 99% level. Vokoun (2003b) found all 99% kernel estimates to be greater than corresponding linear home range estimates. During the growth season in my study, 25% of the fish had 95% use areas exceeding 1,000 m, and 44% had 95% use areas greater than 2,000 m. This is not remarkably different from the findings of Vokoun (2003a) who found 47% of fish used areas less than or equal to 1,000 m and 69% used areas longer than 2,000 m at the 95% level. Core use areas in the Deep River were also larger; 25% of core use areas were less than 100 m, while in the Missouri study, 47% of the core use areas were less than 100 m, and 56% were over 500 m in the Deep River, compared to 86% in the two Missouri rivers.

Location of flathead catfish core use areas in the Deep River varied among seasons. In general, core use areas were farther upstream during the spawning season, relative to the growth and winter seasons, however, only slightly in the case of the growth season. Vokoun and Rabeni (2005a) calculated the median linear home range of flathead catfish and median kernel density estimates at 95%, 90%, and 50% levels in the Grand River and Cuivre River in Missouri in the post-spawn summer period. Their median linear home range for all fish on both rivers was 3,510 m, and the median linear range in my study during the growth season was 10,195 m (Table

3). Flathead catfish in the Deep River had 95%, 90%, and 50% use areas that were approximately 250% larger than those reported by Vokoun and Rabeni (2005a).

Vokoun and Rabeni (2005a) estimated median kernel densities of 1,085 m (95% level), 845 m (90% level), and 135 m (50% level) compared to 3,090 m (95% level), 2,015 m (90% level), and 345 m (50% level) in the Deep River.

Vokoun (2003b) summarized three factors that should be considered using kernel density estimates of home range: selection of bandwidth, sampling interval, and number of relocations for each individual. I used the same bandwidth selection procedure as Vokoun (2003b) to make results of the two studies comparable.

Sampling interval must be wide enough for locations to be independent, but frequent enough to provide a large enough sample size within a biologically defined time period; my sampling interval was approximately one week. Recommended sample sizes for kernel density estimates of home range vary from 30 to 50 location points per fish, with 30 being the minimum (Seaman et al. 1999; Vokoun 2003b). In my study, mean sample sizes by season were 17.3 for spawning (range = 15-20), 21.5 for growth (range = 18-24), and 19.3 for winter (range = 17-20). I have reported kernel density estimates of home range for all fish during all seasons in an effort to expand the knowledge base in this new area of home range estimation for flathead catfish, even though sample sizes were below the minimum recommended size. There is an inherent trade off between independence of observations and obtaining a suitable sample size, and some amount of autocorrelation must be accepted when the researcher is interested in a restricted time period, like biologically defined seasons

(Vokoun 2003b). Kernel density estimates of home range are a more ecologically meaningful method of delineating home range, as long as these three issues are taken into consideration.

#### *Microhabitat Use and Suitability*

Univariate analyses of microhabitat use (depth, bottom velocity, mean column velocity, substrate, and cover) relative to availability indicate that flathead catfish select microhabitats non-randomly annually and for each functional season. My between-season comparison of microhabitat use revealed that flathead catfish vary their microhabitat selection seasonally. Annual mean of depth used by flathead catfish in the Deep River was 4.06 m (Table 7) and was dominated by a mode of depths in the 3-6 m range (Figure 6a). These results are consistent with the findings of Kwak et al. (2004) where flathead catfish in three coastal North Carolina rivers strongly selected the deepest water available. In the Lumber River and Contentnea Creek, fish were consistently found in the maximum depths available to them, which rarely exceeded 2 m. In the deeper Northeast Cape Fear River, fish tended to avoid depths less than 4 m. Depth selection in the flathead catfish's native range is shallower than that observed in introduced populations (present study; Kwak et al. 2004). Flathead catfish selected depths in Perche Creek, Missouri, of 1-3 m (Coon and Dames 1989), 1.5-3.0 m in the Missouri and Cuivre rivers, Missouri (Vokoun 2003a), and 1-4 m in the St. Joseph River, Michigan (Daugherty and Sutton, 2005), even though greater depths were available. Such discrepant findings among populations for a single habitat variable suggest that other factors, such as velocity,

substrate, cover, or biotic variables interact in microhabitat selection and justify the use of multivariate approaches (e.g. PCA in my research) to study fish habitat ecology.

Depths of microhabitats used by flathead catfish that I studied varied by season, with the deepest available depths being selected during winter and significantly shallower depths occupied in the spawning and growth seasons. Similar variations in seasonal depth selection have been observed in studies of flathead catfish in their native range with the deepest water being selected in the winter and shallower depths selected in the spring and summer (Daugherty and Sutton 2005a). Coon and Dames (1989) also observed flathead catfish utilizing microhabitats shallower in depth during the spring, compared to summer or fall. I did not detect statistically significant differences in depth selection between spawning and growth seasons (Table 8); however, the shallowest depths occupied in the Deep River occurred during the spawning season and were largely limited to fish tagged and tracked in the upstream reach.

Bottom velocities of selected microhabitats in my study were the slowest water available, and suitabilities for each season were optimum for velocities less than 0.05 m/s (Figure 12). However, a secondary mode of bottom velocity suitabilities (0.20-0.25 m/s) during spawning was substantially faster (Figure 12b). Kwak et al. (2004) also found that the slowest available bottom velocities were selected in all three coastal North Carolina rivers of that study. In contrast, surface velocity rates selected by native flathead catfish in the St. Joseph River, Michigan,

were generally over 0.20 m/s during all seasons, and they only selected velocities less than 0.20 m/s during the spring and summer. Mean column velocities of flathead catfish microhabitats in my study were the slowest available annually and for each season. My findings on velocity are consistent with those of Kwak et al. (2004) on Contentnea Creek and the Lumber River, North Carolina, but contrast with those for the Northeast Cape Fear River flathead catfish, which strongly selected the highest velocities available. These contrasting results are likely due to differences in geomorphology and tidal influence among rivers.

Modal substrate selection for microhabitats over silt/clay in my research is similar to the results of the previous study on the Coastal Plain of North Carolina (Kwak et al. 2004); however, there is no mention of bedrock microhabitat use in the Coastal Plain study, which was commonly utilized by flathead catfish in my Piedmont study and had very high suitability during the winter season (Figure 14d). This is not surprising since the coarsest substrate types are generally deposited upstream and finer substrates are progressively deposited downstream, with sand substrates being the predominant substrate type where the river meets the sea (Skinner and Porter 1999). Suitabilities for substrate in the coastal North Carolina rivers indicate that hard clay was optimal. Fish in the Northeast Cape Fear and Lumber rivers also utilized sand and silt, with optimal suitability for sand in the Lumber River. Results of both studies list clay as the optimum substrate, however these results are not necessarily identical. The coastal study specifically mentions hard clay (Kwak et al. 2004), while the clay I found in the Deep River could not be

considered hard, and for that reason was aggregated with silt substrate observations. Therefore, it should be concluded that optimum suitability from the Deep River was for softer substrates (except for the winter season) and substrate suitabilities from the coastal North Carolina study were for harder substrates.

Past studies indicate that flathead catfish most frequently utilize woody structure for cover (Minckley and Deacon 1959; Lee and Terrell 1987; Coon and Dames 1989; Kwak et al. 2004; Daugherty and Sutton 2005a), and woody debris is an important microhabitat feature for flathead catfish (Vokoun 2003a). I found flathead catfish associated with coarse woody debris and no cover in about equal proportions (~40%), with some variation seasonally (Figure 10). Others indicate a much higher proportional use of coarse woody debris in the flathead catfish's native range (>70%, Coon and Dames 1989; Daugherty and Sutton 2005a) and introduced range (66%-89%, Kwak et al. 2004). The most notable variation in cover association in my research was during the winter, when a majority of flathead catfish occupied microhabitats without cover a majority of the time. Daugherty and Sutton (2005a) observed a seasonal shift in flathead catfish cover association from large woody debris during summer, fall, and winter, to rip-rap (rock revetment) in the winter. This seasonal shift in substrate may be related more to selection for deeper water than for cover. In my study, the deepest water available occurred most frequently near the mid-channel of the river, away from coarse woody structure that was usually anchored or lodged on the bank.



Cover suitabilities suggested that root wads were optimal microhabitat for flathead catfish in the Deep River (Figure 15a-c); however, root wad was identified in the available habitat on only one occasion out of 625 data points, and only one fish was associated with root wad on eight occasions out of 907 observations. The low number of observations of root wad availability and use may have been confounded by high turbidity (low visibility) in the Deep River. Additionally, a large number of fish were associated with coarse woody debris, and there is likely a functional similarity between coarse woody debris and the presence of root wads.

Methods used to determine cover type were subject to variable observer error, possibly resulting in an underestimation of cover availability and frequency of cover association. The type of cover and distance from each fish location was recorded for each fish location, either by visual confirmation or by contact with it using the submerged sampling equipment. A fish was considered associated with a particular cover type if that cover was within 3 m of the fish's tracked location. The waters of the Deep River are moderately to highly turbid, depending on the amount and timing of rainfall. Under ideal conditions, an observer could see objects below the water surface at a depth of approximately 0.5 m, far less than the annual mean depth of habitats utilized by flathead catfish (4.06 m; Table 7). Thus, it is possible that some fish locations were in fact associated with cover, but were erroneously recorded as having no cover.

Comparisons of flathead catfish and Cape Fear shiner microhabitat suitabilities in the Deep River suggest there is little reason to suspect that adult

flathead catfish present a substantial predation risk to the Cape Fear shiner.

Microhabitat suitabilities for depth and substrate suggest limited similarities between flathead catfish and Cape Fear shiner microhabitats (Figure 16a and d). Cape Fear shiner optimum depth suitability was overwhelmingly for depths less than 0.5 m, and they were never found in water exceeding 1.0 m in depth. Flathead catfish were found in water less than 1.0 m on only 10 occasions, in 1.1% of the total observations for depth. All of these observations of flathead catfish in depths shallower than 1.0 m occurred during the spawning season in the upstream reach during late May and June. Optimal substrate suitability for the Cape Fear shiner was for gravel, and that for flathead catfish was for bedrock and silt/clay. Flathead catfish suitability is optimal for the slowest velocities available, and the Cape Fear shiner optimum velocity is 0.2 m/s, rather moderate (Figure 16 b and c). Suitability results indicated minimal bottom and mean column velocity microhabitat overlap between the species at velocities higher than 0.2 m/s. Flathead catfish utilization of microhabitats with velocities less than 0.05 m/s and 0.05-0.10 m/s consisted of 88% and 8% of locations, respectively. These results suggest minimal predation risk to Cape Fear shiners by adult flathead catfish; however, flathead catfish habitat requirements vary with life stage (Lee and Terrell 1987; Jackson 1999). Young-of-the-year flathead catfish tend to select swift riffles with coarse substrates (Minkley and Deacon 1959; Lee and Terrell 1987; Irwin et al. 1999), habitats that are similar to those selected by Cape Fear shiners. This suggests that juvenile flathead catfish may present a predation risk

to the Cape Fear shiner; however, the degree of this potential interaction between juvenile flathead catfish and Cape Fear shiner is unknown.

Diel analysis of flathead catfish microhabitat use in the Deep River indicate that they generally occupy different habitats between daytime and nighttime hours, except during the winter. Two previous studies suggest that adult flathead catfish occupy deeper habitats during the daytime than at night (Minckley and Deacon 1959; Skains 1992); however, Daugherty and Sutton (2005b) reported no significant difference between daytime and nighttime depth selection by flathead catfish. My results do not support these findings, as flathead catfish in the Deep River generally moved to deeper habitats during nighttime hours. My results demonstrate that flathead catfish utilize slightly faster velocities during the daytime than at night; however, the degree of difference is minimal and may be related to fluctuating river discharges between sampling periods. Daugherty and Sutton (2005b) found no significant difference between daytime and nighttime in velocity selection.

Microhabitat use during the winter season is an exception to the generalization above, when it was similar between daytime and nighttime hours. This is not unexpected, as flathead catfish linear home range during winter was restricted and movements were limited during this season. Depth and bottom velocity of microhabitats occupied during daytime and nighttime were similar during winter, but mean column velocity and substrate were significantly different. Skains (1992) detected no significant difference between daytime and nighttime depth of habitats selected by flathead catfish in the Big Black River, Mississippi; however, he reported that flathead catfish

utilized deeper habitats during the nighttime than during the daytime in the Tallahatchie River, Mississippi. He also reported that flathead catfish utilized similar cover types between daytime and nighttime; however, all fish associated with no cover were found at night. Daugherty and Sutton (2005b) reported that flathead catfish utilized open water habitats in greater proportion during the nighttime than during the daytime. Similarly, in my research, fish not associated with cover were more common at night than during the daytime for all seasons, possibly due to increased movement and selection for deeper habitats during the nighttime hours. Some nighttime cover associations may have been erroneously recorded as no cover due to reduced visibility during the nighttime hours, hindering visual assessments of covers utilized.

Habitat selection by flathead catfish during nighttime is probably related to diel behaviors of prey species. For example, centrarchid (sunfish) and cambarid (crayfish) species are common prey items for flathead catfish (Ashley and Buff 1987; Quinn 1987; Pine et al. 2005). Crayfish emerge from burrows during the night and it has been demonstrated that centrarcids move into open water and actively feed at night in the presence of a predator, presumably to avoid predation of sight-feeding predators (Collins and Hinch 1993; Shoup et al. 2003). Flathead catfish feed at night (Minkley and Deacon 1959), possibly using the cover of darkness and their superior senses to detect and capture unsuspecting prey.

### *Summary and Implications*

In summary, flathead catfish in the Deep River, North Carolina, were generally associated with relatively moderate water depth, slowest velocities, bedrock substrates, and nearly always found in or adjacent to coarse woody debris or associated with no cover at all. Seasonally, these fish utilized different habitats, with faster bottom velocities in the spawning season, silt/clay substrates and faster mean column velocities in the growth season, and during winter, they were found in the deepest water possible and most frequently not associated with cover. On a diel scale, flathead catfish utilized shallower and faster microhabitats during the daytime than at night. This population of flathead catfish's mean linear home ranges were greater than 16 km annually (nearly one-half of the entire section available to them), indicating that these fish are highly mobile. Mean seasonal movements were distinctly restricted during the winter season and at their greatest during the spawning season. The areas of use depicted by the kernel density estimate of home range give a more ecologically meaningful view of flathead catfish behavior and should prove a useful tool for flathead catfish management.

I chose to study flathead catfish in this river section partially due to concerns over the coexistence of a large, piscivorous carnivore and a federally endangered minnow. Results of my research suggest that potential interactions between the two species are highly unlikely for adult flathead catfish, because habitat preferences between these two species are divergent in nearly every category examined. Additionally, Carbonton Dam, the downstream dam in my Deep River study site, has been removed since the conclusion of my study, reverting more than 15 km of

impounded water back to its original free-flowing state and creating more riffle/pool habitat suitable for the Cape Fear shiner and much less suitable for the flathead catfish. However, a source of concern is the long range migrations observed in flathead catfish during the spawning season as well as potential predation by juvenile flathead catfish. Several fish returned to the shallower, faster moving water in the far reaches of the upstream site, from which they were initially captured, and in doing so, negotiated many natural obstacles and shallow water areas to get there. All tracking in the upstream site was completed during the daytime, and I found that flathead catfish move most during night. To better evaluate the potential impacts of flathead catfish on the Cape Fear shiner, flathead catfish would need to be observed diel in the upstream site during the spawning season and a study of juvenile flathead catfish would need to be initiated.

Flathead catfish movements in this restricted area of the Deep River were not as spatially vast as those in three coastal North Carolina rivers (Kwak et al. 2004), but the implications for the species are the same. These are highly mobile fish with the ability to colonize new areas rapidly (Guier et al. 1981), able to inhabit large portions of river systems, and have the potential to severely impact native fish communities (Guier et al. 1981; Thomas 1993; Ashley and Rachels 1998; Moser and Roberts 1999). These fish are not sedentary and must be managed at the ecosystem scale (i.e., river system or water body).

Companion studies to this current study examined predator-prey interactions and population estimates of flathead catfish in this section of the Deep River with the

goal of furthering the knowledge base on introduced flathead catfish in North Carolina. With emerging results of ongoing research of this species in its native and introduced ranges, a more complete picture of its behavior and ecology is being drawn. Such an understanding will improve management of this species and its habitats.

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Table 1. Particle size categories used to describe substrate composition based on a modified Wentworth scale. Continuous variable values aggregated substrate categories used in microhabitat analyses.

Particle category	Particle size (mm)	Continuous variable
Large Boulder	>1024	6
Medium Boulder	508-1024	6
Small Boulder	256-508	6
Large Cobble	128-256	5
Small Cobble	64-128	5
Very Course Gravel	32-64	4
Course Gravel	16-32	4
Medium Gravel	8-16	4
Fine Gravel	2.0-8	4
Sand	0.062-2.0	3
Silt	0.004-0.062	2
Clay	<0.004	2
Bedrock		1

Table 2. Flathead catfish and radio transmitter characteristics for this study in the Deep River, North Carolina.

Transmitter Frequency	Capture Reach	Total Length (mm)	Weight (g)	Number of Relocations
49.014	Downstream	459	994	61
49.034	Downstream	600	2,604	62
49.054	Downstream	820	9,100	59
49.075	Downstream	491	1,360	Angler Mortality
49.095	Downstream	570	2,236	54
49.174	Downstream	505	1,400	Deceased
49.195	Downstream	469	1,238	Deceased
49.211	Downstream	578	2,456	64
49.382	Downstream	423	806	60
49.134	Downstream	904	9,650	55
49.154	Downstream	510	1,500	58
49.561	Upstream	539	1,900	Deceased
49.581	Upstream	775	6,500	57
49.601	Upstream	700	4,100	56
49.115	Downstream	730	4,750	Deceased
49.521	Upstream	624	2,875	Deceased
49.501	Upstream	445	1,000	Deceased
49.541	Upstream	533	1,600	57
49.231	Upstream	951	18,000	53
49.461	Upstream	545	1,400	58
49.272	Downstream	440	1,100	59
49.341	Downstream	409	850	57
49.352	Downstream	435	1,000	59
49.361	Downstream	441	800	Deceased
Mean		579	3,301	58.1
SD		156	4,000	2.9

Table 3. Mean and median estimates, standard deviation, and range of linear home range and kernel density estimates for flathead catfish tracked in the Deep River, North Carolina, annually and by functional season. Linear home range is the distance in meters between the upper most and lower most fish relocations. Univariate kernel density estimates were calculated at the 99%, 95%, 90%, and 50% use levels and represent the utilization distribution at the specified percentage.

Season and Statistic	Linear Home Range (m)	Kernel Density Estimates (m)			
		99%	95%	90%	50%
Annual					
Mean	16,211	7,078	5,448	4,284	687
Median	12,840	7,515	5,775	4,260	595
SD	9,675	4,663	3,960	2,979	592
Min	1,320	690	540	360	60
Max	32,150	14,850	13,030	10,940	2,030
Spawning					
Mean	13,051	6,695	6,639	5,322	1,390
Median	10,525	2,150	2,150	1,970	200
SD	11,377	7,267	7,277	5,694	2,049
Min	520	370	370	290	20
Max	32,150	18,780	18,780	18,590	7,270
Growth					
Mean	10,125	5,179	4,413	3,399	1,077
Median	10,195	3,545	3,090	2,015	345
SD	7,738	4,806	4,274	3,501	1,533
Min	310	340	260	240	50
Max	27,700	13,780	13,780	11,430	4,760
Winter					
Mean	3,854	1,680	1,041	928	364
Median	4,290	1,085	665	550	85
SD	2,547	2,166	1,167	1,174	675
Min	130	100	20	20	20
Max	6,300	8,710	4,340	4,340	2,630



Table 4. Mean daily linear distance moved by Deep River, North Carolina, flathead catfish annually and according to functional season.

Season	<i>N</i>	Mean distance (m)	SD
Annual	21	509	698
Spawning	9	950	1,123
Growth	6	385	376
Winter	6	192	43

Table 5. Statistics and results for a comparison of hourly diel movement distances for flathead catfish in the Deep River, North Carolina. Statistical analyses were performed using the non-parametric Wilcoxon test.

Season and Statistic	Day	Night	<i>Z</i>	<i>P</i>
Annual			38.83	<0.0001
<i>N</i>	260	244		
Mean Distance (m)	5.9	46.7		
SD	41.5	179.9		
Spawning			13.65	0.0002
<i>N</i>	123	93		
Mean Distance (m)	9.4	46.8		
SD	59.1	255.4		
Growth			32.32	<0.0001
<i>N</i>	77	67		
Mean Distance (m)	4.4	70.8		
SD	14.6	124.6		
Winter			2.27	0.13
<i>N</i>	60	84		
Mean Distance (m)	0.8	27.5		
SD	4.2	96.2		

Table 6. Retained principal component loadings from analysis of flathead catfish microhabitat availability in the Deep River, North Carolina.

Variable and statistic	Principal component 1	Principal component 2
Depth	-0.37	0.47
Bottom velocity	0.62	0.34
Mean column velocity	0.63	0.29
Substrate	0.29	-0.76
Eigenvalue	1.96	0.98
Variance explained	49%	25%

Table 7. Summaries and results of statistical comparisons of flathead catfish microhabitat use and availability annually and for each functional season. Comparisons of continuous variables depth, bottom velocity, mean-column velocity, and substrate were performed using the Komogorov-Smirnov two-sample test. The categorical variable cover was compared using likelihood ratio chi-square test.

Season and Variable	<i>N</i>	Mean	SD	Statistic	<i>P</i>
Annual					
Depth (m)	907	4.06	1.24	$D = 0.634$	<0.0001
Bottom Velocity (m/s)	907	0.03	0.06	$D = 0.201$	<0.0001
Mean Column Velocity (m/s)	907	0.06	0.08	$D = 0.254$	<0.0001
Substrate	907	2.08	1.25	$D = 0.307$	<0.0001
Cover	907			$\chi^2 = 280.48$	<0.0001
Winter Season					
Depth (m)	303	4.91	0.98	$D = 0.728$	<0.0001
Bottom Velocity (m/s)	303	0.02	0.05	$D = 0.269$	<0.0001
Mean Column Velocity (m/s)	303	0.06	0.05	$D = 0.248$	<0.0001
Substrate	303	2.05	1.32	$D = 0.275$	<0.0001
Cover	303			$\chi^2 = 102.56$	<0.0001
Spawning Season					
Depth (m)	270	3.64	1.16	$D = 0.603$	<0.0001
Bottom Velocity (m/s)	270	0.03	0.06	$D = 0.126$	0.005
Mean Column Velocity (m/s)	270	0.07	0.09	$D = 0.185$	<0.0001
Substrate	270	2.04	1.22	$D = 0.293$	<0.0001
Cover	270			$\chi^2 = 166.63$	<0.0001
Growth Season					
Depth (m)	334	3.62	1.09	$D = 0.630$	<0.0001
Bottom Velocity (m/s)	334	0.03	0.07	$D = 0.233$	<0.0001
Mean Column Velocity (m/s)	334	0.06	0.10	$D = 0.359$	<0.0001
Substrate	334	2.13	1.21	$D = 0.348$	<0.0001
Cover	334			$\chi^2 = 236.95$	<0.0001
Microhabitat Availability					
Depth (m)	625	1.69	1.55		
Bottom Velocity (m/s)	625	0.06	0.10		
Mean Column Velocity (m/s)	625	0.12	0.14		
Substrate	625	2.71	1.53		
Cover	625				

Table 8. Comparisons of between-season microhabitat use by flathead catfish in the Deep River, North Carolina. Comparisons of continuous variables depth, bottom velocity, mean column velocity, and substrate were performed using the Komogorov-Smirnov two-sample test. The categorical variable cover was compared using likelihood ratio chi-square test. For summary statistics see Table 2.

Variable	Statistic	<i>P</i>
<b>Winter Microhabitat Use vs. Spawning Microhabitat Use</b>		
Depth (m)	$D = 0.459$	<0.0001
Bottom Velocity (m/s)	$D = 0.199$	<0.0001
Mean Column Velocity (m/s)	$D = 0.091$	0.184
Substrate	$D = 0.065$	0.576
Cover	$\chi^2 = 32.247$	<0.0001
<b>Spawning Microhabitat Use vs. Growth Microhabitat Use</b>		
Depth (m)	$D = 0.090$	0.179
Bottom Velocity (m/s)	$D = 0.158$	0.007
Mean Column Velocity (m/s)	$D = 0.228$	<0.0001
Substrate	$D = 0.116$	0.037
Cover	$\chi^2 = 6.216$	0.184
<b>Growth Microhabitat Use vs. Winter Microhabitat Use</b>		
Depth (m)	$D = 0.490$	<0.001
Bottom Velocity (m/s)	$D = 0.094$	0.122
Mean Column Velocity (m/s)	$D = 0.200$	<0.0001
Substrate	$D = 0.181$	<0.0001
Cover	$\chi^2 = 52.743$	<0.0001

Table 9. Depth microhabitat use comparisons between day and night for flathead catfish of the Deep River, North Carolina. Comparisons were performed using the Kolmogorov-Smirnov two-sample test.

Season and Statistic	Day	Night	<i>D</i>	<i>P</i>
Annual			0.250	<0.0001
<i>N</i>	260	244		
Mean	3.82	4.29		
SD	1.13	1.21		
Spawning			0.292	0.0003
<i>N</i>	123	93		
Mean	3.95	4.21		
SD	0.95	1.15		
Growth			0.377	<0.0001
<i>N</i>	77	67		
Mean	2.74	3.46		
SD	0.60	1.20		
Winter			0.200	0.121
<i>N</i>	60	84		
Mean	4.93	5.04		
SD	0.71	0.74		

Table 10. Bottom velocity microhabitat use comparisons between day and night for flathead catfish of the Deep River, North Carolina. Comparisons were performed using the Kolmogorov-Smirnov two-sample test.

Season and Statistic	Day	Night	<i>D</i>	<i>P</i>
Annual				
<i>N</i>	260	244	0.126	0.038
Mean	0.02	0.01		
SD	0.04	0.04		
Spawning				
<i>N</i>	123	93	0.214	0.016
Mean	0.03	0.02		
SD	0.04	0.01		
Growth				
<i>N</i>	77	67	0.047	1
Mean	0.01	0.01		
SD	0.05	0.07		
Winter				
<i>N</i>	60	84	0.133	0.563
Mean	0.01	0.00		
SD	0.02	0.01		

Table 11. Mean column velocity microhabitat use comparisons between day and night for flathead catfish on the Deep River, North Carolina. Comparisons were made using Kolmogorov-Smirnov two-sample test.

Season and Statistic	Day	Night	<i>D</i>	<i>P</i>
Annual			0.185	0.0004
<i>N</i>	260	244		
Mean	0.06	0.04		
SD	0.07	0.04		
Spawning			0.190	0.045
<i>N</i>	123	93		
Mean	0.09	0.06		
SD	0.09	0.04		
Growth			0.503	<.0001
<i>N</i>	77	67		
Mean	0.03	0.01		
SD	0.04	0.01		
Winter			0.288	0.006
<i>N</i>	60	84		
Mean	0.03	0.03		
SD	0.02	0.02		

Table 12. Substrate microhabitat use comparisons between day and night for flathead catfish of the Deep River, North Carolina. Comparisons were performed using the Kolmogorov-Smirnov two-sample test.

Season and Statistic	Day	Night	<i>D</i>	<i>P</i>
Annual			0.089	0.269
<i>N</i>	260	244		
Mean	1.81	2.01		
SD	1.11	1.36		
Spawning			0.081	0.881
<i>N</i>	123	93		
Mean	2.02	2.08		
SD	1.43	1.77		
Growth			0.136	0.519
<i>N</i>	77	67		
Mean	1.87	1.99		
SD	0.52	0.79		
Winter			0.233	0.044
<i>N</i>	60	84		
Mean	1.30	1.96		
SD	0.70	1.29		

Table 13. Cover microhabitat use comparisons between day and night for flathead catfish of the Deep River, North Carolina. Comparisons were performed using likelihood ratio chi-square test.

Season	<i>N</i>		$\chi^2$	<i>P</i>
	Day	Night		
Annual	260	244	13.950	0.003
Spawning	123	93	11.300	0.021
Growth	77	67	23.010	<0.0001
Winter	60	84	35.160	<0.0001



Table 14. Literature summary of linear home ranges of native and introduced populations of flathead catfish.

River and State	Mean Linear Range (km)	Source	Method	Time frame
Missouri River, MO	12.5	Coon and Dames (1989)	Telemetry	Annual
Big Black River, MS	0.8	Skains and Jackson (1993)	Telemetry	Jun-Jan
Tallahatchie River, MS	1.0	Skains and Jackson (1993)	Telemetry	Jun-Jan
Apalachicola River, FL	minimal	Dobbins et al. (1999)	Anchor tags	May-Jul
Mississippi River, MS	1.0	Pugh and Schramm (1999)	Anchor tags	Annual
Grand River, MO	63.0	Vokoun and Rabeni (2005)	Telemetry	Annual
Cuivre River, MO	23.0	Vokoun and Rabeni (2005)	Telemetry	Annual
Northeast Cape Fear River, NC	13.4	Kwak et al. (2004)	Telemetry	Annual
Contentnea Creek, NC	25.0	Kwak et al. (2004)	Telemetry	Annual
Missouri River, MO	6.5	Travnicheck (2004)	Anchor tags	Annual
Deep River, NC	16.2	present study	Telemetry	Annual

Table 15. Literature summary of seasonal linear home ranges in kilometers of native and introduced populations of flathead catfish.

River and State	Spring (spawning)	Summer (growth)	Fall	Winter	Source
Grand River, MO	52.8 (mid-Apr to mid-Jul)	12.7 (late Jul to mid-Oct)		4.1 (mid-Nov to mid Mar)	Vokoun and Rabeni (2005)
Cuivre River, MO	19.6 (mid-Apr to mid-Jul)	6.3 (late Jul to mid-Oct)		3.0 (mid-Nov to mid Mar)	Vokoun and Rabeni (2005)
St. Joseph River, MI	1.5 (mid-Mar to mid-Jun)	0.6 (mid-Jun to mid-Sep)	1.3 (mid-Sep to mid-Dec)	0.0 (mid-Dec to mid-Mar)	Daugherty and Sutton (2005)
Deep River, NC	13.1 (mid-Mar to Jun)	10.1 (Jul to mid-Nov)		3.9 (mid-Nov to mid-Mar)	present study

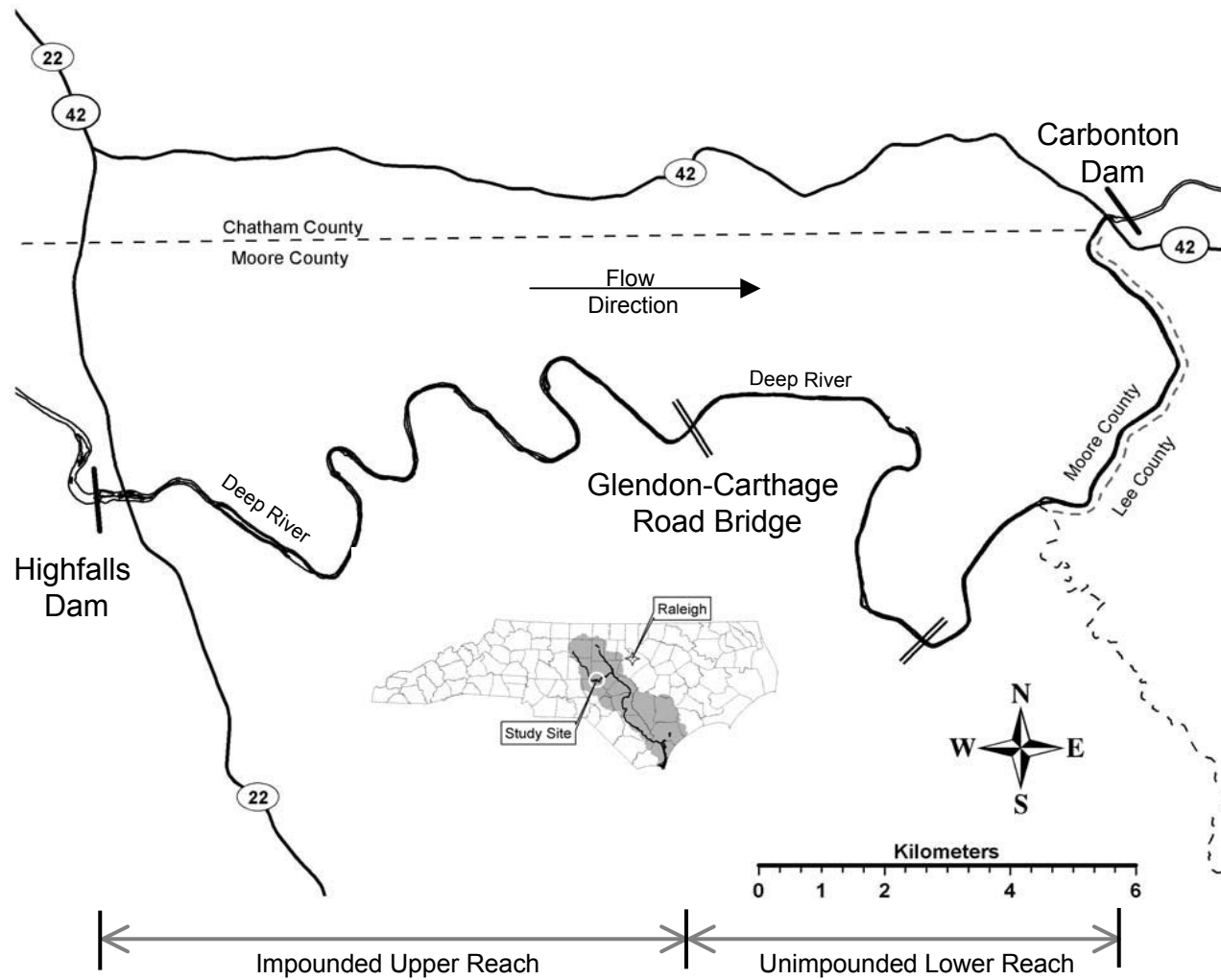


Figure 1. Map of study site on the Deep River, North Carolina.

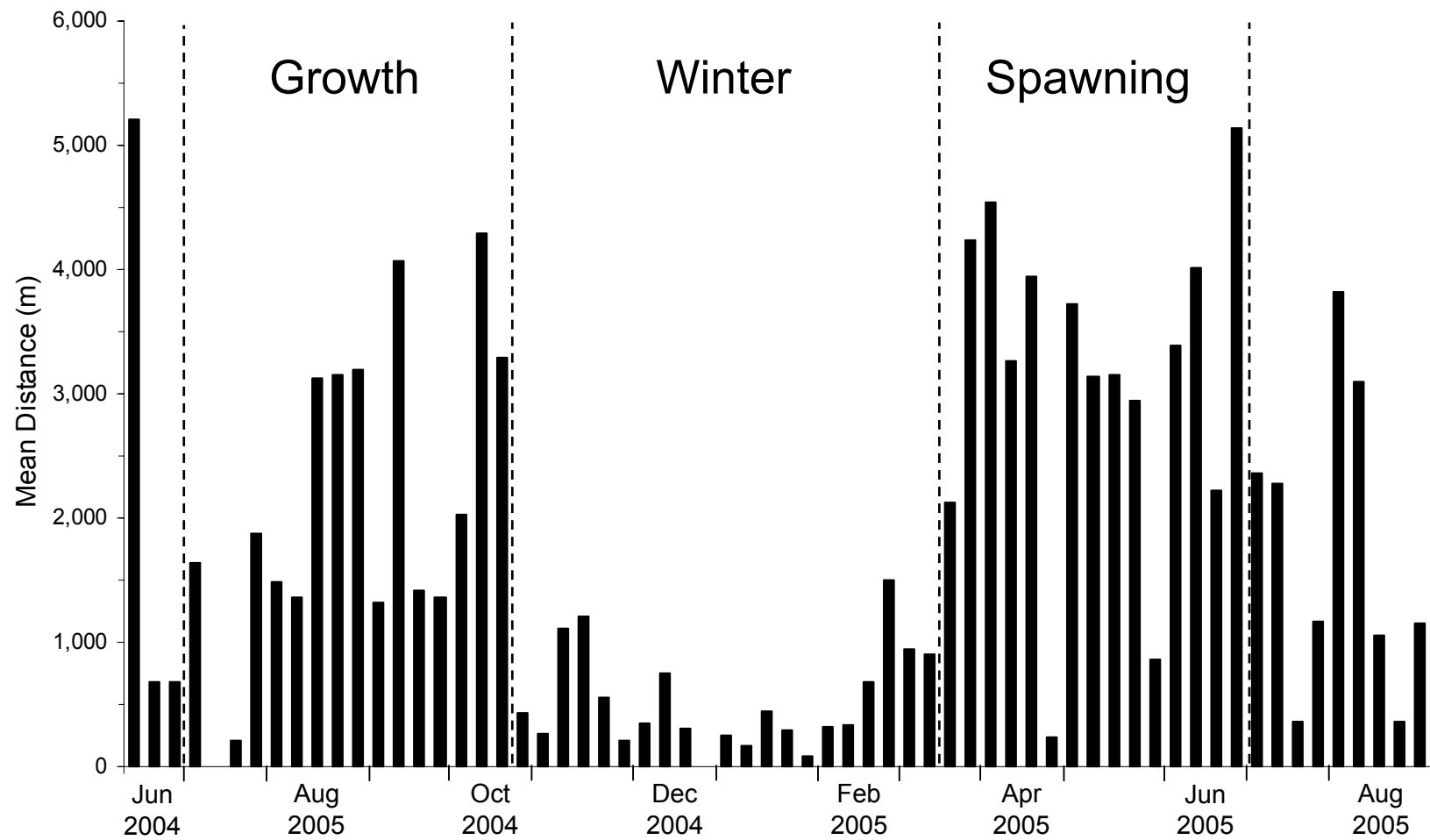


Figure 2. Mean weekly movement (linear range) of flathead catfish in the Deep River, North Carolina.

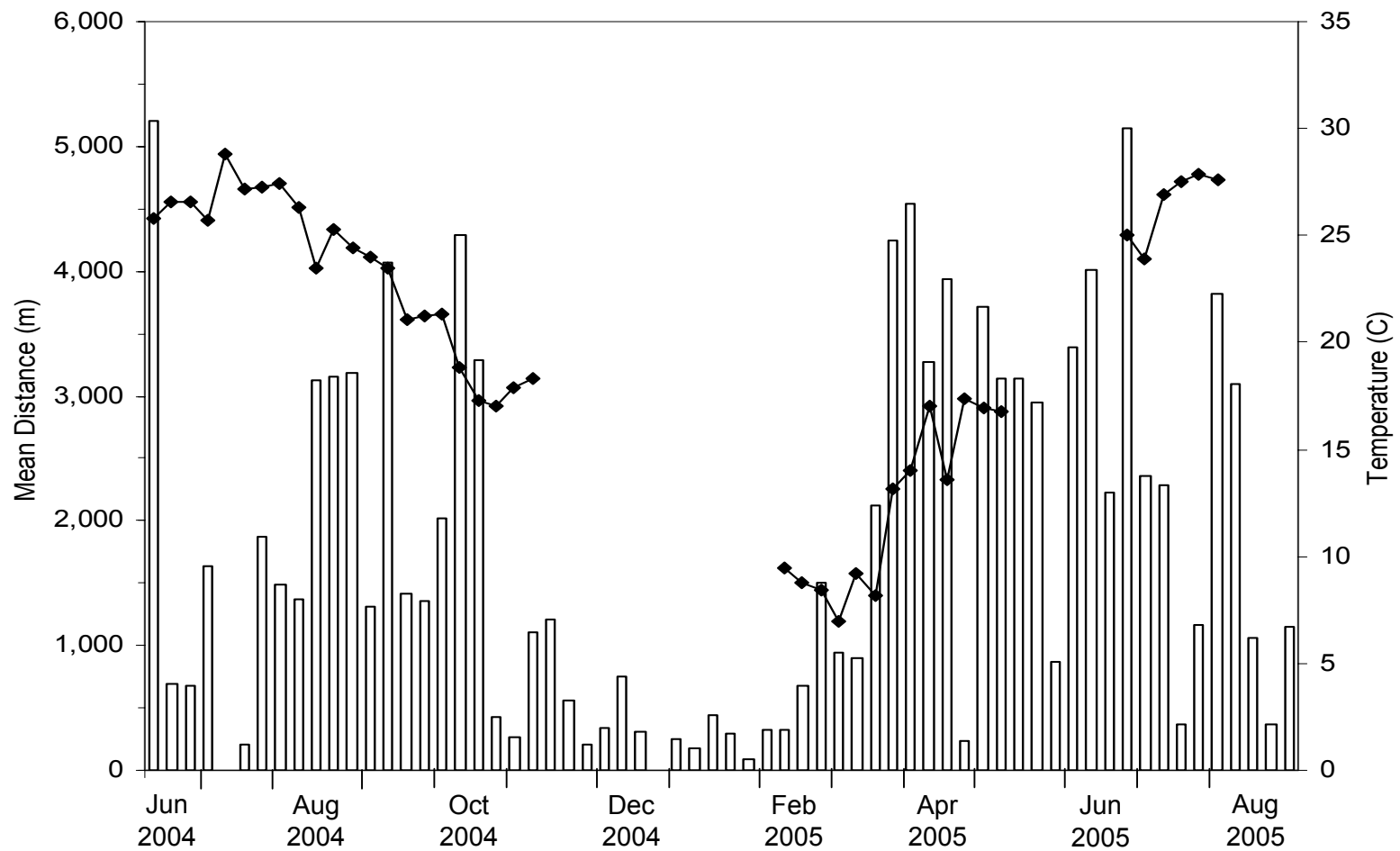


Figure 3. Mean weekly movements (bars) and water temperature (lines) over time in the Deep River, North Carolina.

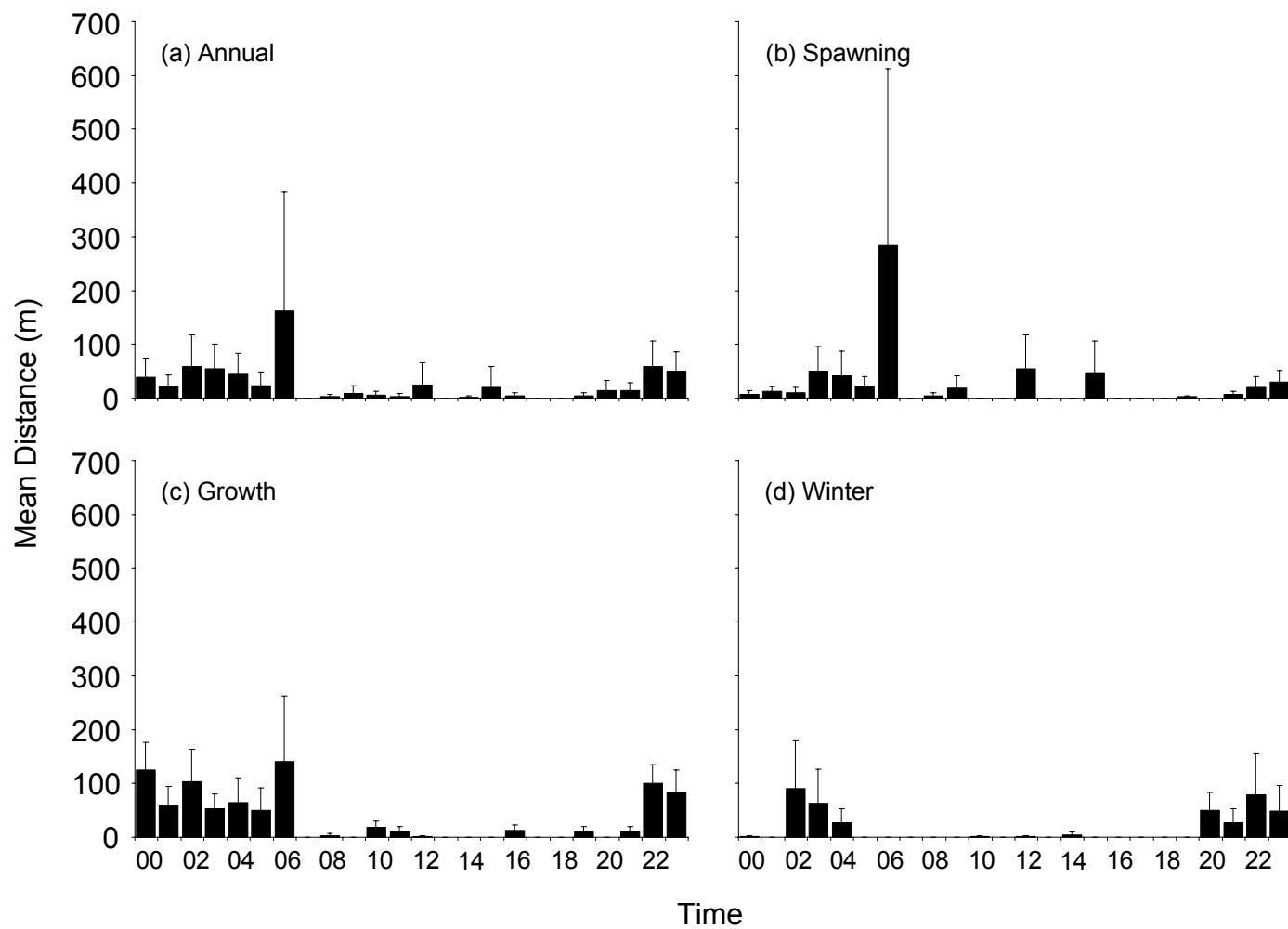


Figure 4. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter mean distances moved and associated standard errors by flathead catfish in the Deep River, North Carolina. Sample sizes and statistical analysis appear in Tables 4 and 5.

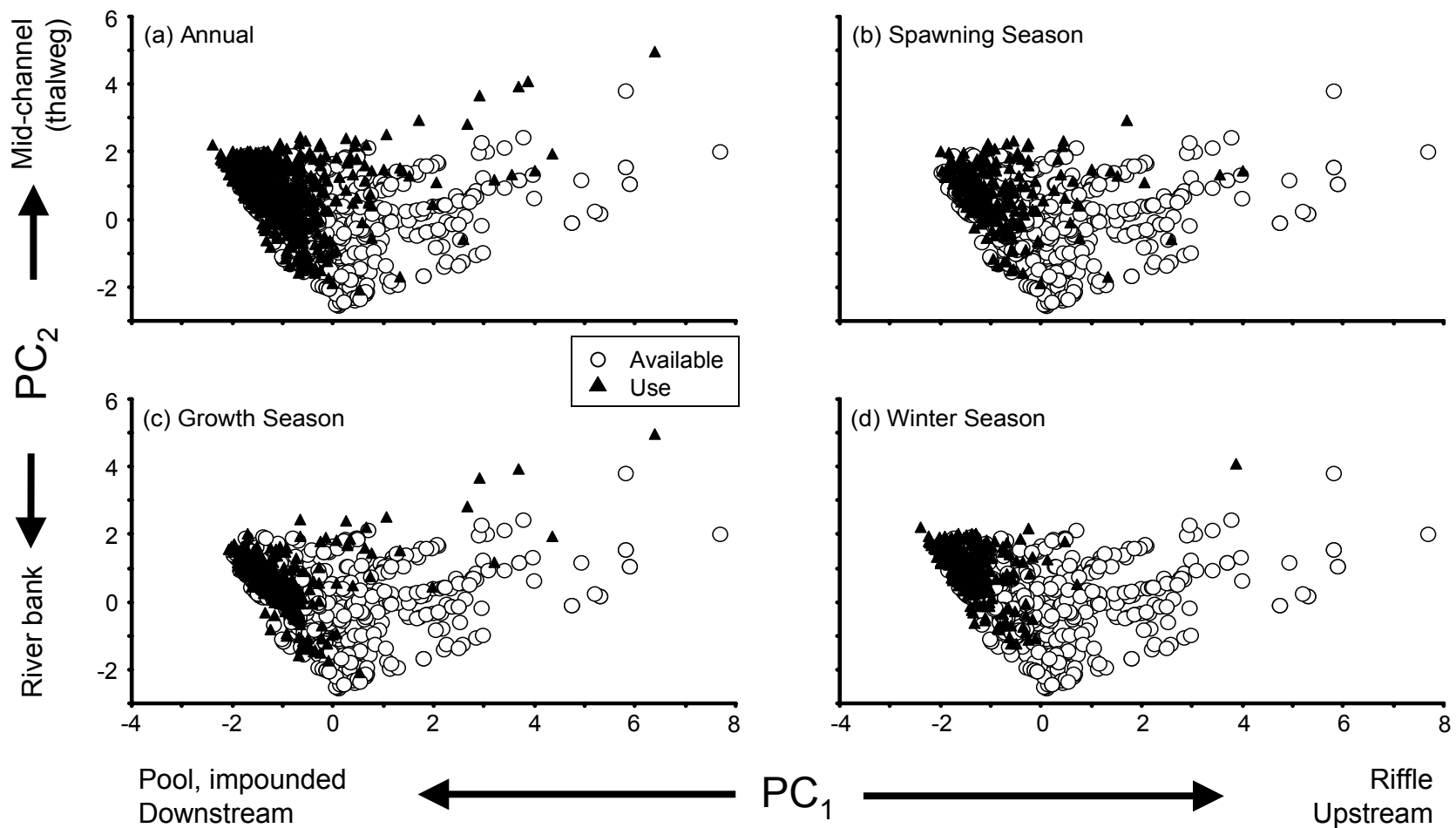


Figure 5. Plots of (a) Annual, (b) Spawning, (c) Growth, and (d) Winter flathead catfish microhabitat use and available principal component scores in the Deep River, North Carolina. Principal component loadings appear in Table 6.

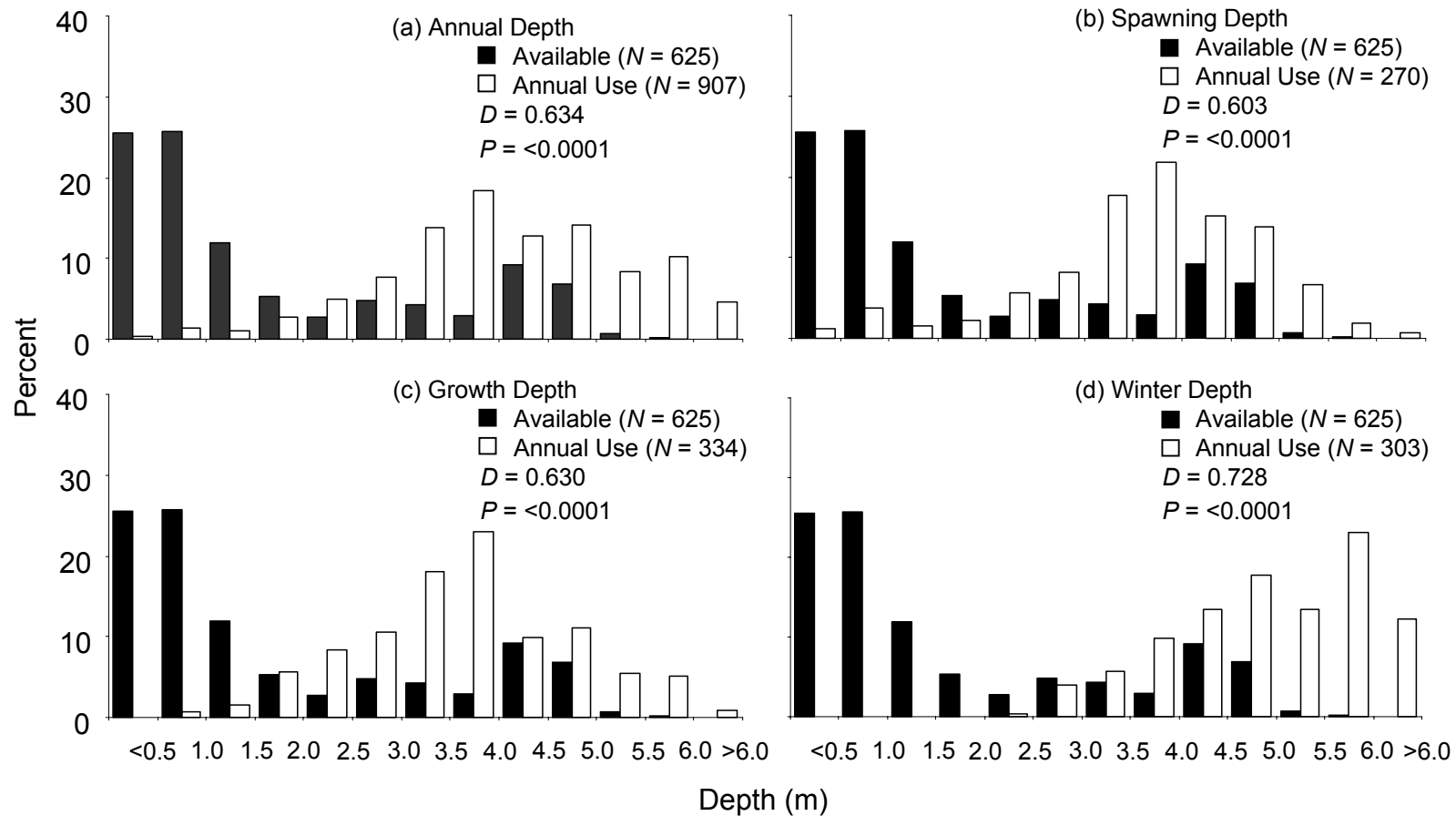


Figure 6. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter frequency distributions and associated statistics for depth of flathead catfish microhabitats in the Deep River, North Carolina. Depth microhabitat availability and use data were compared using a Kolmogorov-Smirnov two sample test.

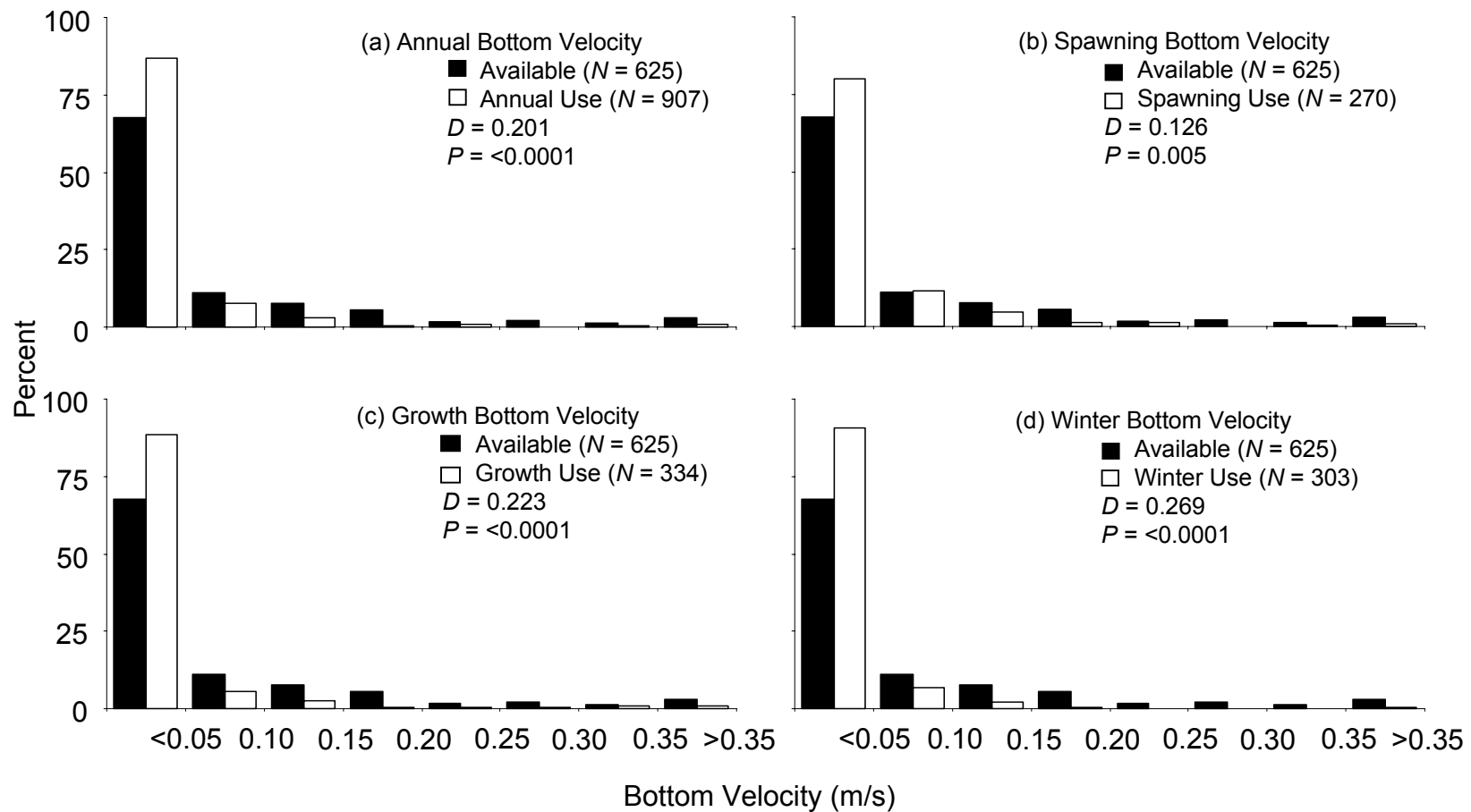


Figure 7. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter frequency distributions and associated statistics for bottom velocity of flathead catfish microhabitat in the Deep River, North Carolina. Bottom velocity microhabitat availability and microhabitat use data were compared using a Kolmogorov-Smirnov two sample test.



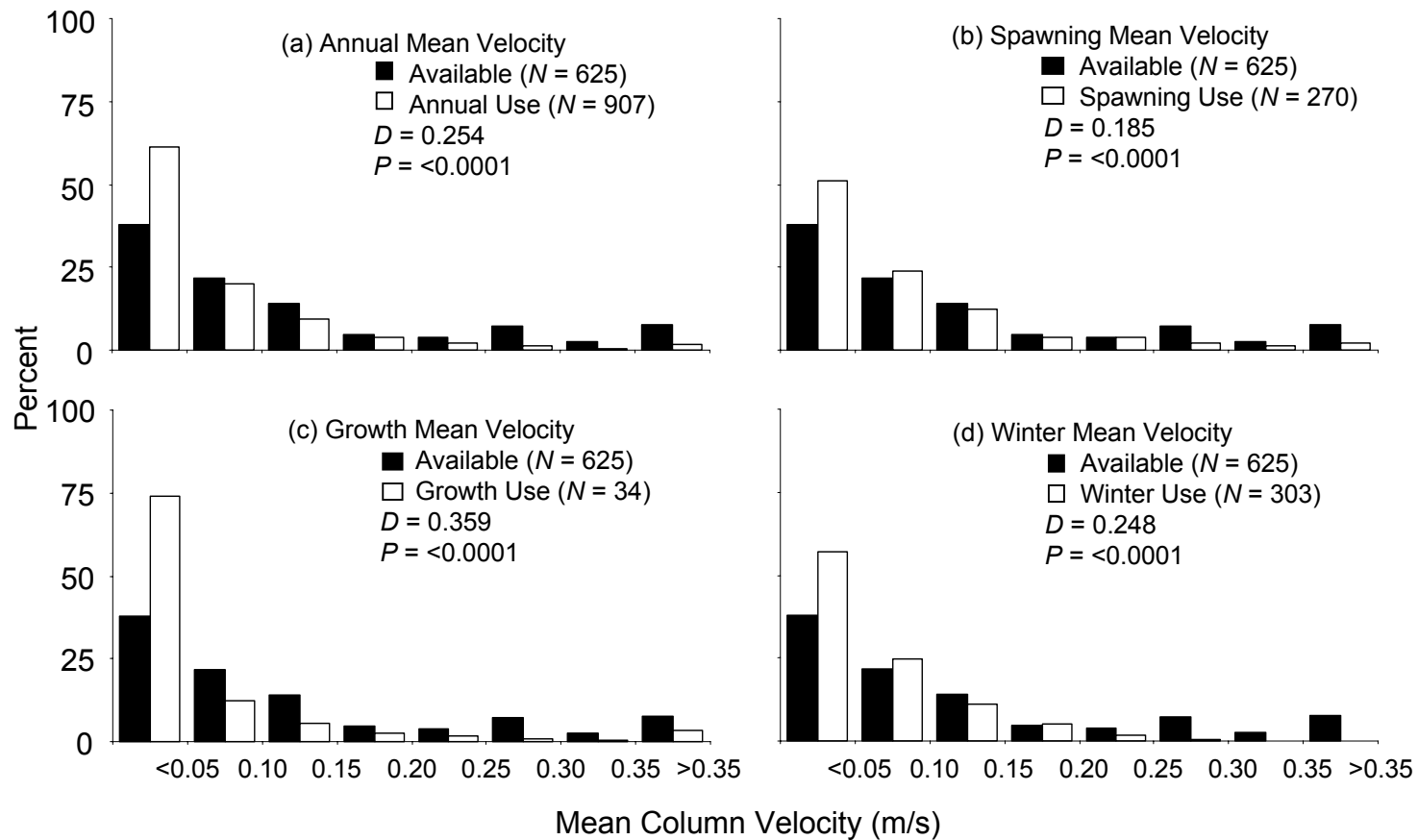


Figure 8. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter frequency distributions and associated statistics for mean column velocity of flathead catfish microhabitat in the Deep River, North Carolina. Mean column velocity microhabitat availability and microhabitat use data were compared using a Kolmogorov-Smirnov two sample test.

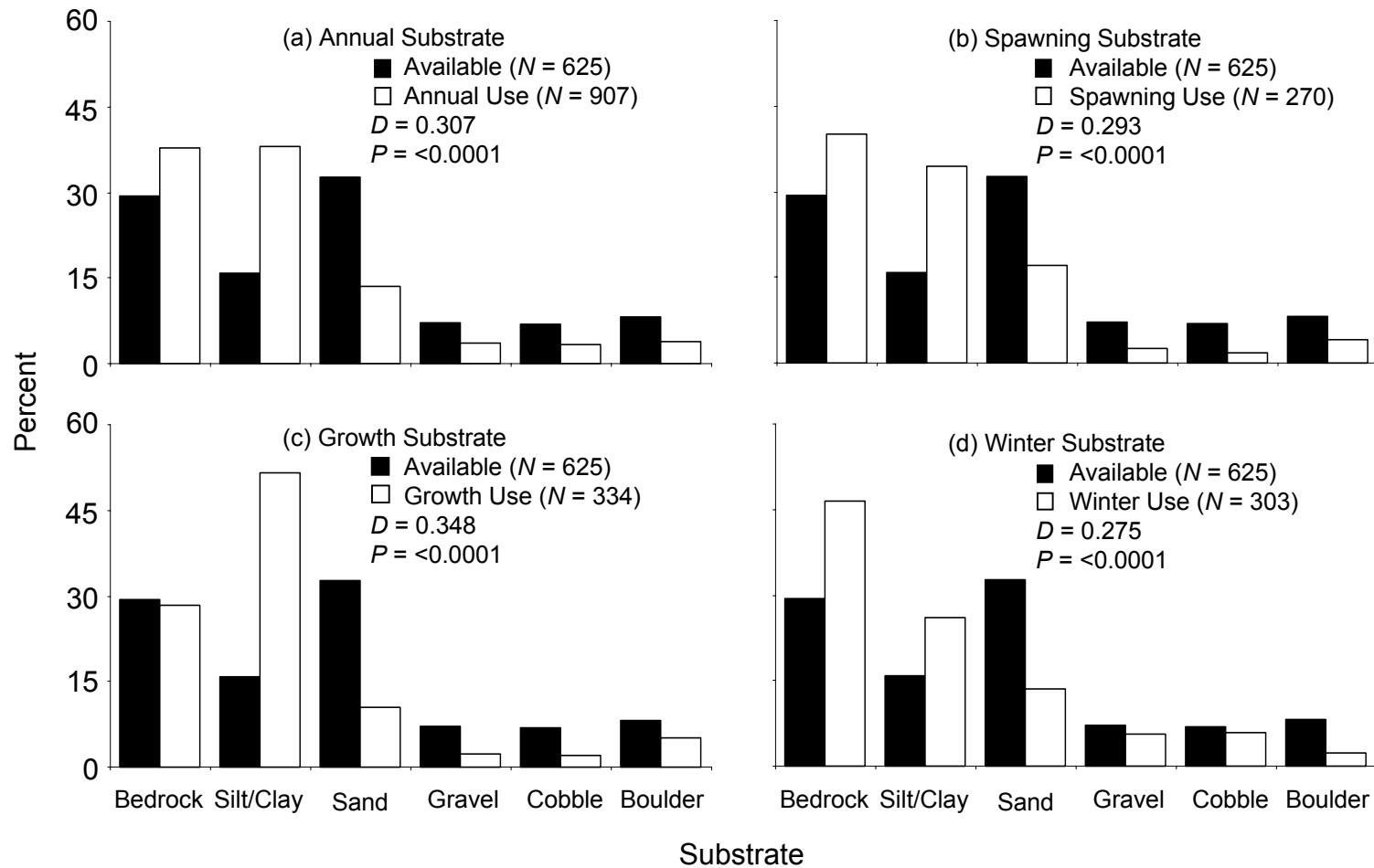


Figure 9. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter frequency distributions and associated statistics for substrate of flathead catfish microhabitats in the Deep River, North Carolina. Substrate microhabitat availability and microhabitat use data were compared using a Kolmogorov-Smirnov two sample test.

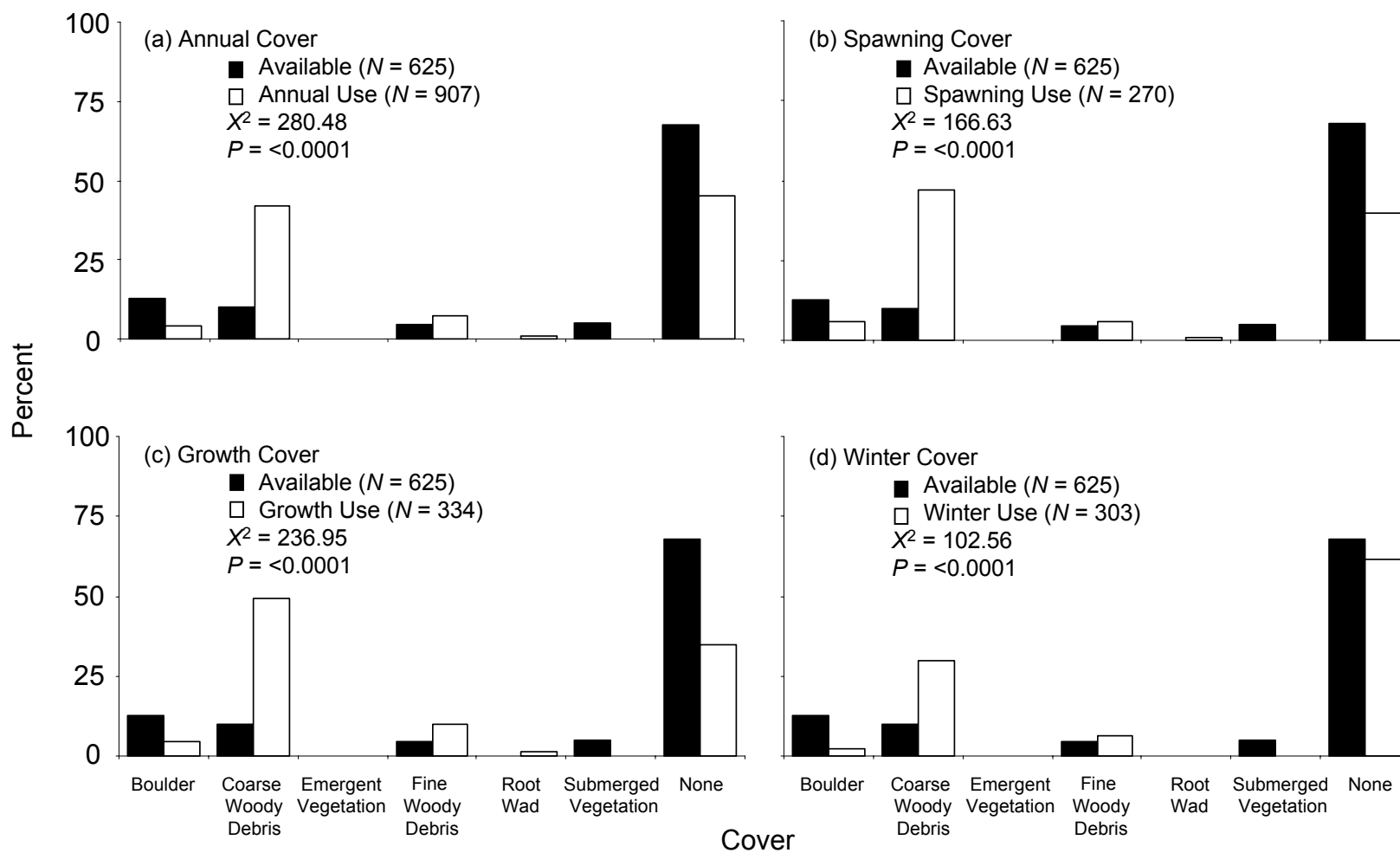


Figure 10. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter frequency distributions and associated statistics for cover of flathead catfish microhabitat in the Deep River, North Carolina. Cover type microhabitat availability and microhabitat use data were compared using a Likelihood Ratio Chi-square test.

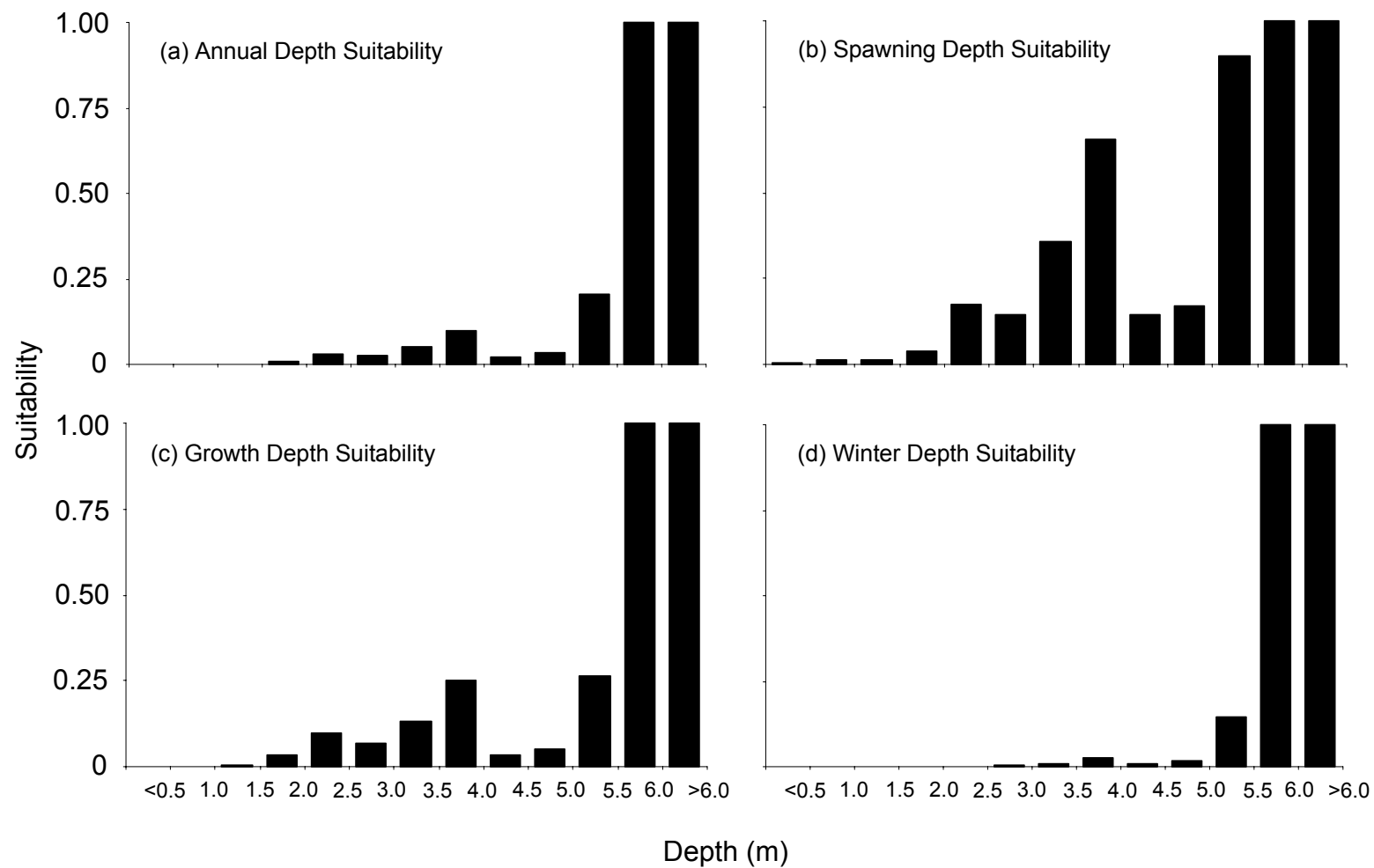


Figure 11. Annual and seasonal microhabitat suitabilities for depth of flathead catfish in the Deep River, North Carolina.

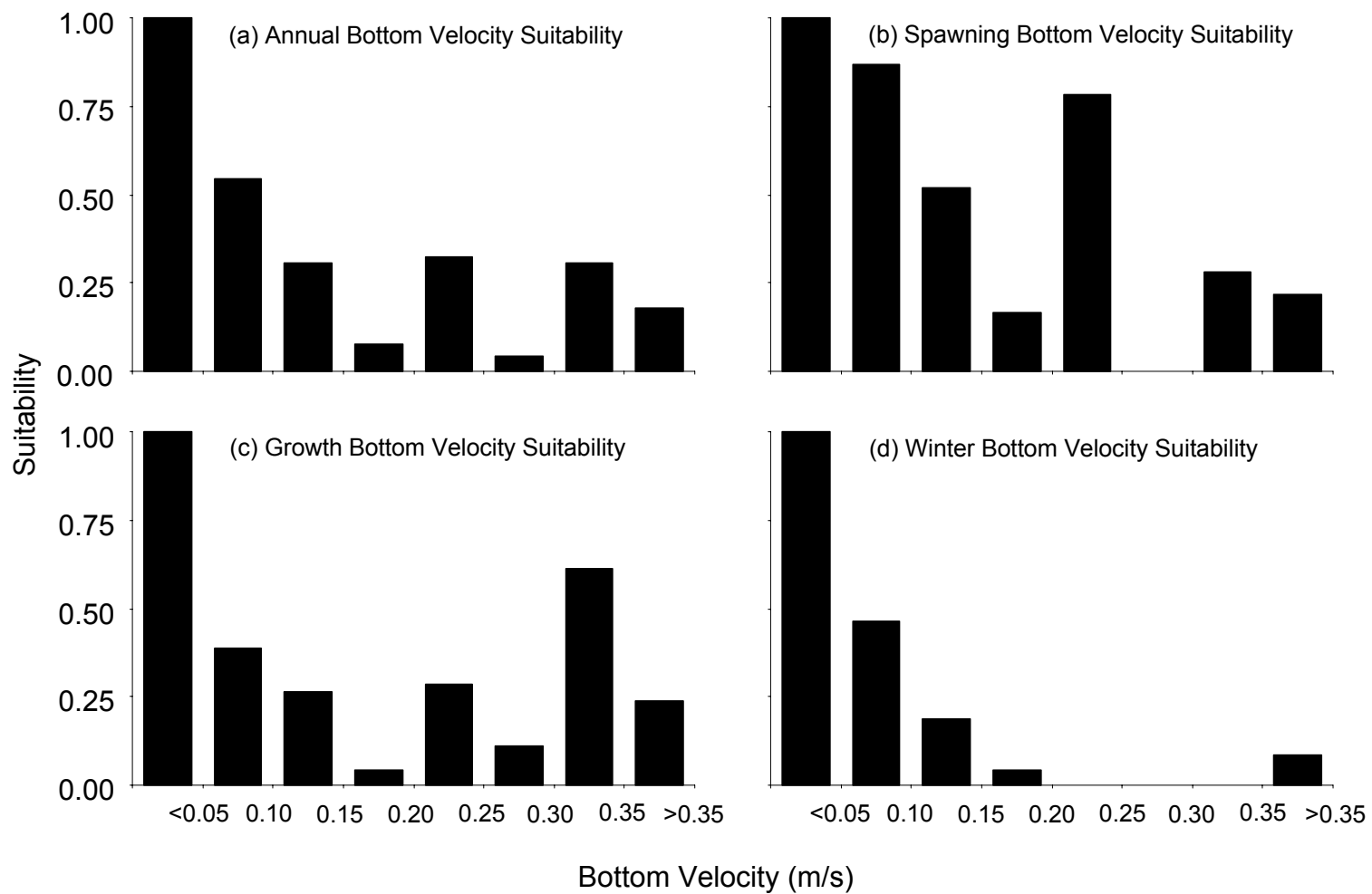


Figure 12. Annual and seasonal microhabitat suitabilities for bottom velocity of flathead catfish in the Deep River, North Carolina.

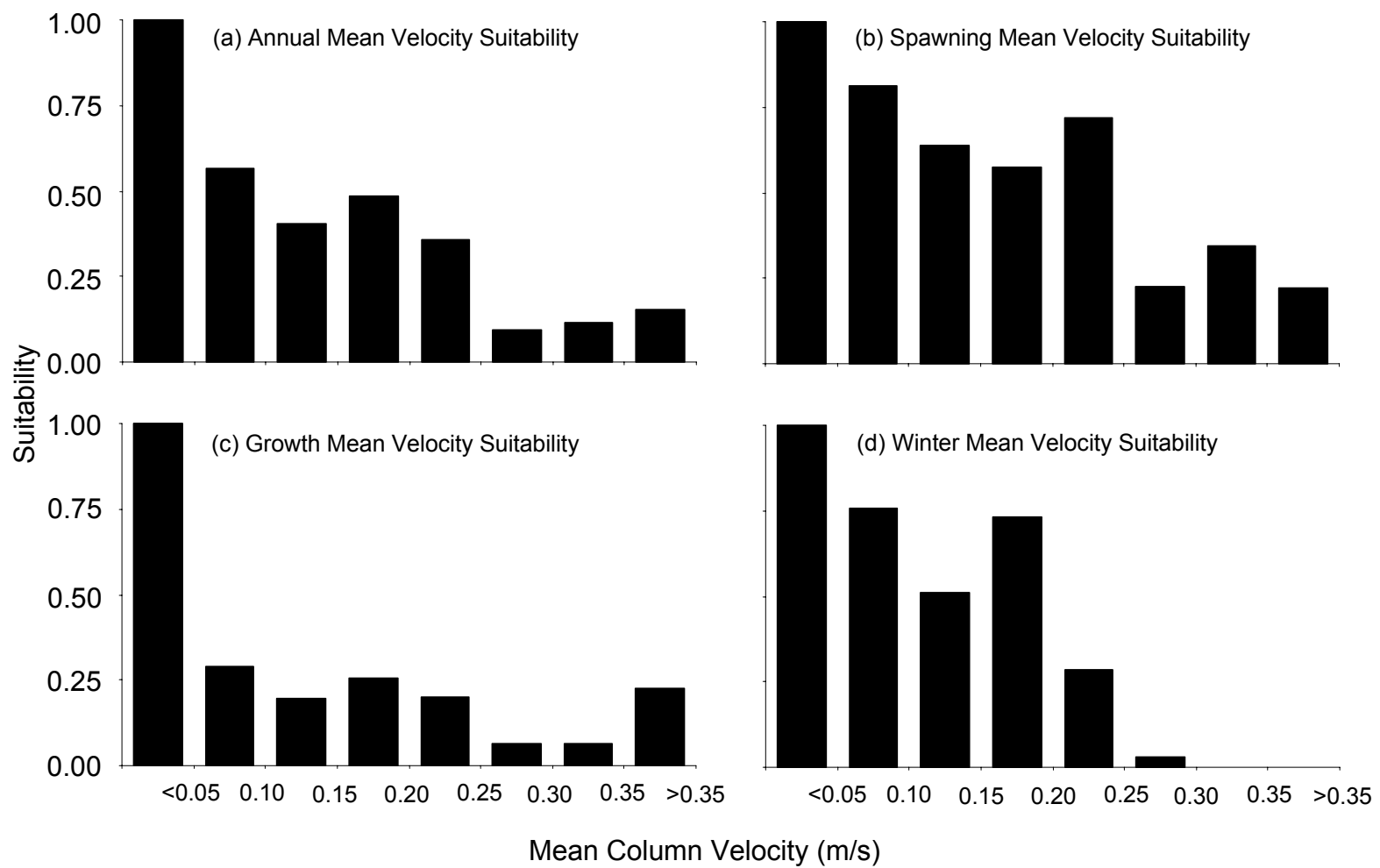


Figure 13. Annual and seasonal microhabitat suitabilities for mean column velocity of flathead catfish in the Deep River, North Carolina.

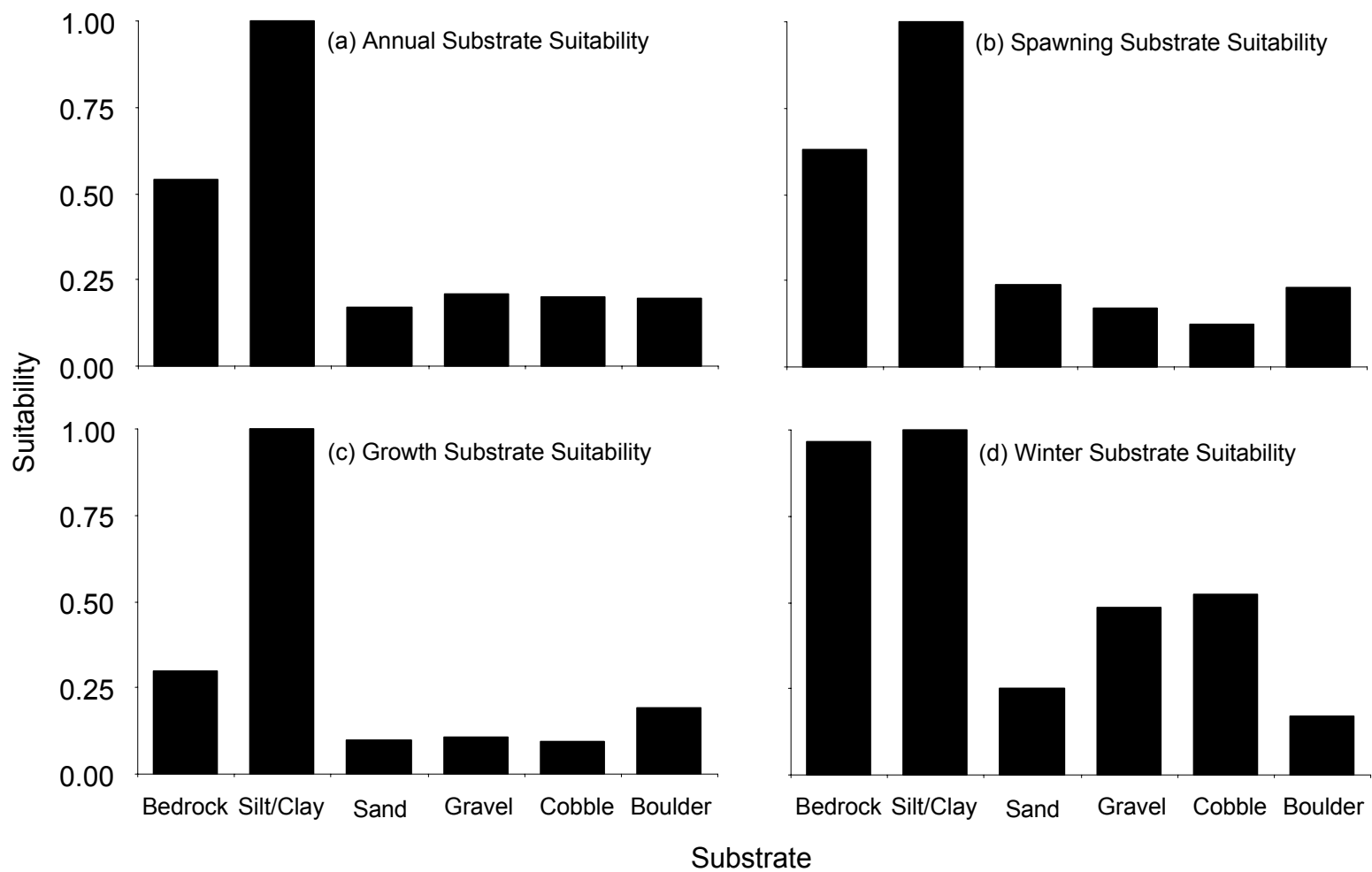


Figure 14. Annual and seasonal microhabitat suitabilities for substrate of flathead catfish in the Deep River, North Carolina.

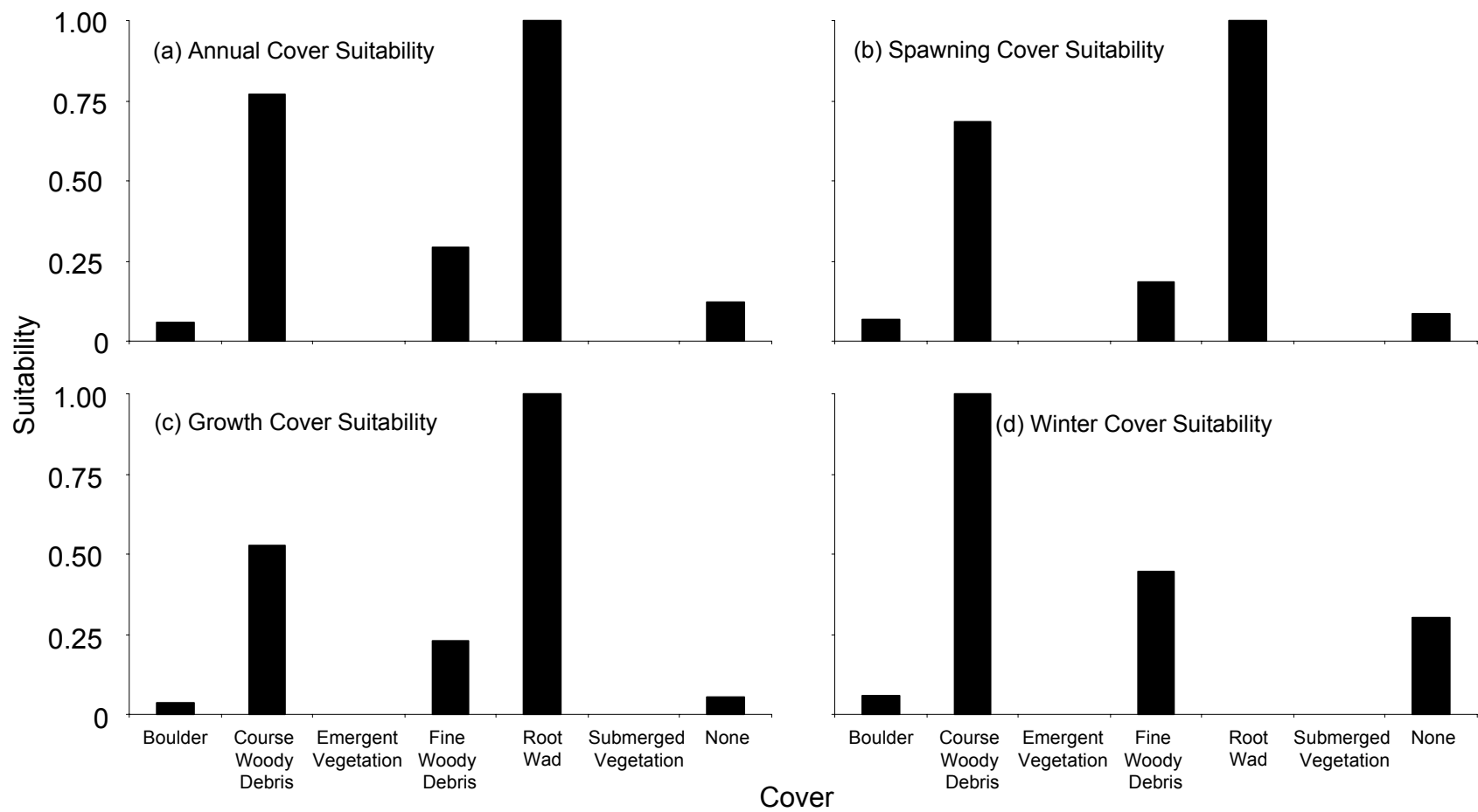


Figure 15. Annual and seasonal microhabitat suitabilities for Cover of flathead catfish in the Deep River, North Carolina.



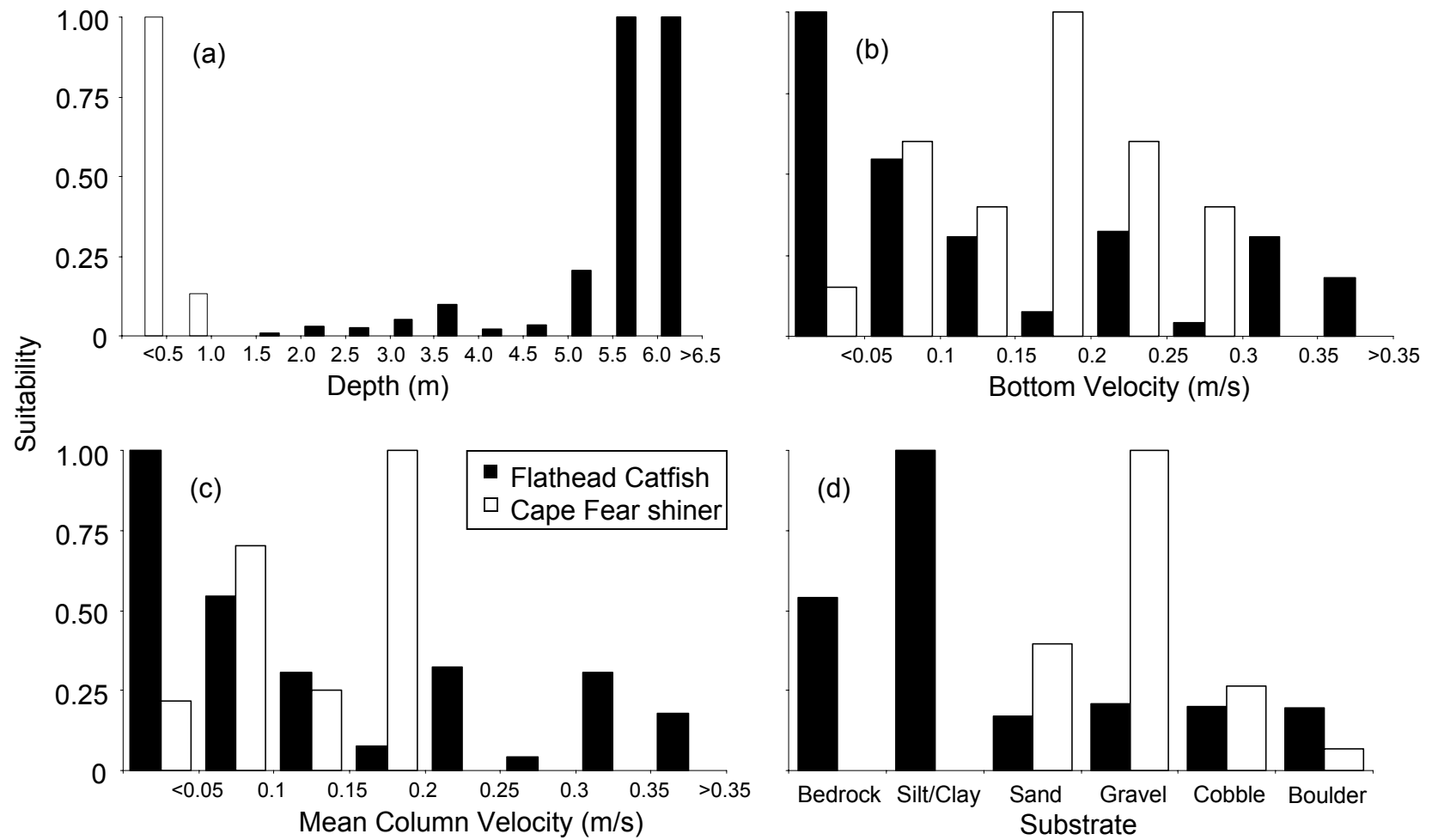


Figure 16. Comparison of flathead catfish and Cape Fear shiner microhabitat suitabilities for (a) depth, (b) bottom velocity, (c) mean column velocity, and (d) substrate in the Deep River, North Carolina.

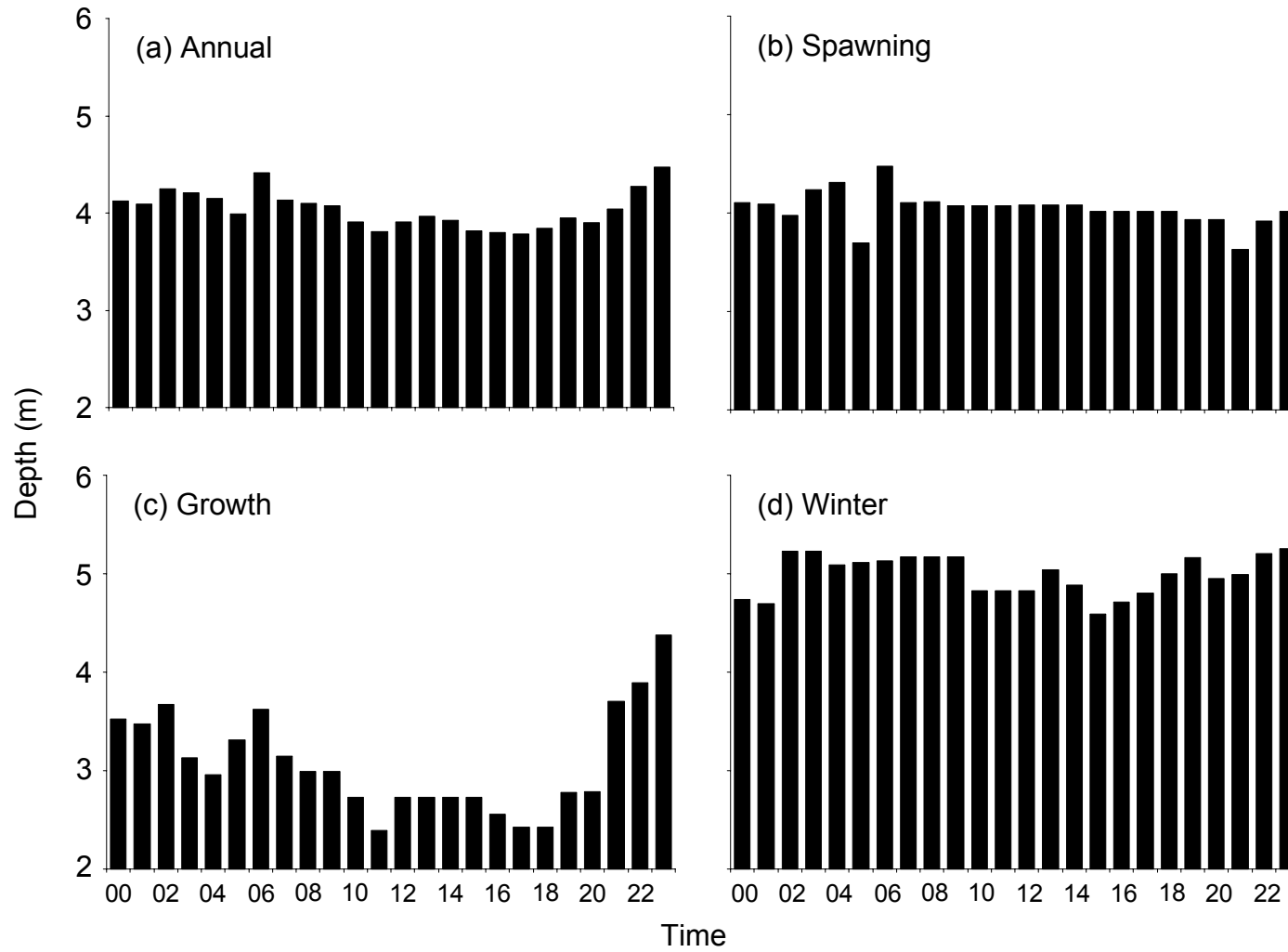


Figure 17. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter mean depths according to hour of day for flathead catfish in the Deep River, North Carolina. Statistical analysis and sample sizes appear in Table 9.

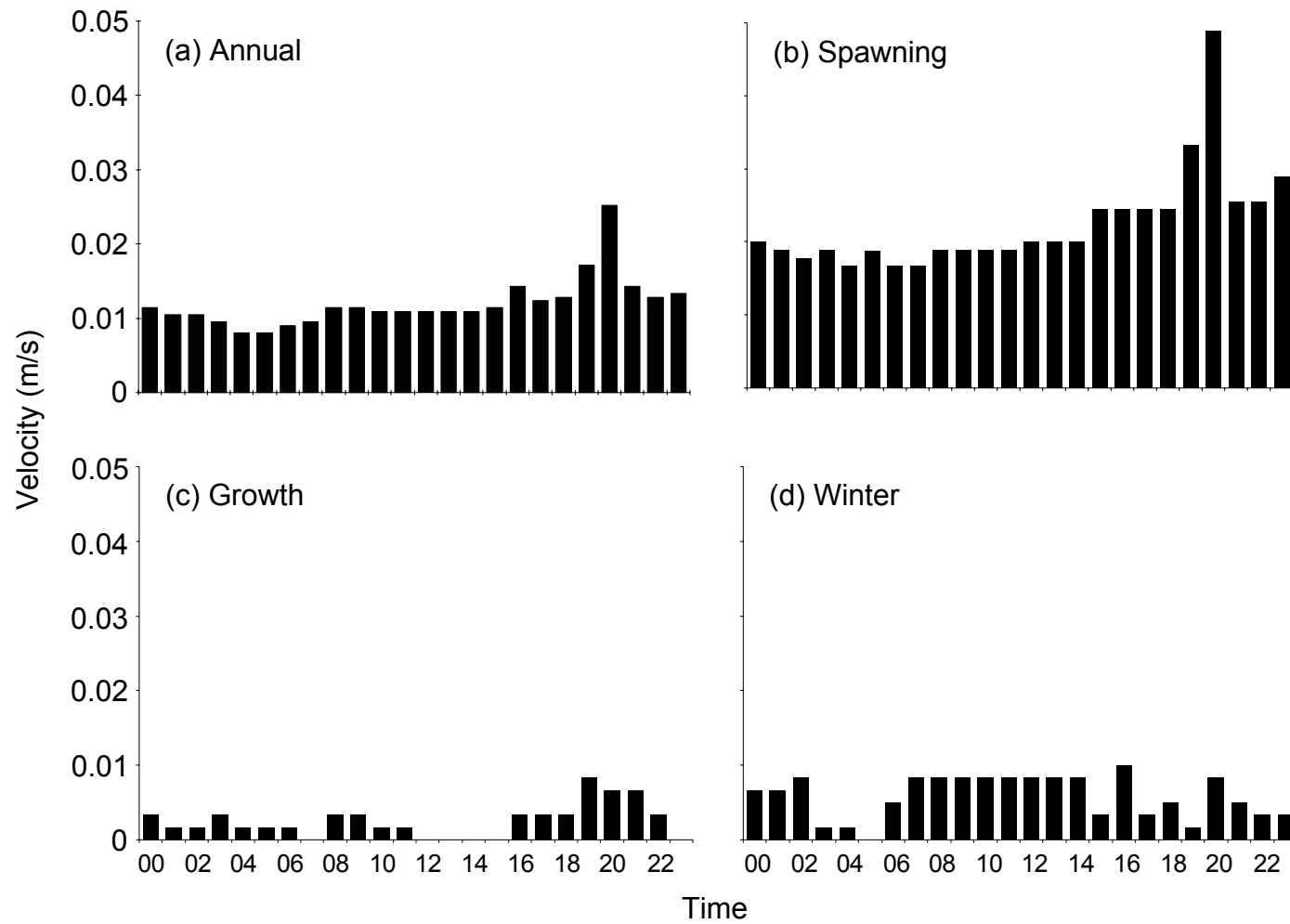


Figure 18. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter mean bottom velocity according to hour of day for flathead catfish in the Deep River, North Carolina. Statistical analysis and sample sizes appear in Table 10.

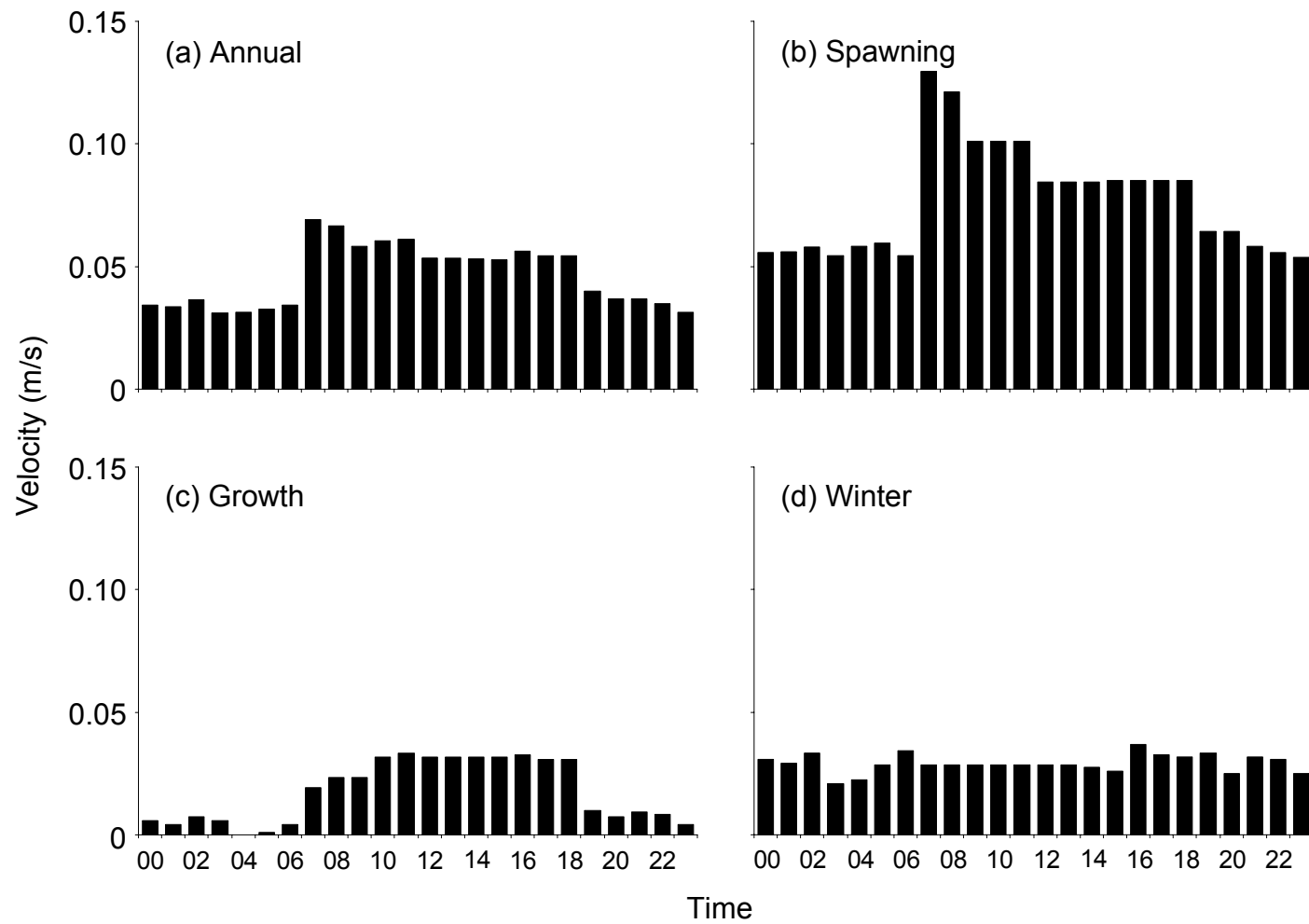


Figure 19. (a) Annual, (b) Spawning, (c) Growth, and (d) Winter mean column velocity according to hour of day for flathead catfish in the Deep River, North Carolina. Statistical analysis and sample sizes appear in Table 11.

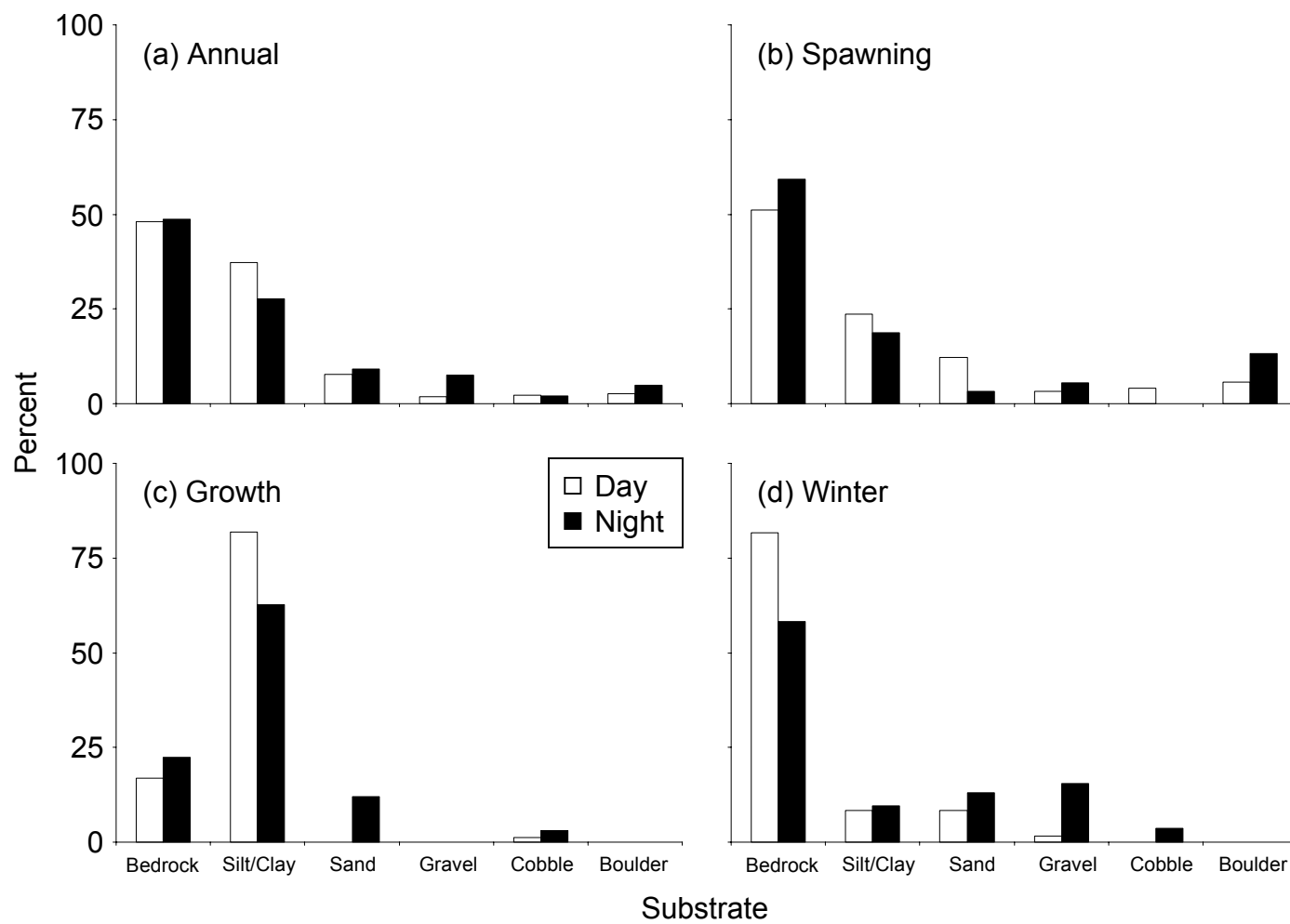


Figure 20. Frequency distributions of (a) Annual, (b) Spawning, (c) Growth, and (d) Winter diel substrate for flathead catfish in the Deep River, North Carolina. Statistical analysis and sample sizes appear in Table 12.

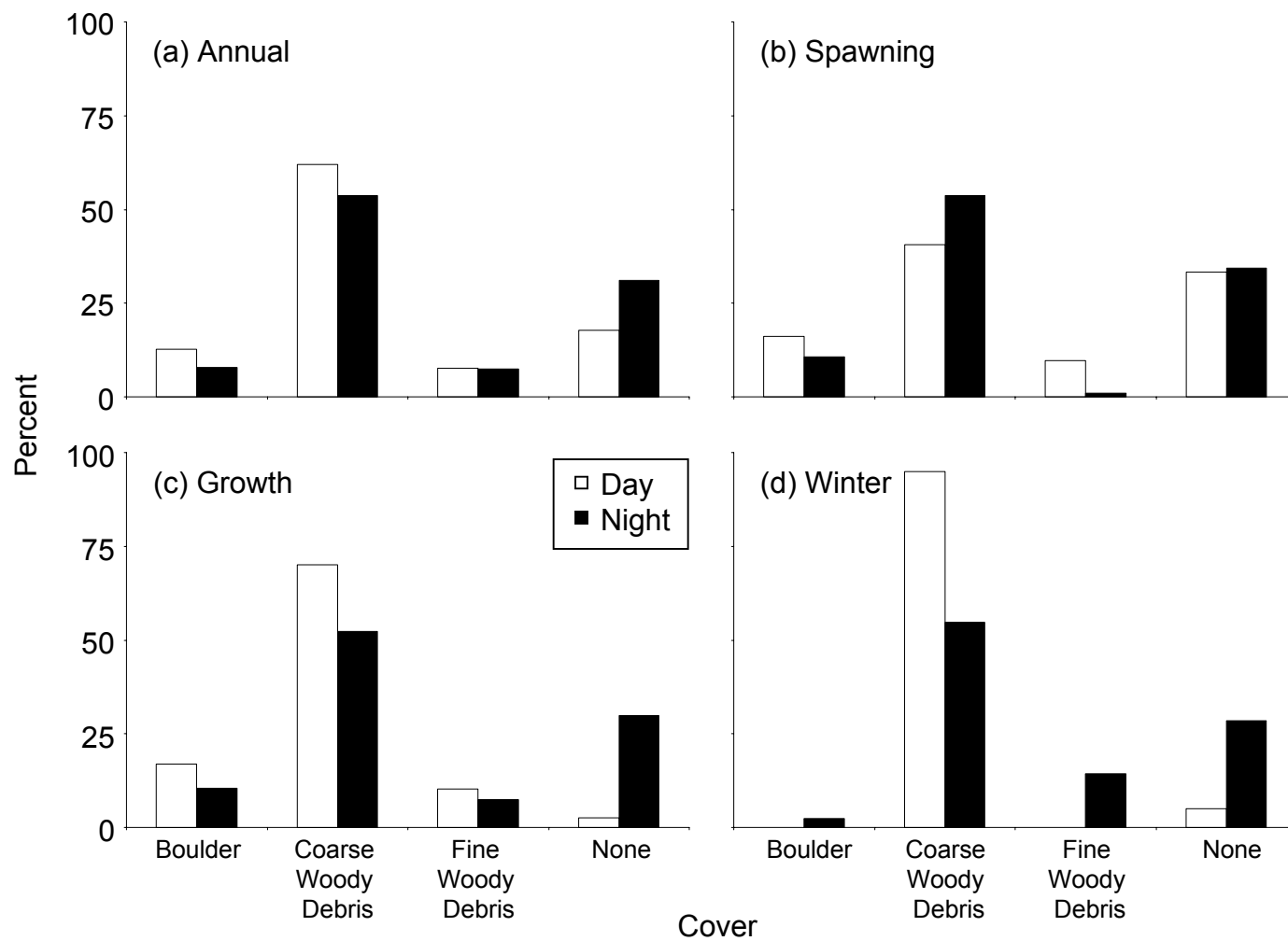
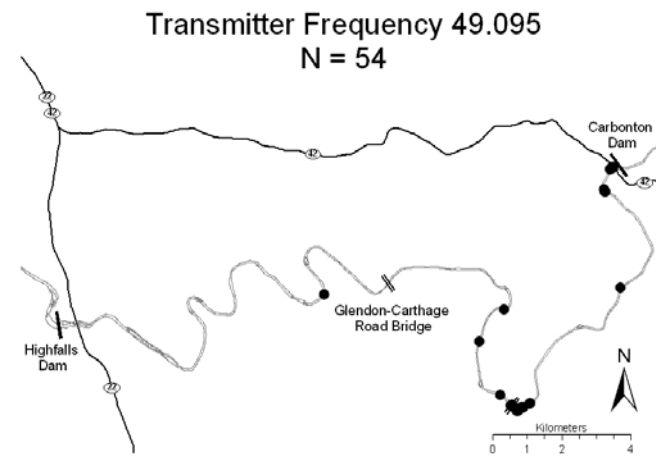
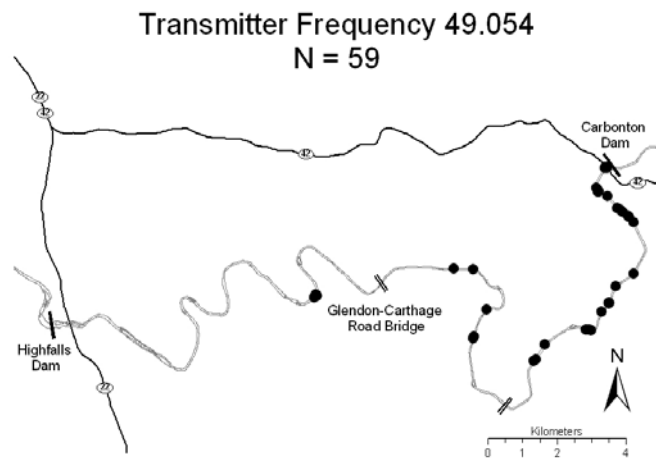
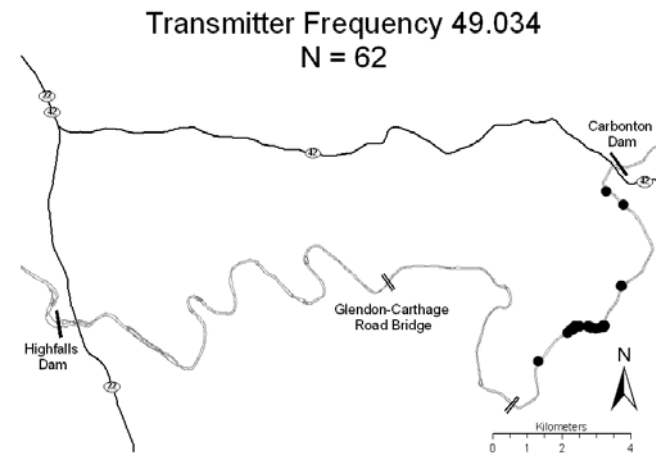
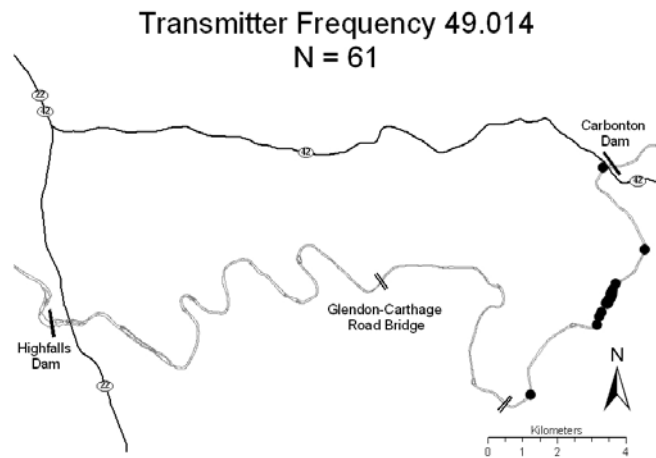


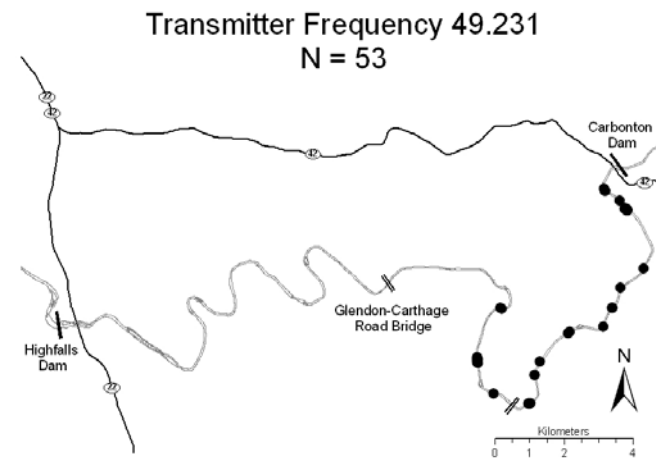
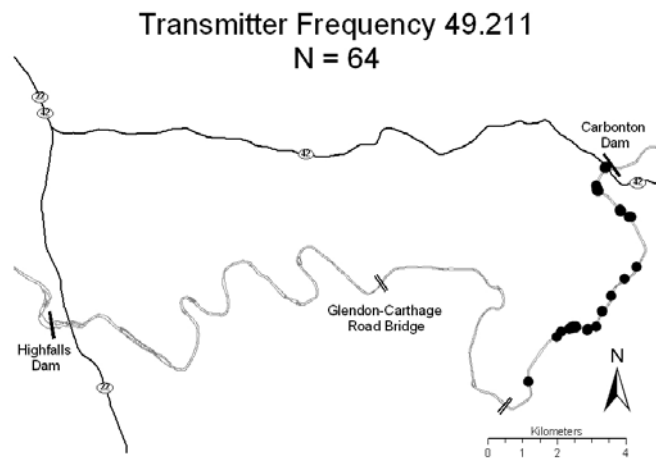
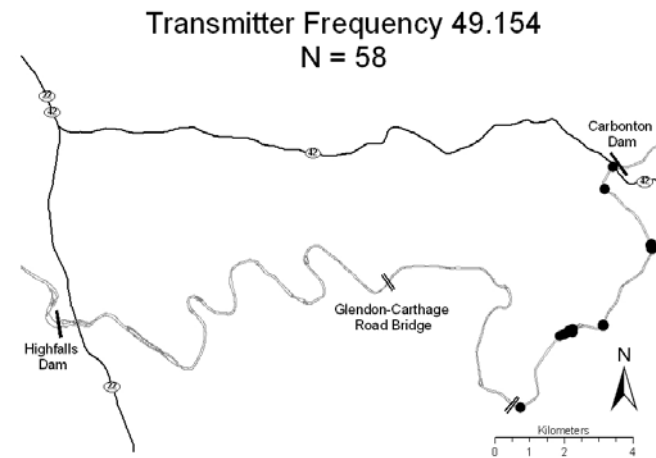
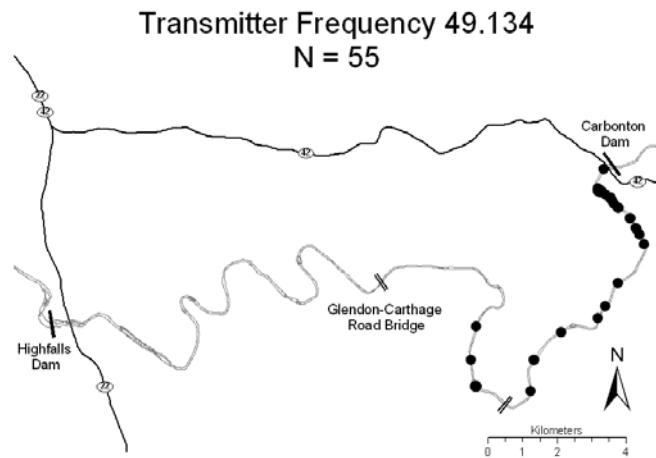
Figure 21. Frequency distributions of (a) Annual, (b) Spawning, (c) Growth, and (d) Winter diel cover associations for flathead catfish in the Deep River, North Carolina. Statistical analysis and sample sizes appear in Table 13.

## Appendix

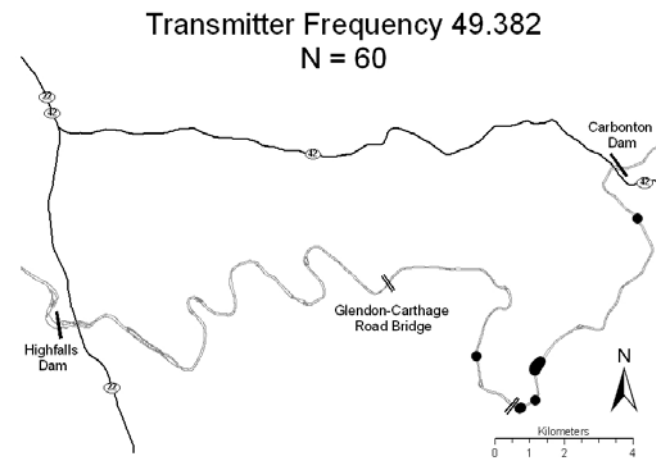
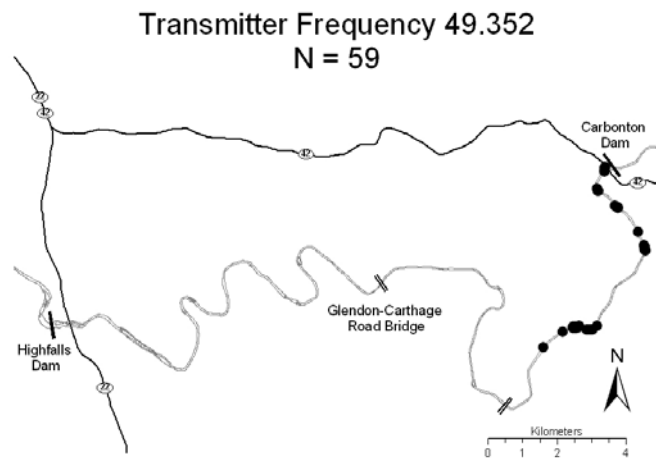
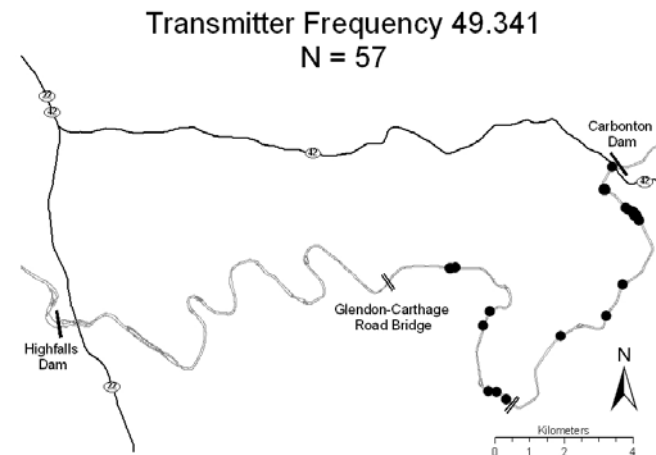
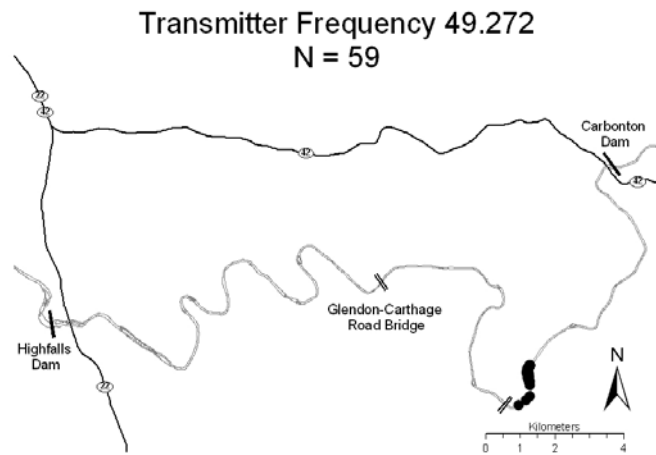


Appendix 1. Relocation points and sample size of four flathead catfish in the Deep River, North Carolina.

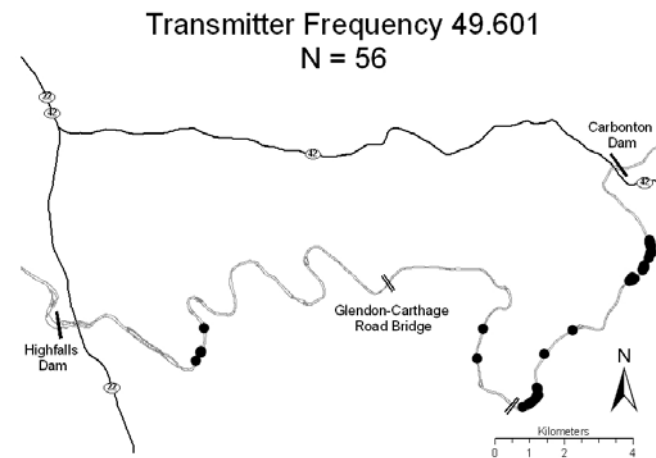
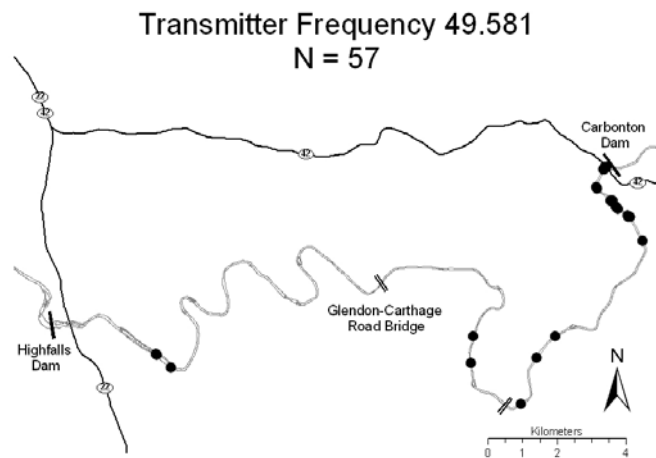
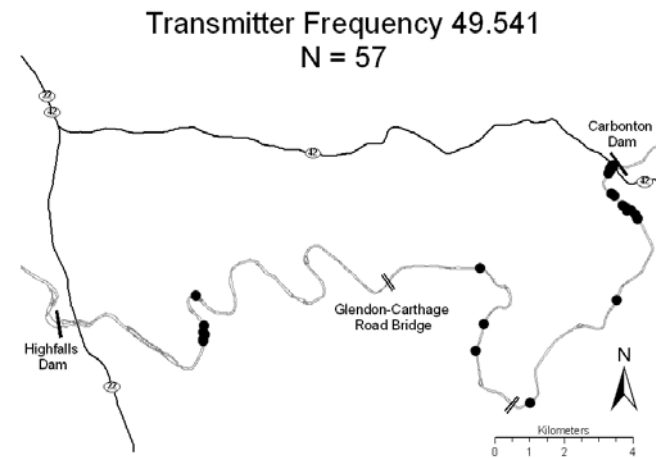
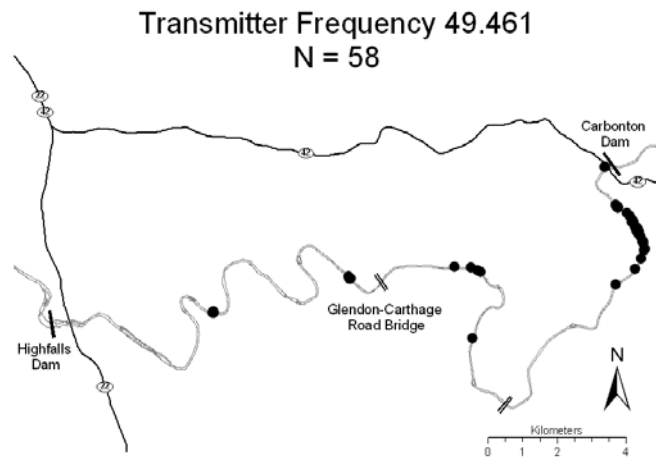




Appendix 1 (continued). Relocation points and sample size of four flathead catfish in the Deep River, North Carolina.



Appendix 1 (continued). Relocation points and sample size of four flathead catfish in the Deep River, North Carolina.



Appendix 1 (continued). Relocation points and sample size of four flathead catfish in the Deep River, North Carolina.