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ARTICLE

Mortality, Dispersal, and Habitat Use of Stocked Juvenile Muskellunge in Two Western North Carolina Rivers

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Abstract

The Muskellunge *Esox masquinongy* is a highly sought-after sport fish that is native to the Tennessee River drainage of western North Carolina. After the extirpation of Muskellunge from North Carolina in the 1950s, the North Carolina Wildlife Resources Commission began a stocking program to re-establish the species and produce viable Muskellunge fisheries in North Carolina. Although stocking efforts have created a Muskellunge fishery in, for example, the French Broad River (where the species was native), there is little evidence of success in North Carolina sections of the New River (where the species was not native). Possible mechanisms inhibiting stocking success are unclear because there is relatively little information available on the juvenile life stage of the Muskellunge, especially in the southern portion of its distribution. We addressed the perceived differences in recruitment between the two fisheries by using telemetry to investigate dispersal, mortality, and habitat use by stocked juvenile Muskellunge. Fifty hatchery-reared, age-0 Muskellunge (282–307 mm TL) were tagged prior to stocking in the New River (fall 2013) and French Broad River (fall 2014). Three months after stocking, known survival of tagged fish was 4% in the New River and 29% in the French Broad River; the survival probability after 3 months was estimated at 9% (range = 4–17%) in the New River and 37% (range = 25–56%) in the French Broad River. Extended survival in the French Broad River was 14% at 252 d poststocking. High dispersal was observed, with maximum individual dispersal of 67.4 km in the New River and 55.5 km in the French Broad River. Habitat suitability analyses indicated that juvenile Muskellunge in the FBR selected shallow nearshore areas with low water velocity, fine substrate, and substantial cover in the form of woody debris and overhanging vegetation. Information on the survival and behavior of stocked Muskellunge can facilitate efforts to successfully manage these fisheries.

The Muskellunge *Esox masquinongy* is an economically important sport fish that is popular with anglers because of its potential to reach large sizes. Fishery managers are presently facing demand to improve and expand Muskellunge fisheries within and outside of the fish's native range (Kerr 2011; Wagner and Wahl 2011), which includes the Ohio River and Mississippi River drainages as well as drainages of the Great Lakes and Hudson Bay (Crossman 1978; Kerr 2011). In the southern portion of its distribution, early reports documented that Muskellunge were native to the Tennessee River drainage of North Carolina (Jordan 1889), but the species was extirpated from North Carolina by the 1950s, likely due to point-source pollution and habitat loss from logging and mining practices (Monaghan 1985; Kerr 2011). After water quality began to improve throughout the state in the 1960s (mostly due to the development of water treatment facilities), the North Carolina Wildlife Resources Commission (NCWRC) began stocking Muskellunge fry and fingerlings into several western North Carolina waters in 1970, with the goal of re-establishing the species within and outside of its native range and creating a trophy fishery (Monaghan 1985; Borawa 1990). However, the success of this stocking program has varied widely among North Carolina river systems.

The success of fish stocking programs is generally variable and can depend on factors as simple as stocking rates or as complex as system-specific ecological interactions (e.g., Gunn

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et al. 1987; Wahl 1999; Henry et al. 2008). An understanding of these interactions, as well as the life history of the stocked species, is critical to predicting and facilitating the success of stocking efforts. Although research has examined aspects of Muskellunge life history, such as adult behavior and spawning viability (e.g., Crossman 1990; Zorn et al. 1998; Casselman et al. 1999), relatively little is known about the juvenile life stage (but see Hanson and Margenau 1992; Margenau 1992; Farrell and Werner 1999; Wagner and Wahl 2011), and data are especially lacking in the southern portion of the species' distribution. Regional studies have focused on population density, distribution, harvest rates, and habitat use of adult Muskellunge (Monaghan 1985; Borawa 1990; Murphy et al. 2003; Cole 2011), but to our knowledge there has been only one study of stocked juvenile Muskellunge in the southeastern United States (Warren 2013). Studies of stocked juveniles in other geographical areas have been primarily limited to lentic environments (e.g., Hanson and Margenau 1992; Margenau 1992; Wagner and Wahl 2011).

It is intuitive that the survival of stocked fish immediately after release could significantly affect the overall success of hatchery-supported fisheries. Studies documenting the post-stocking mortality of juvenile Muskellunge have reported divergent findings ranging from low mortality (11–23%) for fish stocked in Wisconsin lakes (Hanson and Margenau 1992) to much higher mortality (70–97%) for fish stocked elsewhere (Carline et al. 1986; Margenau 1992; Wahl and Stein 1993; Warren 2013). Collectively, these studies suggest that survival of stocked Muskellunge is system-specific. It is also important to note that these studies were focused on lentic systems, so their relevance to stocking success in lotic waters is unknown.

Poststocking mortality is often connected to other important drivers of stocking success, such as dispersal. Dispersal from stocking sites can significantly impact the recruitment of stocked fish into a fishery (e.g., Bettinger and Bettoli 2002; Kerr 2011; Skov et al. 2011), and studies have shown an association between high dispersal and increased mortality rates (Bettinger and Bettoli 2002; Aarestrup et al. 2005). High dispersal can also lead to emigration, which is especially problematic in systems containing dams and for species that, like Muskellunge, are prone to dam escapement (Wolter et al. 2013). Although high dispersal rates have not yet been documented for juvenile Muskellunge, emigration in lotic systems could be a factor contributing to the limited success of stocking in western North Carolina fisheries.

Availability of suitable habitat may also impede stocking success (e.g., Mittelbach 1981; Hewitt et al. 2009; Brown and Bozek 2010), and habitat degradation has been cited as a primary obstacle to the creation of successful Muskellunge fisheries (Kerr 2011). Availability of suitable habitat in a stocked system can be especially critical for Muskellunge and other species that are known to exist in low population densities (Dombeck et al. 1984; Hewitt et al. 2009; Kerr 2011) and that are selective in the types of habitat they use (Hanson and Margenau 1992; Wagner et al. 2015). Furthermore, habitat suitability can be directly linked to both dispersal and mortality, contributing to (1) increased dispersal if fish are required to search for suitable locations or (2) increased mortality if inadequate habitat increases vulnerability to predators.

Although there have been no formal studies on Muskellunge in North Carolina since 1991, evidence indicates substantial differences in stocking success between the New River and the French Broad River, both of which have been stocked on an annual or biennial basis for more than 30 years (J. C. Borawa, NCWRC, unpublished data). Angler reports and routine sampling efforts by the NCWRC indicate that a viable Muskellunge fishery has been established in the French Broad River, but stocking has not been similarly successful in the New River upstream of the Virginia border (Western North Carolina Muskie Club, unpublished data; D. L. Yow, NCWRC, personal communication). To better understand the perceived difference in stocking success between these two North Carolina rivers and to address the limited research on factors affecting stocking success in lotic systems, we evaluated the fate of stocked juvenile Muskellunge in each system. Specifically, we used radiotelemetry to estimate the mortality, dispersal, and habitat use of stocked age-0 Muskellunge in the New and French Broad rivers during the first 3 months poststocking, and we estimated habitat selection by comparing habitat use to habitat availability in the French Broad River. Radiotelemetry is a commonly used method of studying behavioral patterns in Muskellunge (e.g., Hanson and Margenau 1992; Wagner and Wahl 2011) and can be an ideal technique for collecting fine-scale mortality, dispersal, and habitat use data on fish species that are otherwise difficult to sample (Kapuscinski et al. 2012). A robust assessment of stocked juvenile Muskellunge in contrasting lotic systems should provide information that can be used by fishery biologists to better predict stocking success for this popular sport species.

METHODS

Study sites.—The New River, a tributary of the Ohio River system, is a low-gradient (2.3 m/km), sinuous mountain river with long pools, riffle–run characteristics, and an abundance of boulders and bedrock ridges. The river, which flows northward through North Carolina and Virginia before converging with the Kanawha River in West Virginia, drains 1,950 km^2 in North Carolina (Monaghan 1985); the general water quality within the basin is characterized as good (NCWRC 2005). Although the New River is outside the native range of the Muskellunge, the NCWRC has stocked approximately 150 Muskellunge annually or biennially over approximately 20 km (~8 fish/km) of the south fork and main-stem portions of the New River upstream of the Virginia border since 1978 (NCWRC, unpublished data). Our 56-km study area included the south fork and main-stem portions of the New River in North Carolina, where Muskellunge have traditionally been stocked, along with approximately 27 km of the main-stem New River in Virginia (Figure 1). Fields Dam (~4-m high, concrete structure) is located in the middle of this study area, approximately 5.7 km downstream from the Virginia border.

The French Broad River flows northward through western North Carolina for 188 km between its headwaters (near Rosman, North Carolina) and the Tennessee border, encompassing a watershed that drains 7,300 km^2 (Monaghan 1985). Based on hydrological conditions, the French Broad River in North Carolina is best considered as two sections. The upper section (87 km) between Brevard and Asheville is a sinuous, low-gradient (0.5 m/km) river that meanders through a wide floodplain. Downstream of Asheville, the lower portion of the French Broad River has a higher gradient (3.3 m/km) as it cuts through a steep valley (Monaghan 1985; NCWRC 2005). The upper section contains habitat that is considered more suitable for Muskellunge, with an abundance of fallen trees and deep pools, whereas the lower section contains riffle–run habitats that are traditionally considered to be better suited for Smallmouth Bass *Micropterus dolomieu* (Monaghan 1985). Since 1976, the NCWRC has stocked approximately 1,700 Muskellunge annually or biennially over 174 km (~10 fish/km) of the French Broad River between the Tennessee border and Brevard, with approximately two-thirds of the fish being stocked in the upper section (NCWRC, unpublished data). Our study area included approximately 65 km of the upper French Broad River, where most of the juvenile Muskellunge have traditionally been stocked (Figure 1).

Fish tagging.—Radio transmitters were implanted into 50 age-0 Muskellunge during October 2013, and the fish were stocked into the New River. In October 2014, another 50 Muskellunge were tagged and stocked into the French Broad River (Table 1). Surgical implantation of the radio tags occurred at the Table Rock Fish Hatchery (Morganton, North Carolina) via the methods outlined by Wagner et al. (2011). All tools, sutures, and tags were sterilized or disinfected prior to surgeries. The Muskellunge were anesthetized with tricaine methanesulfonate (MS-222) buffered with sodium bicarbonate (Hanson and Margenau 1992) and received Advanced Telemetry Systems (ATS) Model F1440 radio-transmitting tags (9 × 19 × 7 mm, 3.3 g, with a 200-mm trailing whip antenna; ATS, Isanti, Minnesota). The tag antenna was

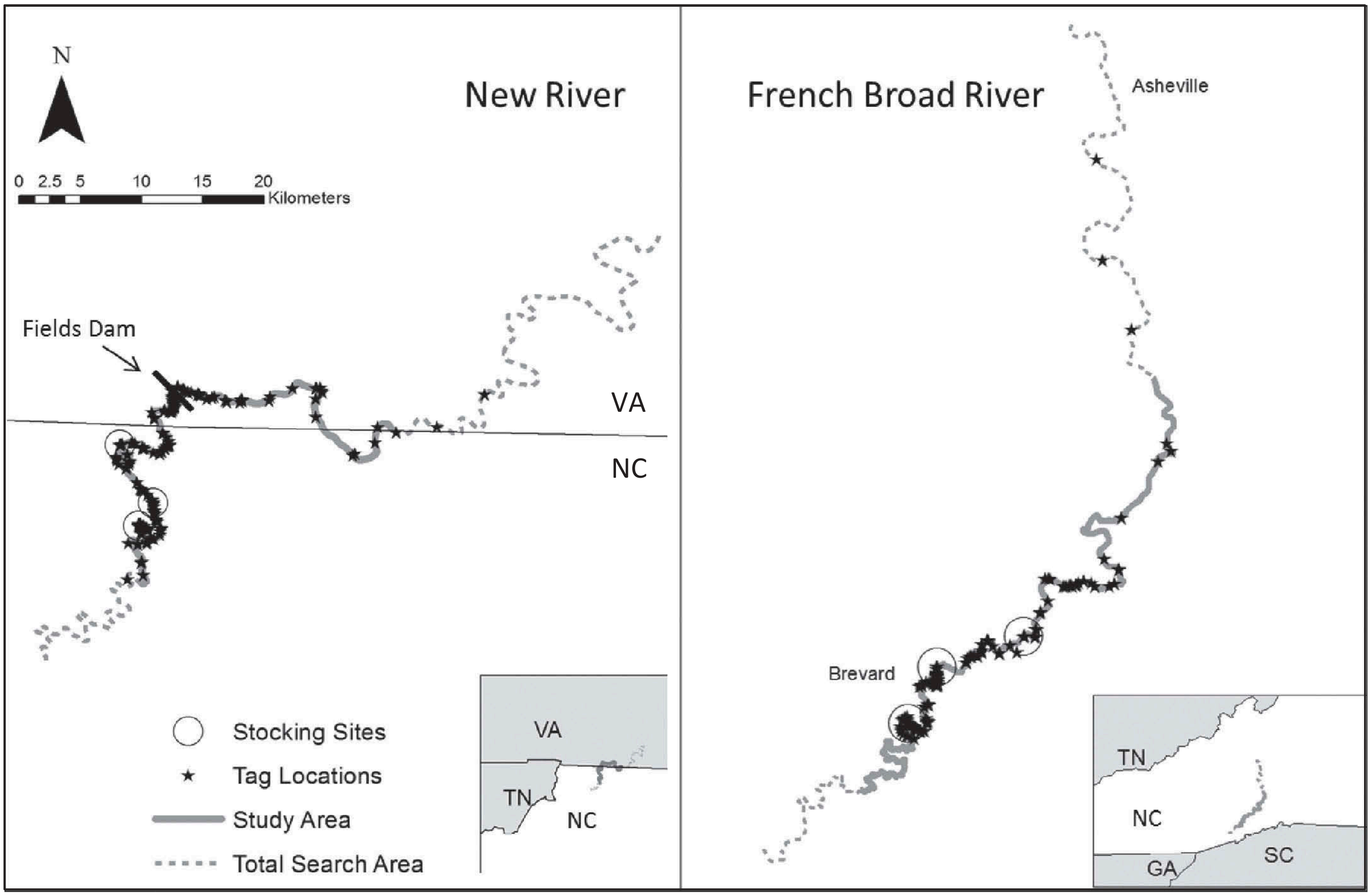

FIGURE 1. Study area, total search area, stocking sites, and tag locations of radio-tagged juvenile Muskellunge that were stocked in the New River (Virginia–North Carolina) during fall 2013 and in the French Broad River (North Carolina) during fall 2014.

TABLE 1. Sample size, mean, SD, and range for TL (mm) and weight (g) of age-0 Muskellunge that were used for telemetry at each study site (New River and French Broad River) and in the tag retention study.

System or group	*N*	Variable	Mean	SD	Range
Telemetry					
New River	50	TL	282.2	12.7	255–325
		Weight	116.7	19.0	82–186
French Broad River	50	TL	306.5	12.7	277–335
		Weight	138.7	19.5	101–183
Tag retention					
Dummy tagged	15	TL	289.9	13.7	270–323
		Weight	126.1	21.5	98–178
Control	15	TL	275.9	13.7	252–298
		Weight	105.9	19.2	78–146

inserted through the incision and pulled through the body cavity over the pelvic girdle and out through the abdominal wall posterior to the pelvic girdle by using the shielded-needle technique (Ross and Kleiner 1982). The incision was closed with two simple interrupted sutures (Wagner et al. 2011) made of absorbable monofilament material. Radio-tagged fish were allowed to recover for 4 d at the hatchery before being transported to their stocking locations on the New and French Broad rivers.

To assess the possibility of surgery-related mortality or tag loss, we conducted a tag retention study during fall 2013 by using 15 juvenile Muskellunge that received dummy tags and 15 control fish. The dummy-tagged fish were treated in an identical manner to radio-tagged fish except that they were implanted with a replica tag of similar size, weight, and material as a functioning radio tag. Control fish were treated the same as the dummy-tagged fish except that they did not undergo surgery. The control and dummy-tagged fish were evenly interspersed with radio-tagged fish throughout the tagging process to ensure that they experienced similar conditions; fish from the tag retention study were then collectively retained in a circular holding tank and were fed live minnows for 30 d in the hatchery, where their survival and behavior were monitored daily. At the end of the tag retention study, the dummy-tagged fish were euthanized in an overdose solution of MS-222 (>200 mg/L) so that internal and external examination of the incision sites could be performed.

Telemetry.—At each river, the tagged fish were divided equally among three stocking sites separated by 16 km between the upstream-most and downstream-most locations (Figure 1). Water temperatures were similar at each study site upon stocking (12°C in the New River; 17°C in the French Broad River). One fish that was released into the French Broad River was censored from the data set used in analysis because we noticed that its tag was not functioning properly upon stocking. Fish were tracked at each study site by using an ATS Model R410 receiver with a three-element, folding Yagi antenna. While floating the river, we continuously scanned the frequency range of all tags used at each study site (149–150 MHz) until a tag was detected. By adjusting the sensitivity of the receiver via the gain function, we were able to determine tag locations within 1 m. Tag locations were recorded by using a handheld Global Positioning System unit (accuracy = 2–8 m).

The study area (56 km) in the New River was split into four approximately even sections that were tracked at least biweekly (once every 2 weeks). Areas upstream and downstream of the study area were also intermittently searched (1–3 times/section) in an attempt to locate tags that disappeared during the study period; this generated a total search area of 160 km (Figure 1). The study area (65 km) in the French Broad River was also split into four approximately even sections that were tracked at least biweekly. Additional sections of the river upstream and downstream of the study area were searched intermittently (1–2 times/section), resulting in a total search area of 116 km (Figure 1). The primary study period at each site lasted for 3 months after stocking. We returned to the French Broad River at 122 and 252 d poststocking to evaluate the extended survival of tagged juvenile Muskellunge.

Mortality.—An encounter history was developed by assigning a fate (alive, dead, or missing) to each fish for each biweekly tracking period within the primary (i.e., 3 months) study period for each system. We assumed that a fish had died if its tag was recovered or remained in the same location for three or more consecutive tracking periods (a minimum of 14 d). Otherwise, encountered tags were considered to represent live fish. Any fish that was not detected at the end of the study period was considered missing and was assumed to have disappeared during the first interval in which it went undetected. To calculate the probability that stocked juvenile Muskellunge survived each study period, we entered the encounter history of each fish into Program MARK version 7.2 (Gary White, Colorado State University). Survival probabilities were estimated by using the known-fate model in Program MARK, with seven biweekly encounter occasions. The known-fate model is ideal for telemetry studies when (1) the fate of most animals is known throughout the study period, (2) the detection probability is close to 1.0, and (3) there are few disappearances (Cooch and White 2014). Initial length and weight were included in the model as individual covariates.

We used three modeling approaches to account for uncertainty in survival estimates resulting from the unknown fates of tagged fish that disappeared during the study period. The initial model ("missing fish censored") accounted for fish that disappeared during the study period by censoring their data from analysis (i.e., censored from the interval in which they disappeared until the end of the study period). The second model ("missing fish died") treated missing fish as if they had actually died during the interval in which they disappeared. The third model ("missing fish survived") treated missing fish as if they had survived through the duration of the study period. Therefore, we were able to create upper and lower bounds of estimated survival to account for missing fish. Each model was run with and without covariates and with varying (biweekly) and constant survival probabilities. The best model for each design was selected by using Akaike's information criterion in Program MARK (Cooch and White 2014).

Dispersal.—Tagged fish locations were analyzed in ArcGIS version 10.1 (ESRI, Redlands, California) to measure dispersal distance. We measured maximum dispersal as the distance within the river channel between the stocking site of each tagged fish and the farthest location where its tag was encountered (representing either a live encounter or a mortality). Any tags that were never detected or that disappeared before the end of the study period were censored from this analysis. We also measured live dispersal as the farthest distance within the river channel between the stocking site and the last location at which each fish was found alive; all fish were used in the analysis of live dispersal.

Habitat use, availability, and selection.—Habitat use data were collected while we actively tracked fish in each study area. When a fish was detected, surface velocity and depth were measured at the observed location of that individual; substrate type, percent cover, and cover type were estimated for a 1-m^2 area centered at the fish's location. On the French Broad River, surface velocity was determined by measuring the amount of time taken (to the nearest second) for an orange to float 1 m downstream over the fish's location (Bain and Stevenson 1999). Primary substrate type was recorded from visual and tactile observations based on a modified Wentworth scale (silt: <0.059 mm; sand: 0.06–1.00 mm; gravel/pebble: 2–63 mm; cobble: 64–256 mm; boulder: >256 mm; Bain and Stevenson 1999). Cover type was described categorically (Table 2). Percent cover was estimated aerially to the nearest 10% as the amount of structure on the bottom, in the water column, or within 1.5 m above the water surface within a 1-m^2 area around the fish's location. Surface velocity and percent cover data were visually estimated on the New River and thus were not included in quantitative analysis.

Habitat availability data were only collected on the French Broad River. Available habitat was quantified by sampling characteristics along transects within representative reaches of the upper French Broad River. All habitat availability data were collected during summer 2014 under base flow conditions. Within each section of each study area, we selected representative reaches that extended 40 times the mean stream width of that section (Simonson et al. 1994; Hartman and Logan 2010). Transects were evenly spaced at twice the mean stream width throughout each reach for a total of 21 transects/reach (Simonson et al. 1994). Habitat observations (N = 858) were made by using a 1-m^2 quadrat at equidistant intervals along each transect (at every 2 m for the upper section, every 3 m for the middle sections, and every 4 m for the lower section) for approximately 10 intervals/transect; the initial observation began within 1 m of the river's left shoreline. The measured habitat parameters included depth, mean water column velocity (measured at 60% of the water column depth by using a Marsh-McBirney Flo-Mate 2000 digital flowmeter), primary substrate type, and cover (percentage and type; Bain and Stevenson 1999). As with habitat use observations, depth and velocity were measured at the center of the 1-m^2 quadrat, whereas substrate type, percent cover, and cover type were observed for the entire quadrat area. Deciduous leaves attached to live plants were ignored in estimates of percent cover to account for seasonal differences between availability and use observations (although this issue rarely occurred because overhanging vegetation generally consisted of evergreen species or brush with dense woody biomass). Quantitative parameters for habitat use and availability data were grouped into 3–8 bins/parameter during analyses.

TABLE 2. Descriptions of cover type categories used for the habitat availability and Muskellunge habitat use observations. All observed cover types were included in the analyses.

Cover type	Description
None	No cover observed
Boulder	One or more boulders
Emergent vegetation	Aquatic macrophytes growing from the substrate to beyond the surface of the water
Large woody debris	Woody structure over 100 mm in diameter and over 1 m long; or a combination of woody structure over 50 mm in diameter and small sticks, leaves, or other types of submerged or floating debris
Overhanging vegetation	Brush, tree, limb, or grass less than 1.5 m above the water surface
Small woody debris	More than one of the following: sticks, leaves, roots, or other types of submerged or floating debris less than 25 mm in diameter and less than 300 mm long; or a single woody structure over 25 mm in diameter and over 300 mm long, but no more than 100 mm in diameter and no more than 1 m long
Undercut bank	Horizontal protrusion of bank extending over 300 mm away from shore at the surface of the water or within the water column

To describe habitat that was selected by stocked age-0 Muskellunge, we compared habitat use to habitat availability on the French Broad River by using univariate and multivariate analyses. Univariate analysis allowed us to describe the individual habitat characteristics (e.g., depth and cover) that the Muskellunge selected, while multivariate analysis was used to describe combinations of habitat characteristics that were correlated with each other to form any habitat associations that were selected or avoided by the fish (Bovee 1986; Midway et al. 2010). All habitat use observations were incorporated into our analysis, except that we censored any observations that were made within 10 d after another observation for each individual fish, thereby allowing sufficient time for each Muskellunge to select alternate habitats between observations. To calculate univariate habitat suitability describing the degree of selection for each habitat parameter, we first divided the ratio of use observations by the ratio of available habitat observations for each variable. These values were then ranked to identify the optimal ranges or categories within each habitat parameter by normalizing variables to the greatest value for the habitat parameter such that the most suitable habitat was given a normalized suitability of 1.0 (Hewitt et al. 2009; Midway et al. 2010).

To determine whether fish were selecting locations based on correlated habitat characteristics, we used principal components analysis (PCA) for the five numerical habitat parameters (distance from shore, depth, water velocity, substrate type, and percent cover). We converted surface velocity measurements to mean column velocity for habitat use data by dividing the surface velocity observations by 1.16 (Hulsing et al. 1966). Not all habitat parameters could be measured at each location where habitat availability or Muskellunge use was observed, as some parameters varied markedly within the 1-m location range; for this analysis, we only included locations at which all five habitat parameters could be accurately measured (0.98 of all habitat availability observations; 0.53 of all habitat use observations). We used the PCA to extract linear descriptions based on the correlation matrix from the combined habitat parameters (i.e., availability and use observations were pooled for analysis) using R version 3.1.3 (R Foundation for Statistical Computing, Vienna; Kwak and Peterson 2007; Midway et al. 2010). Each habitat parameter was assigned ordinal values across the ranges of values for the use and availability observations. Loadings for the two components that explained most of the variation in the data were then used to describe habitat use relative to availability in a two-dimensional component space. Only loadings greater than $|0.4|$ were used to interpret the components (Petty et al. 2001; Kwak and Peterson 2007). A Kolmogorov–Smirnov (K–S) two-sample test was performed on each component to test for statistically significant differences between habitat use and availability distributions ($P < 0.05$; Hewitt et al. 2009; Midway et al. 2010).

RESULTS

Mortality

The known survival of tagged Muskellunge at 3 months poststocking was low in both study areas but was seven times higher (29%) in the French Broad River than in the New River (4%). There were 39 confirmed mortalities (78%) of tagged fish in the New River and 22 confirmed mortalities (45%) in the French Broad River. We recovered 26 tags (52%) from the New River, 9 (18%) of which were found on land; 17 tags (35%) were recovered from the French Broad River, all of which were recovered in the water. Throughout the study periods, 9 fish (18%) eventually disappeared from the New River, and 12 fish (24%) disappeared from the French Broad River. In the New River, all tags were located at least once during the 86-d study period; 35 of the 50 tagged Muskellunge were located alive, and 9 of the fish were located between 10 and 14 times. Within the French Broad River, all but three tags were located at least once during the 89-d study period; 38 of those 47 tagged individuals were located alive, and 7 of the fish were located 10–12 times. There were no indications of transport-related injury at the time of stocking for Muskellunge stocked at either study site. Furthermore, there was no tag loss or mortality for the dummy-tagged fish or control fish at the end of the 30-d tag retention study; in examining dummy-tagged fish, we found that all sutures remained intact and the incisions were completely healed, with only minor inflammation at suture sites in a few of the fish. Dissection of dummy-tagged fish revealed that there was no tag encapsulation in the body wall.

Using our encounter histories in Program MARK with the “missing fish censored” model, we estimated that stocked juvenile Muskellunge had a survival probability of 0.093 (SE = 0.04; total instantaneous mortality rate [Z_{daily}] = 0.024) at 3 months poststocking in the New River and 0.370 (SE = 0.08; $Z_{\text{daily}} = 0.010$) in the French Broad River. However, depending on which “missing fish” model we used (missing fish censored, missing fish died, or missing fish survived), the estimated survival probability ranged from 0.035 to 0.173 for Muskellunge stocked into the New River and from 0.253 to 0.558 for those stocked in the French Broad River (Table 3). A constant survival rate for each biweekly tracking period best described each model for the New River as well as the “missing fish censored” model for the French Broad River. However, the “missing fish died” and “missing fish survived” models for the French Broad River were best described by lower survival rates during the first tracking period and relatively constant survival rates thereafter (Figure 2).

After the primary study period, return trips to the French Broad River revealed that survival rates of the remaining fish increased (Table 4). We found that 11 individuals (22%) were still alive in the study area at 122 d poststocking, and 7 fish (14%) were still alive in the study area at 252 d. To compare these interval survival rates at equal time periods, we log-transformed the interval survival rates and then calculated daily discrete survival rates (Table 4). Regardless of the designated fates of missing fish, the survival rates of Muskellunge remaining in the study area increased after the primary study period.

We found evidence of predation on stocked Muskellunge in both rivers, where great blue heron *Ardea herodias*, North American river otter *Lontra canadensis*, and American mink

TABLE 3. Survival probabilities for radio-tagged age-0 Muskellunge at 3 months poststocking in the New River and French Broad River, as estimated in Program MARK (CI = confidence interval; Z_{daily} = instantaneous total mortality rate). Different estimates for each river depend on the designation for fish that went missing throughout the study periods.

Model and system	Survival probability	SE	95% CI	Z_{daily}
Missing fish censored				
New River	0.093	0.04	0.04–0.20	0.0010
French Broad River	0.370	0.08	0.23–0.54	0.0048
Missing fish died				
New River	0.035	0.02	0.01–0.09	0.0004
French Broad River	0.253	0.07	0.15–0.40	0.0030
Missing fish survived				
New River	0.173	0.05	0.09–0.30	0.0020
French Broad River	0.558	0.08	0.41–0.70	0.0084

Neovison vison were seen frequently. On the New River, one tag was tracked directly to a great blue heron; two tags were recovered together on a bank entangled in small pebbles and scales, which we concluded to be great blue heron regurgitation. Two other tags were detected onshore adjacent to avian feces, whereas another tag was found enveloped in pieces of crayfish shell next to an apparent North American river otter den. On the French Broad River, two tags were discovered on separate occasions below a log that was covered in avian feces and feathers. In addition, we collected multiple tags with frayed antennae, consistent with having been gnawed on by mammals.

Dispersal

We observed high dispersal of tagged juvenile Muskellunge in both systems (Figure 1), but dispersal was nearly twice as high in the New River as in the French Broad River. The maximum dispersal distance for all tagged fish averaged 23.3 km in the New River (maximum = 67.4 km, SD = 16.6; N = 41) and 8.8 km in the French Broad River (maximum = 55.5 km, SD = 14.8; N = 39). When only live encounters were considered, the live dispersal distance of tagged fish averaged 10.1 km in the New River (maximum live dispersal = 49.6 km, SD = 12.2; N = 50) and 4.7 km in the French Broad River (maximum live dispersal = 35.1 km, SD = 7.3; N = 49; Figure 3). Most of the dispersal was downstream; the maximum observed upstream dispersal was 16.4 km in the New River and 11.0 km in the French Broad River. During the study periods, there were two high-flow events in the New River (>57 m^3/s at U.S. Geological Survey [USGS] station 03161000) and three high-flow events in the French Broad River (>85 m^3/s at USGS station 03443000; USGS 2015). However, there was no evidence of increased dispersal during any of these high-flow

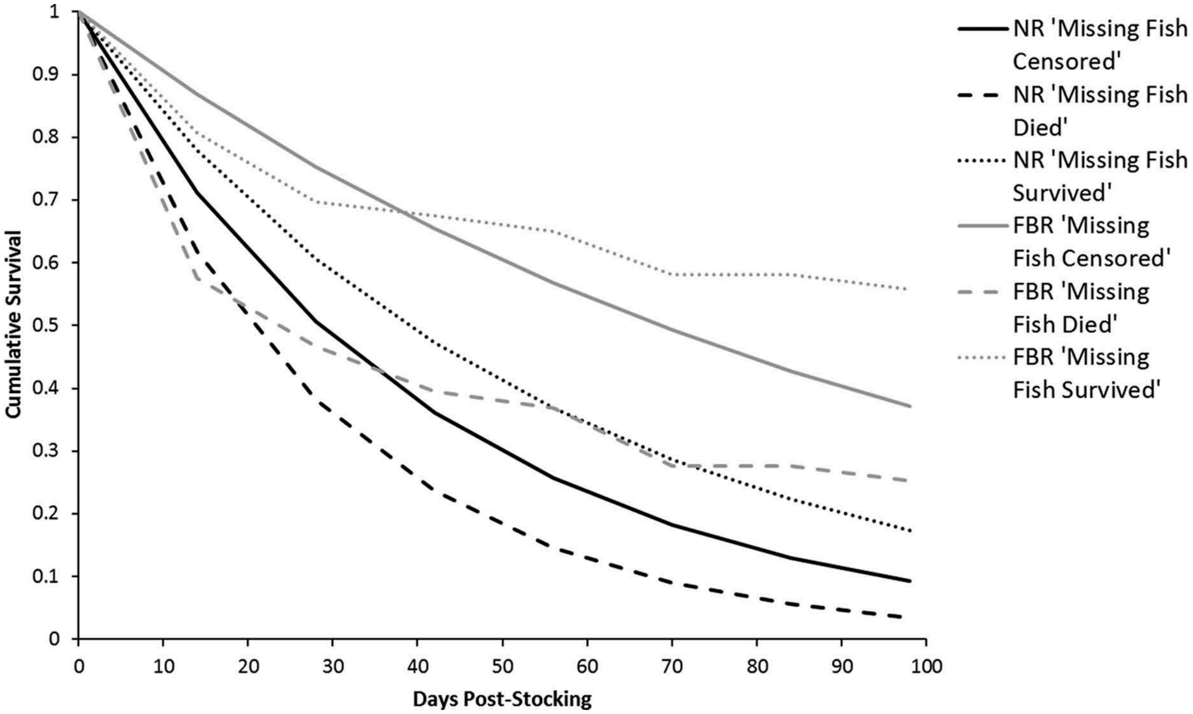

FIGURE 2. Cumulative survival probabilities of radio-tagged juvenile Muskellunge stocked in the New River (NR) and French Broad River (FBR) based on three different methods of treating fish that disappeared during the study period: censored from the data set (missing fish censored), treated as mortalities (missing fish died), or considered to have been alive throughout the study period (missing fish survived).

TABLE 4. Known survival rate scenarios for radio-tagged juvenile Muskellunge in the French Broad River during the primary and extended study periods based on three analytical approaches for missing fish.

Analysis type	Days poststocking	Interval survival rate	Daily discrete survival rate	Normalized daily discrete survival rate
Missing fish censored	89	0.38	0.989	1.0000
	122	0.85	0.995	1.0059
	252	0.70	0.997	1.0082
Missing fish died	89	0.29	0.986	1.0000
	122	0.79	0.993	1.0068
	252	0.64	0.997	1.0107
Missing fish survived	89	0.53	0.993	1.0000
	122	0.86	0.995	1.0025
	252	0.73	0.998	1.0047

events. At 13 d poststocking on the New River, we observed 15 tags (30%) downstream of Fields Dam (Mouth of Wilson, Virginia). By the end of the study period, we located 20 tags (40%) beyond this dam, which is 12.7 km below our downstream-most stocking site. Among the 20 tags that were located below the dam, only 8 were confirmed to be from live fish. Because Fields Dam is approximately 4 m in height, it would likely inhibit emigrating juvenile Muskellunge from returning upstream.

Habitat Use and Selection

In the French Broad River, we collected 115 habitat use observations from 33 tagged juvenile Muskellunge (1–7 observations/fish). Due to the continuously shrinking sample size as fish died or disappeared during the study period, some individuals were observed more often than others. However, observations for each habitat use category were not dominated by a few fish observed many times, but instead were distributed broadly among fish that were detected different numbers of times (Figure 4). We also completed a diagnostic analysis using only median values of the habitat use observations for each fish (i.e., only one value per fish per habitat parameter). Although this method did not considerably alter the overall use distributions for each habitat parameter, it did result in a loss of data. Therefore, we determined that it was most appropriate to use the individual observations in our habitat use analysis. Habitat suitability analysis indicated that stocked juvenile Muskellunge in the French Broad River were selective in the types of habitat they occupied (Figure 5). They tended to select nearshore (<3 m from the bank), shallow (≤0.9 m), low-velocity (≤0.23 m/s) habitats even though most of the river's habitats consisted of offshore (>3 m from the bank), deeper (>0.9 m), swifter (>0.23 m/s) areas. The locations selected by tagged Muskellunge were also dominated by silt and sand rather than coarse substrate. Tagged juveniles generally selected habitat locations with high amounts of cover (≥40%), mostly made up of overhanging vegetation, woody debris, and undercut banks.

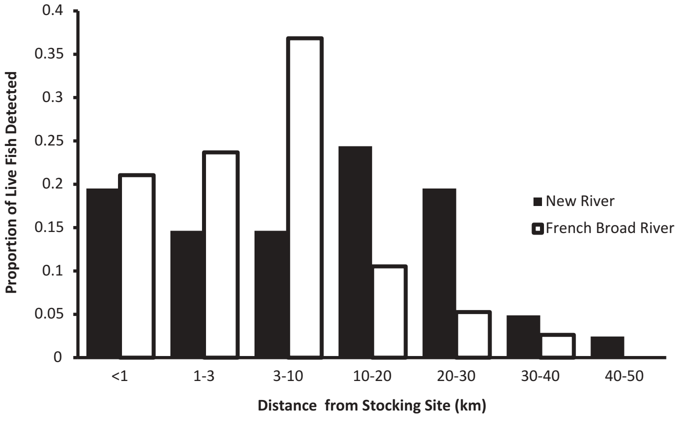

FIGURE 3. Comparison of live dispersal by radio-tagged juvenile Muskellunge in the New River and the French Broad River.

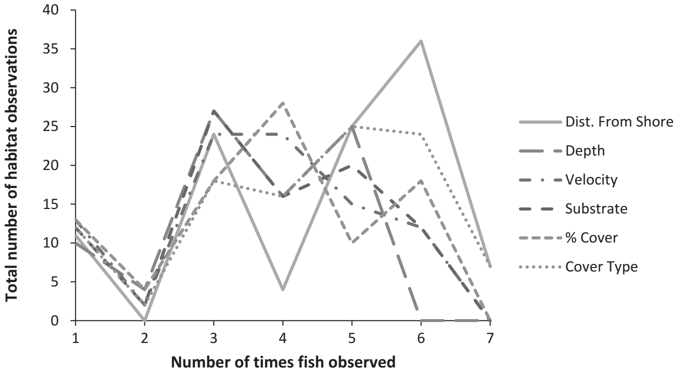

FIGURE 4. Total number of times that individual radio-tagged juvenile Muskellunge were observed for each habitat parameter in the French Broad River.

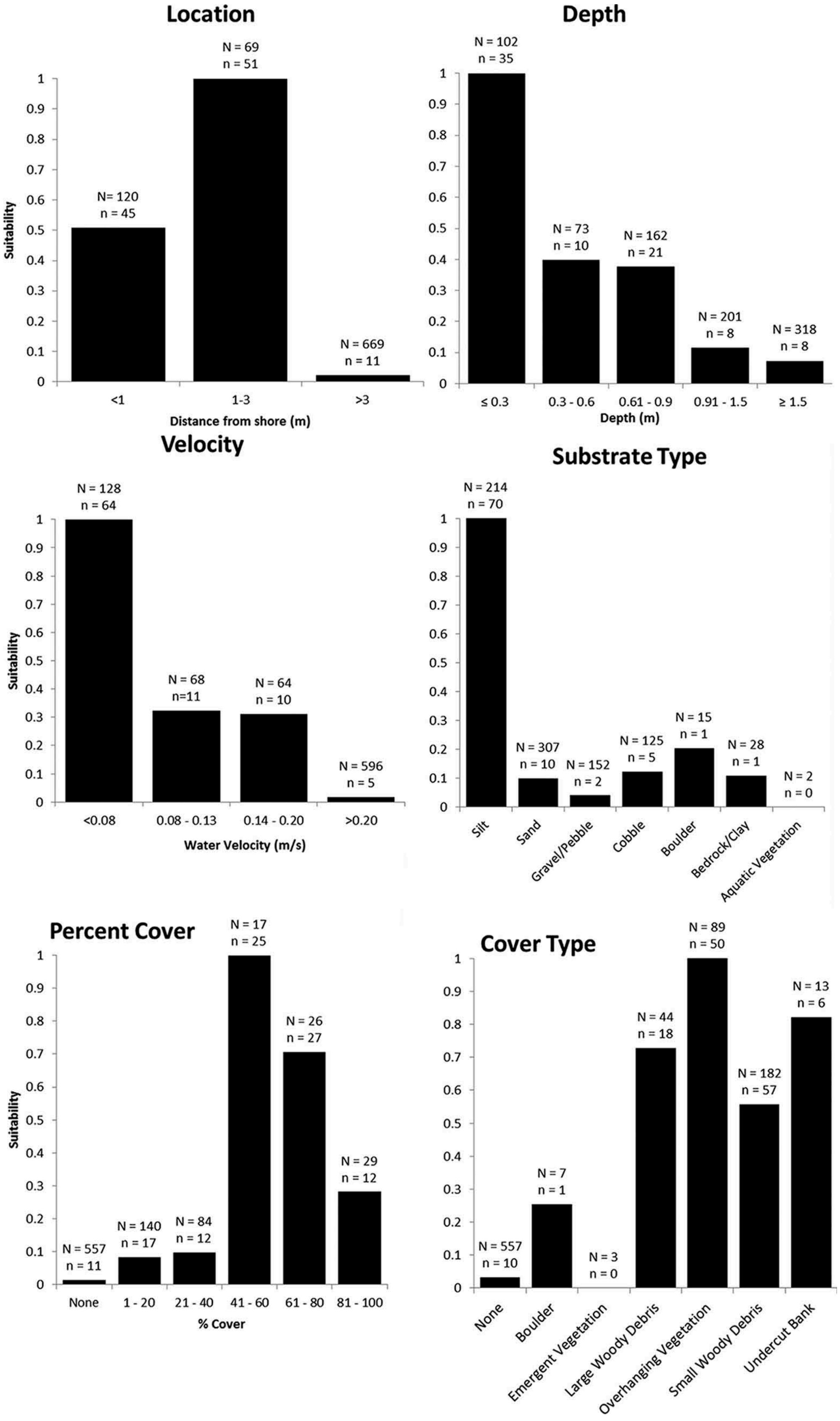

FIGURE 5. Habitat suitability values for radio-tagged juvenile Muskellunge in the French Broad River (*N* = total habitat availability observations; *n* = total habitat use observations).

TABLE 5. Retained principal component (PC) loadings (based on a correlation matrix) from principal components analysis of habitat availability (N = 842 observations) and habitat use (n = 71 observations) by radio-tagged juvenile Muskellunge in the French Broad River. Significant loadings are shown in bold italics. Kolmogorov–Smirnov (K–S) two-sample test results indicated that the habitat use and availability distributions were significantly different.

Cover type or statistic	PC1	PC2
Distance from shore	***–0.51***	0.16
Depth	***–0.46***	0.36
Water velocity	***–0.50***	–0.02
Primary substrate type	–0.35	***–0.91***
Percent cover	0.40	–0.13
Variance explained (%)	61	15
D-statistic (K–S test)	0.69	0.36
P-value (K–S test)	<0.001	<0.001

The PCA indicated that there were correlations among distance to shore, depth, and water velocity. The first principal component (PC1) explained 61% of the variance in the combined habitat data and was driven by distance to shore, depth, and water velocity. The second principal component (PC2) explained an additional 15% of the variance in the combined habitat data and was driven by substrate type (Table 5). The PC1 specified that more negative values corresponded to offshore areas correlated with deeper, faster-moving water, whereas less-negative (or positive) values corresponded to shallow nearshore areas with slower-moving water; PC2 indicated that positive values were associated with small substrate and, conversely, that negative values were associated with larger substrate (Figure 6). Results of the K–S test showed that the habitat used by juvenile Muskellunge was significantly different than habitat availability in the two-dimensional PCA space (Table 5), indicating that the fish were using nearshore, low-velocity, shallow-water areas with smaller substrate even though the available habitat was more randomly distributed along these habitat parameters.

In the New River, we collected 93 habitat use observations from 37 tagged Muskellunge. In many respects, the habitat use exhibited by these tagged juveniles was similar to that of fish in the French Broad River (Figure 7); fish occupied nearshore (<3 m from shore), shallow (<1 m), low-velocity to slack water areas. However, fish in the New River were less reliant on silt substrate than those in the French Broad River and instead were more commonly found over boulders. Likewise, these juveniles were associated more with boulders as cover and less with overhanging vegetation than fish in the French Broad River.

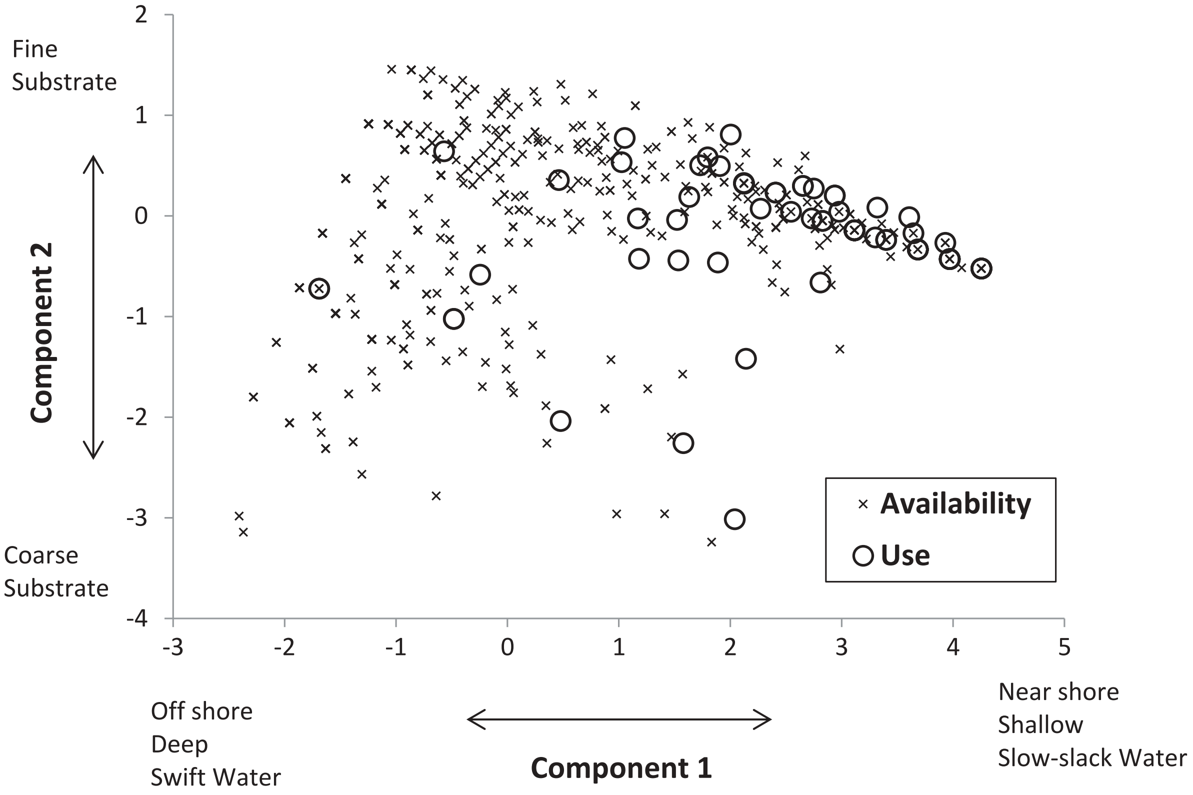

FIGURE 6. First and second principal component (PC) scores from a principal components analysis of habitat availability and habitat use by radio-tagged juvenile Muskellunge in the French Broad River, with descriptions of significant PC loadings for each axis. The PC loadings and sample sizes are given in Table 5.

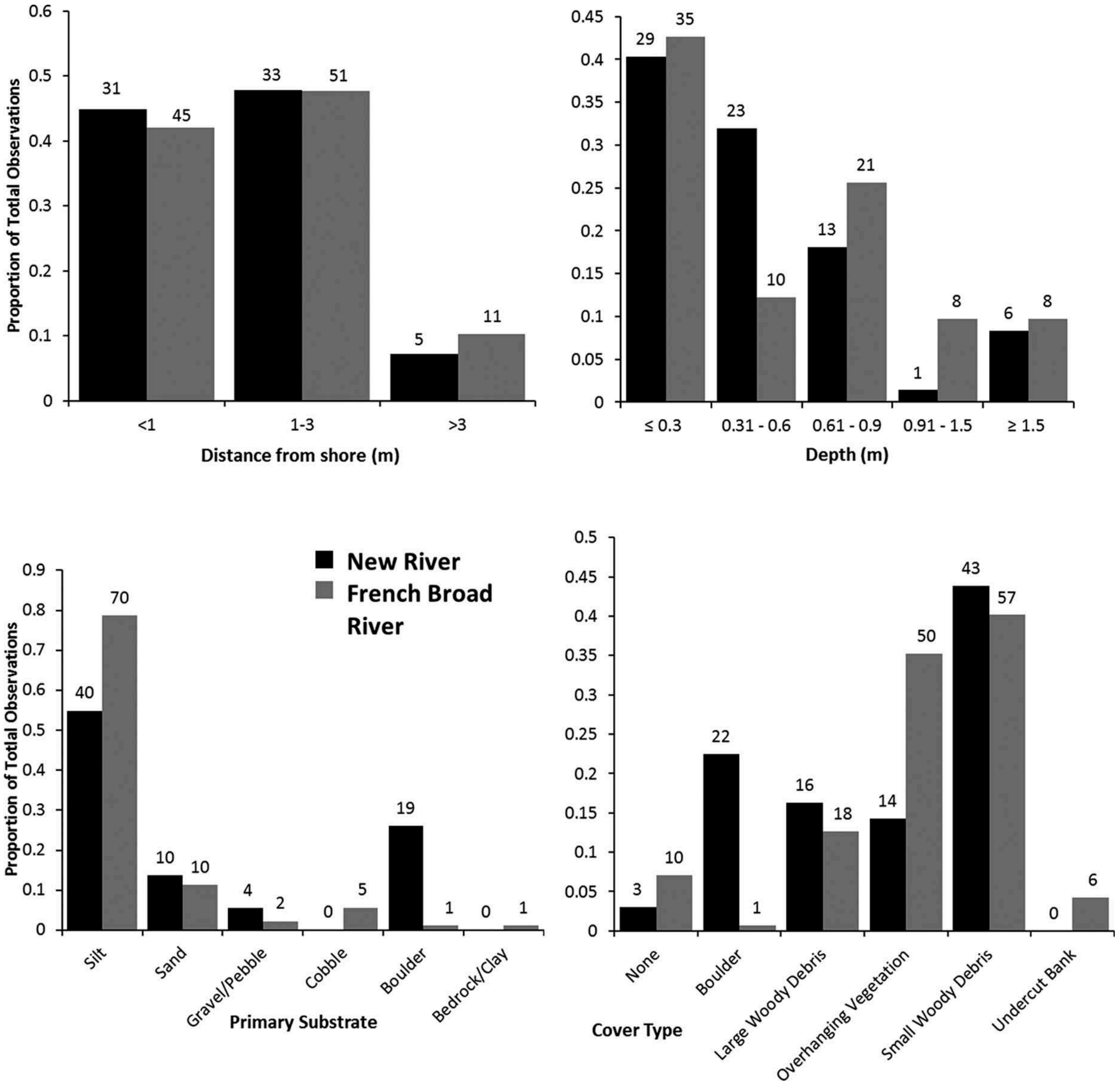

FIGURE 7. Comparison of habitat use by radio-tagged juvenile Muskellunge in the New River and French Broad River. The number of observations for each type of habitat is indicated above each bar.

DISCUSSION

We observed high mortality and dispersal of stocked age-0 Muskellunge in both study sites at 3 months poststocking. However, mortality and dispersal were higher in the New River than in the French Broad River. Habitat use was similar between the two systems except that fish in the New River were more associated with boulders as substrate and cover and were generally less associated with overhanging vegetation than fish in the French Broad River. If our results are representative of annual patterns in each river, then the higher mortality of stocked juvenile Muskellunge in the New River is likely inhibiting fishery success in that system. Even without high mortality, poststocking dispersal could compromise the success of stocking if the stocked fish do not remain where the fishery managers intended. Furthermore, habitat suitability may indirectly contribute to increased mortality and dispersal if the fish are more vulnerable to predators or if they are forced to search farther for suitable habitat.

Low survival of stocked fish is unlikely to be the only factor that limits the overall fishery success in our study systems, as the relatively high observed mortality rates are consistent with mortality that has been documented for successful, hatchery-supported Muskellunge fisheries in lentic systems. Wahl and Stein (1993) documented low survival (3–9%) through the first fall for stocked juvenile Muskellunge in three Ohio reservoirs supporting viable Muskellunge fisheries. Likewise, Margenau (1992) reported low overwinter survival (19%) for juvenile Muskellunge that were stocked during the fall and low summer survival (20%) for yearlings that were stocked during the spring in four northern Wisconsin lakes. In the only previous study of stocked juvenile Muskellunge survival within the southeastern United States, Warren (2013) observed low survival (21%) at 56 d poststocking for fish in the Collins River, Tennessee; that survival rate was lower than what we observed for fish in the New River (26%) and French Broad River (57%) at 56 d poststocking. However, Warren (2013) also found evidence of natural reproduction, so the contribution of stocking to the overall success of the Muskellunge fishery in that system is unclear.

Although our combined models estimated that the total overall survival at 3 months poststocking was 4–17% for juvenile Muskellunge in the New River and 25–56% for fish in the French Broad River, actual survival rates were probably closer to the lower bounds of those estimates, as it is likely that missing tags were due to mortality rather than to emigration (the lower bounds were produced by the "missing fish died" model). We searched long distances upstream and downstream beyond the tag detection sites that were farthest from the stocking locations (constituting 41% [66 km] of the total search area in the New River; 35% [41 km] of the total search area in the French Broad River), and no tags were detected in those extended areas, so it is unlikely that the disappearances were due to emigration. Furthermore, no fish was ever detected alive outside of the study areas, indicating that even if the Muskellunge did emigrate, their survival for the duration of the study period is doubtful. Combining this information with the substantial evidence of predation we observed leads to the conclusion that the missing tags were probably lost via fish consumption by predators, many of which (e.g., great blue heron and American mink) would have the potential to carry tags beyond the detection range of our receiver (100–400 m). Warren (2013) tracked two tagged juvenile Muskellunge to a single great blue heron, and 20% of her tags were recovered with frayed antennae, likely resulting from chewing by predators. Other studies have documented high rates of predation on stocked Muskellunge by North American river otters (Margenau 1993) and piscivores including black bass *Micropterus* spp. and Northern Pike *Esox lucius* (Carline et al. 1986; Hanson et al. 1986; Szendrey and Wahl 1996; Wahl et al. 2012). Furthermore, Hodgens et al. (2004) estimated that a great blue heron population (n = 227) consumed nearly 50,000 catchable-sized Rainbow Trout *Oncorhynchus mykiss* per year in a stocked Arkansas tailwater fishery; those authors reported that the birds were most successful when feeding in shallow waters (<0.2 m)—habitat that was frequented by juvenile Muskellunge in our study systems.

Biologists who wish to prevent high poststocking mortality may want to consider holding fish in the hatchery for a longer period prior to stocking. Studies have demonstrated that the stocking of larger, older spring yearlings (Larscheid et al. 1999) and fall yearlings (Margenau 1999) increases poststocking survival. Alternatively, managers could consider increasing the number of surviving fish simply by stocking more individuals. The annual stocking rate that would be needed to create a viable Muskellunge fishery could be estimated given survival at age and the desired size of the fishable population. In the absence of that information, we can make a rough approximation based on the current stocking rates and estimated poststocking survival of juvenile Muskellunge from the New and French Broad rivers. Because we know that stocking maintains a successful fishery in the French Broad River, we can use the estimated survival from this study and the number of Muskellunge currently stocked in that system to estimate the number of juveniles that would need to be stocked in the New River to compensate for the lower survival rates observed there. Based on our calculations, approximately 1,650 Muskellunge (or roughly 12 times the number of fish currently stocked) must be stocked in the New River to achieve the same number of fish per kilometer surviving for 3 months poststocking as in the French Broad River. However, it is unclear whether stocking more fish would maintain a successful fishery in the North Carolina portion of the New River, as downstream dispersal and density-dependent mechanisms may still inhibit successful recruitment.

Although high dispersal similar to what we observed was documented by Younk et al. (1996) for adult Muskellunge (average dispersal distance = 21.4 km for 920–1,210-mm fish) over a 3-year study period, high dispersal has not been reported in studies of juvenile Muskellunge. Warren (2013) noted that the maximum dispersal distance was only 9 km (and maximum "live" dispersal was only 1 km) by 56 d poststocking for juvenile Muskellunge in a Tennessee river; Hanson and Margenau (1992) reported a maximum dispersal of only 5.6 km by 34 d poststocking in two lentic systems in Wisconsin. It is unclear why we observed such high dispersal distances in our two study systems or why dispersal distances were greater in the New River than in the French Broad River. Because Muskellunge mortality was higher in the New River, there is a possible correlation between mortality and dispersal—a relationship that has been observed in other studies (e.g., Bettinger and Bettoli 2002; Aarestrup et al. 2005). However, the lack of difference in dispersal distance that we observed between fish that died and fish that did not die indicates that the linkage is not strong. Alternatively, the difference in dispersal could result from inherent differences in hydrology between the two rivers; the New River in North Carolina has a gradient of 2.3 m/km and is dominated by riffle–run habitat, whereas the upper French Broad River has a gradient of only 0.5 m/km with few riffle areas (Monaghan 1985). Based on the observed habitat selection patterns in relation to water velocity, stocked Muskellunge could be inclined to move downstream when surrounded by faster-flowing water. This explanation was also not supported by observations: we did not detect an increase in dispersal during or after high-flow events, and the nearshore habitat that the fish used most often likely provided adequate refuge from swiftly moving water during elevated flows. Nevertheless, the high dispersal and dam passage observed in the New River are additional factors that could hinder the stocking success of Muskellunge upstream of the North Carolina–Virginia border.

Finally, the habitats occupied by juvenile Muskellunge in our study—nearshore, shallow, low-velocity areas with high amounts of cover—suggest that these fish select similar habitats in both lentic and lotic systems. Hanson and Margenau (1992) found that tagged juvenile Muskellunge in a lentic ecosystem primarily selected relatively shallow water (<3 m) with sandy substrate and varying amounts of vegetation. In other studies, juvenile Muskellunge were observed to associate with moderate (20–60%) vegetative cover in shallow nearshore areas (Farrell and Werner 1999; Murry and Farrell 2007) and with coarse woody debris of moderate complexity in littoral areas (Wagner et al. 2015). Our PCA results provided further evidence that juvenile Muskellunge were selective in the type of habitat they used. However, the occurrence of the selected habitats was correlated, so the fish may not have been selecting for any specific parameter (distance to shore, depth, or water velocity) individually. The exception to this was percent cover, which was strongly selected by juvenile Muskellunge and was not significantly correlated with the other measured habitat variables. Generally, the pattern of habitat preference observed here appears to be consistent for Muskellunge across systems and throughout their life cycle (Cook and Solomon 1987).

Higher mortality of Muskellunge in the New River than in the French Broad River might be mediated by differences in habitat availability. Hanson and Margenau (1992) suggested that high survival of stocked juvenile Muskellunge was due to the availability of the aquatic vegetation, downed trees, and overhanging vegetation that were selected by the fish. Likewise, the upper portion of the French Broad River contains an abundance of overhanging vegetation and large woody debris, whereas available habitat in the North Carolina section of the New River is more limited to boulders and ridges of bedrock (Monaghan 1985). Compared with juvenile Muskellunge in the French Broad River, the fish in the New River associated less with overhanging vegetation in favor of small woody debris and boulders; this contrast in habitat use would likely render the stocked juveniles in the New River more susceptible to predation, especially from piscivorous birds like great blue herons.

Taken collectively, our results suggest (1) that high mortality and dispersal of juvenile Muskellunge immediately after stocking may contribute to the apparent failure of the Muskellunge fishery in the North Carolina portion of the New River; and (2) more broadly, that mortality and dispersal patterns are important considerations when Muskellunge are to be stocked in lotic systems. The high dispersal that we observed suggests that fishery managers should expect stocked Muskellunge to move downstream, and therefore it may be warranted to consider stocking sites upstream from the target fishery area. Poststocking dispersal requires careful consideration in systems like the New River, where dams are located downstream of stocking sites, because dam escapement would likely prevent recruitment of stocked fish to the upstream fishery. In addition, differences in habitat availability between the New and French Broad rivers may have indirectly contributed to mortality and dispersal differences, suggesting that habitat characteristics should also be a key consideration in future Muskellunge stocking decisions.

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