ABSTRACT

OWENSBY, DYLAN PATRICK. Mortality, Dispersal, and Habitat Use of Stocked Juvenile Muskellunge in Two Western North Carolina Rivers. (Under the direction of Dr. James A. Rice and Dr. D. Derek Aday).

Muskellunge *Esox masquinongy* is a highly sought-after sport fish native to the Tennessee River drainage of western North Carolina. High levels of water pollution led to its extirpation in North Carolina by the 1950s. After water quality began to recover with the implementation of the Clean Water Act, the North Carolina Wildlife Resources Commission (NCWRC) began a stocking program in the 1970s to reestablish this native species and provide viable Muskellunge fisheries in North Carolina. Although those efforts have resulted in an established Muskellunge fishery in areas such as the French Broad River, there is little evidence of success in North Carolina sections of the New River. Possible mechanisms inhibiting stocking success are unclear because there is relatively little information available on the juvenile life stage of this important sport fish, especially in the southern range of its distribution. This study aimed to address the perceived differences in recruitment to these two fisheries, and to provide additional information on the juvenile life stage of stocked juvenile Muskellunge. Specifically, we initiated a radio telemetry study to investigate dispersal, mortality, and habitat use by stocked juvenile Muskellunge and habitat suitability for them in these two systems. Fifty age-0, hatchery-reared Muskellunge (TL 282-307 mm) were tagged prior to stocking in the New River (fall 2013) and French Broad River (fall 2014). The fish were tracked on a bi-weekly basis in each study area for 3 months poststocking. Known survival of the tagged Muskellunge at the end of the study period was 4% on the New River and 29% on the French Broad River, and the overall survival probability was estimated to be 9% (4-17%) and 37% (25-56%) for the two rivers. High dispersal was observed, with maximum individual dispersal of 67.4 km (23.3 ± 16.6 km [mean $\pm$ SD]) on the New River and 55.5 km (8.8 ± 14.8 km) on the French Broad River. The maximum dispersal of fish known to be alive was 49.6 km (8.8 ± 12.2 km) on the New River and 35.1

km (4.7 ± 7.3 km) on the French Broad River. Habitat suitability analyses indicated that juvenile Muskellunge in the French Broad River selected nearshore, shallow areas with slow-slack water velocity, fine substrate and high amounts of cover from woody debris and overhanging vegetation. Information on the survival and behavior of stocked Muskellunge should be useful in the context of managing these fisheries.

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

by
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BIOGRAPHY

Growing up in the foothills of North Carolina, I always enjoyed spending my free time outdoors and on the water. After graduating from Freedom High School in 2007, I attended the University of North Carolina at Chapel Hill to study Environmental Sciences. When it was time to get serious thinking about a career, it was an obvious choice to combine my education with my enthusiasm for the outdoors and passion for ecological conservation in pursuing a higher degree studying freshwater fisheries ecology. Since landing my first fisheries job in Yellowstone National Park out of college, I have been fortunate to work alongside many enjoyable and compassionate colleagues that were integral in further developing my interest in aquatic sciences. My time at North Carolina State University has equipped me with the education and experience necessary to complete the next step of my career in the field of freshwater ecology.

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Introduction

Muskellunge *Esox masquinongy* is an economically important sport fish that is popular with anglers due to 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 drainages of the Ohio and Mississippi rivers as well as drainages of the Great Lakes and Hudson Bay (Crossman 1978; Kerr 2011). In the southern end of its distribution early reports documented Muskellunge as a species native to the Tennessee River drainage of North Carolina (Jordan 1889), but it was extirpated from the state 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 fry and fingerling Muskellunge in several western North Carolina waters in 1970 with the goal of preserving this native species and creating a trophy fishery (Monaghan 1985; Borawa 1990). However, success of this stocking program has varied widely among North Carolina river systems.

The success of fish stocking programs is generally variable and typically depends on complex ecological interactions that can be system-specific (e.g., Gunn et al. 1987; Wahl 1999; Henry et al. 1998). Understanding these interactions as well as the life history of the stocked species is critical to predicting and facilitating stocking success. 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; Wagner and Wahl 2011) and data are especially lacking in the southern range 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 only been one study of stocked juvenile Muskellunge in the Southeast (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 following release could significantly affect the overall success of hatchery-supported fisheries. Studies documenting poststocking 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 higher mortality (70-97%) for fish stocked elsewhere (Carline et al. 1986; Margenau 1992; Wahl and Stein 1993; Warren 2013). Taken collectively these studies suggest that survival of stocked Muskellunge is system-specific. It is also important to note that these studies have focused on lentic systems, so their relevance to stocking success in flowing waters is unknown.

Poststocking mortality is often connected to other important drivers of stocking success such as dispersal. It has been documented with many fish species that 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 such as Muskellunge that are prone to dam escapement (Wolter et al. 2013). Although high dispersal rates have so far not been documented for juvenile Muskellunge, emigration in lotic systems could be a contributing factor to limited stocking success in these fisheries.

An additional mechanism that might impede stocking success is the availability of suitable habitat (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 species of fish such as Muskellunge that are known to exist in low population densities (Dombeck 1984; Hewitt et al. 2009; Kerr et al 2011) and are selective in the types of habitat they use (Hanson and Margenau 1992; Wagner et al. 2015). Further, habitat suitability can be directly linked to both dispersal and mortality, contributing to increased dispersal if fish are required to search for suitable locations or to 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 and French Broad rivers, both of which have been stocked on an annual or biannual basis for more than 30 years (J. C. Borawa, unpublished NCWRC internal report). Angler reports and routine sampling efforts by the NCWRC indicate that a viable Muskellunge fishery has been established in the French Broad River, but similar success has not been experienced 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 regarding factors affecting stocking success in lotic systems, we evaluated the fate of stocked juvenile Muskellunge in each system. Specifically, we used radio telemetry to estimate the mortality, dispersal and habitat use of stocked, age-0 Muskellunge in the New and French Broad rivers, and we estimated habitat selection by comparing habitat use to habitat availability on the French Broad River. Radio telemetry is a commonly used method to study behavioral patterns of 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 a species of fish that can otherwise be difficult to sample (Kapuscinski et al. 2012). A robust assessment of stocked juvenile Muskellunge in contrasting lotic

systems should provide fishery biologists with better information for predicting 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 that flows north through North Carolina and Virginia before converging with the Kanawha River in West Virginia. The river drains 1,950 km² in NC (Monaghan 1985), and the general water quality within the basin is characterized as good (NCWAP 2005). Since 1978, the NCWRC has stocked approximately 150 Muskellunge annually or biannually over approximately 20 km of the South Fork and main-stem portions of the New River upstream of the Virginia border (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 river in Virginia (Figure 1).

The French Broad River flows north through western North Carolina for 188 km between its headwaters near Rosman, NC and the Tennessee border, encompassing a watershed that drains 7,300 km² (Monaghan 1985). Based on hydrological conditions the French Broad River in North Carolina is best considered as two sections. The upper, 87-km section between Brevard and Asheville, NC is a sinuous, low gradient (0.5m/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; NCWAP 2005). The upper section of the river contains habitat that is considered more suitable for Muskellunge with an abundance of fallen trees and deep pools, while the lower section of the river contains riffle-run characteristics 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 biannually

over 174 km between the Tennessee border and Brevard, with approximately two-thirds of the fish being stocked in the upper section of the river (NCWRC, unpublished data). Our study area included approximately 65 km of the upper French Broad River, where the majority of juvenile Muskellunge have traditionally been stocked (Figure 2).

Fish Tagging

We used radio telemetry to quantify mortality, dispersal, and habitat use of hatchery-reared Muskellunge during the first 3 months after stocking. Fifty age-0 Muskellunge to be stocked in the New River were tagged in October 2013 and 50 fish to be stocked in the French Broad River were tagged in October 2014 (Table 1). A radio transmitting tag was surgically implanted in each fish at the Table Rock Fish Hatchery in Morganton, North Carolina, following methods outlined by Wagner et al. (2011). Surgeons wore a new pair of sterile latex surgical gloves for each surgery, and surgical tools were either sterilized in an autoclave or disinfected in glutaraldehyde for at least 15 minutes and rinsed with deionized water prior to use (Wagner et al. 2011). Glutaraldehyde was also used to disinfect radio tags overnight prior to surgical implantation. We used Advanced Telemetry Systems (ATS, Isanti, MN) F1440 radio transmitting tags (9x19x7 mm; 3.3 g in air [$\leq 4\%$ of body weight], 200-mm trailing whip antenna, 30 pulses per minute, 316-d active life).

Muskellunge were anesthetized in an aerated, 70-L induction tank containing 50 mg/L of tricaine methanesulfonate (MS-222) buffered with sodium bicarbonate (Hanson and Margenau 1992). After symptoms of disequilibrium were observed fish were transferred to a v-shaped trough lined with a plastic-membrane protective barrier. The fish were kept anesthetized during the surgery process (approximately 7 minutes) by constantly pumping a recirculating maintenance dose (30 mg/L) of buffered MS-222 over their gills. Using a sterile scalpel an incision approximately the width of the tag (9 mm) was made anterior to the pelvic girdle along the linea alba (Wagner et al. 2011). The tag antenna was inserted through the incision, pulled through the body cavity over the

pelvic girdle and out through the abdominal wall posterior to the pelvic girdle using the shielded needle technique (Ross and Kleiner 1982) with a size 2, 3/8 circle reverse cutting needle. Then the tag was placed in the body cavity parallel and posterior to the incision and the incision was closed using two simple interrupted sutures (Wagner et al. 2011) of absorbable monofilament suture material with a 3-0, 3/8 circle reverse-triangle needle. After surgery, each fish was placed in a 70-L recovery tank containing hatchery water treated with Stress Coat[®] (Aquarium Pharmaceuticals, Franklin, TN) until it regained equilibrium, then was transferred to a circular, flowthrough holding tank containing 315 L of hatchery water (Harnish and Brown 2010). Temperature in all induction, surgery, and recovery tanks was monitored and water was replaced as needed to maintain constant temperatures. Radio-tagged fish were allowed to recover for 4 d at the hatchery before being transported in a hatchery truck 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 in fall 2013 using 15 juvenile Muskellunge tagged with dummy tags and 15 control fish. 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 and weight as a functioning radio tag. Control fish were treated the same as the 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, after which they were collectively retained in a circular holding tank containing 315 L of hatchery water and fed live minnows for 30 d in the hatchery, where 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 incision sites could be inspected internally and externally.

Telemetry

At each river the tagged fish were divided equally among three stocking sites separated by 16 km between the most upstream and downstream locations (Figures 1 and 2; Appendix A). One fish was censored from data analysis at the French Broad River because we noticed that the tag was not functioning properly upon stocking. Fish were tracked at each study site using an ATS R410 receiver with a 3-element folding yagi antenna. The frequency range of all tags used at each study site (149-150 MHz) was continuously scanned while floating the river 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 using a handheld Global Positioning System (GPS) unit (accuracy 2-8 m).

On the New River the study area (56 km) was split into four approximately even sections that were tracked at least bi-weekly. Areas upstream and downstream of the study area were also intermittently searched in an attempt to locate tags that disappeared during the study period, which generated a total search area of 160 km (Figure 1). The French Broad River study area (65 km) was also split into four approximately even sections that were tracked at least bi-weekly. Additional sections of the river upstream and downstream of this study area were also searched intermittently, generating a total search area of 116 km (Figure 2).

Mortality

An encounter history was developed by assigning a fate (alive, mortality, or missing) to each fish for each bi-weekly tracking period. We assumed mortality of a fish 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 alive 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 interval when it was initially undetected. To calculate the probability of

stocked juvenile Muskellunge surviving each study period we entered the encounter history of each fish into Program MARK 7.2 (Gary White, Colorado State University). Survival probabilities were estimated using the known-fate model in Program MARK with seven (bi-weekly) encounter occasions. The known-fate model is ideal for telemetry studies when the fate of most animals is known throughout the study period, the detection probability is close to one, and 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 fate 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 the interval in which they disappeared until the end of the study period) from analysis. A second model ('missing fish died') treated missing fish as if they had actually died (in the interval in which they disappeared), and a third model ('missing fish survived') treated missing fish as if they 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 (bi-weekly) and constant survival probabilities. The best model for each design was selected using the Akaike Information Criterion (AIC) provided in Program MARK (Cooch and White 2014).

Dispersal

Tagged fish locations were analyzed in ArcGIS 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 an alive encounter or mortality). Any tags that were never detected or disappeared before the end of the study period were censored from this analysis. We

also measured 'alive 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 this analysis.

Habitat Use, Availability, & Preference

Habitat use data were collected while actively tracking fish in each study area. When a fish was detected, surface velocity and depth were measured at its observed location, and substrate, percentage of cover and cover type were estimated for a 1-m² area centered at its 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). On the New River surface velocity was visually estimated and assigned to one of four bins (<0.09, 0.09-0.15, 0.16-0.23, and >0.23 m/s). Primary substrate type was recorded based on a modified Wentworth scale (silt: <0.059 mm, sand: 0.06-1 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 as the amount of structure on the bottom, in the water column, or within 1.5 m above the water surface within a 1-m² area around the fish. Percent cover was not recorded on the New River.

Habitat availability data were only collected on the French Broad River. There, available habitat was quantified by sampling habitat characteristics along transects within representative reaches of the upper French Broad River. All habitat availability data were collected in summer of 2014 under base flow conditions. We selected representative reaches within each section of the study area (described above) 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 per reach (Simonson et al. 1994). Habitat observations (N = 858) were made using a 1-m² quadrat at equidistant intervals along each

transect (at every 2 m for the upper section, 3 m for middle sections, and 4 m for the lower section) for approximately 10 intervals per transect, with the initial observation beginning within 1 m of the river-left shoreline. The habitat parameters that we measured included depth, mean water column velocity (measured at 60% of water column depth) using a Marsh-McBirney 2000 digital flowmeter, primary substrate, 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-m² quadrat, while substrate, percent cover, and cover type were observed for the entire quadrat area. Habitat use and availability data were grouped into bins for each parameter during analysis.

To describe habitat that stocked age-0 Muskellunge selected, we compared habitat use to habitat availability on the French Broad River using univariate and multivariate analyses. Univariate analysis allowed us to describe the individual habitat characteristics (e.g., depth, cover) that fish selected, while multivariate analysis was used to describe combinations of habitat characteristics that were correlated with each other to form any habitat associations that fish were selecting or avoiding (Bovee 1986; Midway et al. 2010). We used all habitat use observations in our analysis, except that we censored any observations that were made within 10 d after another observation for each individual fish, thereby allowing each Muskellunge a sufficient amount of time to select alternate habitats between observations. To calculate univariate habitat suitabilities 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 each habitat parameter, such that the most suitable habitat was given a normalized suitability of 1 (Hewitt et al. 2009; Midway et al. 2010).

To determine whether fish were selecting locations based on correlated habitat characteristics, we used a Principal Component Analysis (PCA) for the five numerical habitat

parameters (distance from shore, depth, water velocity, substrate, and percentage of cover). Not all habitat parameters could be measured at each availability or Muskellunge-use observation location; for this analysis we only included locations for which all five habitat parameters were measured. We used the PCA to extract linear descriptions based on the correlation matrix from these combined habitat parameters using Program R 3.1.3 (Vienna, Austria) (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. Component loadings for the two components that explained most of the variation in the data were then used to describe habitat use compared 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%) on the French Broad River than the New River (4%). There were 39 confirmed mortalities (78%) on the New River and 22 confirmed mortalities (45%) on the French Broad River. We recovered 26 tags (52%) on the New River, 9 (18%) of which were found on land. On the French Broad River 17 tags (35%) were recovered, all in the water. Throughout the study periods there were nine fish (18%) that eventually disappeared on the New River and 12 fish (24%) that disappeared on the French Broad River. On the New River all tags were located at least once during the 86-d study period and nine fish were located between 10-14 times, whereas on the French Broad River all but three tags were located at least once during the 89-d study period and seven fish were located between 10-12 times (Appendices B and C). There was no tag loss or

mortality for the dummy-tagged or control fish at the end of the 30-d tag retention study and we found that all sutures remained intact and incisions were completely healed with only minor inflammation at suture sites in a few of the fish.

Using our encounter histories (Appendices D and E) 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, $Z_{daily} = 0.024$) at 3 months poststocking on the New River, and a survival probability of 0.370 (SE 0.08, $Z_{daily} = 0.010$) on the French Broad River. However, depending on which ‘missing fish’ model (see Methods) we used, the true survival probability ranged from 0.035-0.173 on the New River and 0.253-0.558 on the French Broad River (Table 3). A constant survival rate for each bi-weekly tracking period best described each model for the New River and the ‘missing fish censored’ model on the French Broad River. However, the ‘missing fish died’ and ‘missing fish survived’ models on the French Broad River were best described with lower survival rates during the first tracking period, and then with relatively constant survival rates thereafter (Figure 3).

We found evidence of predation on stocked Muskellunge in both rivers, where great blue heron *Ardea herodias*, river otter *Lontra canadensis*, and mink *Neovison vison* were seen frequently. On the New River, one tag was tracked directly to a great blue heron and 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 found on shore adjacent to avian feces, while another tag was found enveloped in pieces of a crayfish shell next to an apparent otter den. On the French Broad River, two tags were found on separate occasions below a log that was covered in avian feces and feathers. Also, multiple tags were collected with frayed antennae, consistent with having been gnawed on by mammals.

Dispersal

We observed high dispersal in both systems (Figures 1 and 2), but dispersal was nearly twice as high on the New River as on the French Broad River. The 'maximum dispersal' for all tags averaged 23.3 km on the New River (maximum = 67.4 km, N = 41, SD = 16.6) and 8.8 km on the French Broad River (maximum = 55.5 km, N = 39, SD = 14.8). When only considering live encounters, 'alive dispersal' averaged 10.1 km on the New River (maximum = 49.6 km, N = 50, SD = 12.2), and 4.7 km on the French Broad River (maximum = 35.1 km, N = 49, SD = 7.3) (Figure 4). Most of the dispersal was downstream; the maximum upstream dispersal observed was 16.4 km on the New River and 11.0 km on the French Broad River.

Additionally, at only 13 d poststocking on the New River we observed 15 tags (30%) below Fields Dam in Mouth of Wilson, VA. By the end of the study period we located 20 tags (40%) beyond this dam, which is 5.7 km below the Virginia border and 12.7 km from our lowest stocking site. At approximately 4 m in height, the dam would likely inhibit emigrating juvenile Muskellunge from returning upstream.

Habitat Use and Selection

On the French Broad River we collected 115 habitat use observations from 33 fish (1-7 observations per fish). Due to the continuously shrinking sample size as fish died or disappeared during the study period, there were some fish that were observed more often than others. However, habitat use observations for each category were not dominated by observations from a small number of fish observed many times, but were distributed broadly among fish observed different numbers of times (Figure 5). 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). While we found that 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 habitats they occupied (Figure 6). They tended to select nearshore (<3 m from the bank), shallow (≤ 0.9 m), low-velocity (≤ 0.23 m/s) habitats, even though the majority of the river was comprised of offshore (>3 m from the bank), deeper (>0.9 m), swifter (>0.23 m/s) areas. The locations that they selected were also dominated by silt and sand rather than coarse substrate. Finally, tagged juvenile Muskellunge generally selected habitat locations with high amounts of cover ($\geq 40\%$), mostly made up of overhanging vegetation, woody debris, and undercut banks.

Principle Component Analysis indicated that there was correlation among distance to shore, depth, and substrate. The first principal component explained 61% of the variance in the combined habitat data, and was driven by distance to shore, depth and flow. The second principal component explained an additional 15% of the variance in the combined habitat data and was driven by substrate type (Table 4). The first principal component specifies that more negative values correspond to offshore areas that are correlated with deeper, faster moving water and larger substrate, while less negative or positive values correspond to shallow, nearshore areas with slower moving water. The second principal component indicates that positive values are associated with small substrate and, conversely, that negative values are associated with larger substrate (Figure 7). Results of the K-S test show that habitat used by juvenile Muskellunge was significantly different than habitat availability in the two-dimensional PCA space (Table 4).

On the New River we collected 93 habitat use observations from 37 fish. In many respects, habitat used by these tagged juvenile Muskellunge was similar to that on the French Broad River (Figure 8); fish occupied nearshore (<3 m from shore), shallow (<1 m) areas of slow-to-slack water velocity (<0.15 m/s). However, Muskellunge on the New River were less reliant on silt substrate than in the French Broad River, and instead were found in association with boulders. Likewise,

these fish were associated more with boulders as cover type, and less with overhanging vegetation than the fish on the French Broad River.

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. We also observed similar habitat use between both systems, except that fish on the New River used areas associated more with boulders as substrate and cover type, and were generally less associated with overhanging vegetation than fish on the French Broad River. Given that stocking maintains a successful fishery on the French Broad River, it appears that the higher mortality of stocked juvenile Muskellunge that we observed might inhibit the overall Muskellunge fishery success on the New River in North Carolina. Poststocking dispersal could also influence stocking success by effectively shifting the fishery away from stocking locations. Further, habitat suitability may indirectly contribute to increased mortality and dispersal if fish are more vulnerable to predators or forced to search farther for preferred habitat.

Low survival of stocked fish is unlikely to be the only factor limiting overall fishery success in our systems, as our results are consistent with documented mortality in 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. The authors also noted that most of the mortality occurred in the first 2 months poststocking, making their results comparable to the low survival (9%) that we observed on the New River over 3 months. Similarly, survival rates closer to what we observed on the French Broad River (37%) were measured in stocked impoundments in Ohio, where only approximately 30% of juvenile Muskellunge survived after 50 d in 16 stocking trials (Carline et al. 1986). A study on four northern Wisconsin lakes found low overwinter survival (19%) for juvenile Muskellunge stocked in

the fall and low summer survival (20%) for yearling Muskellunge stocked in the spring (Margenau 1992). The only previous study of stocked juvenile Muskellunge survival in the Southeast found low survival (21%) at 56 d poststocking for fish in the Collins River in Tennessee (Warren 2013), which was lower than we observed on the New (26%) or French Broad (57%) rivers at 56 d poststocking. However, the author also found evidence of natural reproduction, so stocking contribution to the overall fishery success in that system is unclear. In sum, these investigations provide evidence that factors other than, or in addition to, high mortality rates of stocked juvenile Muskellunge currently prevent the development of a successful Muskellunge fishery in North Carolina sections of the New River.

Although our combined models estimated total overall survival at 3 months poststocking of 4-17% on the New River and 25-56% on the French Broad River, actual survival rates are likely closer to the lower bounds of these estimates because of the likelihood that missing tags were due to mortality rather than emigration (the lower bounds were produced by the 'missing fish died' model). We searched long distances upstream and downstream beyond the tags encountered farthest from the stocking locations (constituting 41% and 35% of the total search areas, or 66 km and 41 km, on the New and French Broad rivers) where no tags were ever detected, so it is unlikely that disappearances were due to emigration. Also, no fish were ever detected alive outside of the study areas, indicating that even if fish did emigrate it is doubtful that they survived the duration of the study period. Combining this information with the substantial evidence of predation we observed leads to the conclusion that missing tags were likely lost to consumption by predators, many of which (e.g., great blue heron, mink) would have the potential to carry tags beyond the detection range of our receiver (100-400 m).

High mortality rates of juvenile Muskellunge in hatchery-supported fisheries are often attributed to predation. 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 predation on stocked Muskellunge by 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). Also, Margenau (1993) reported juvenile Muskellunge predation by river otters within net enclosures in Wisconsin Lakes. Although it has not been formally documented, Margenau (1992) suggested that cannibalism by adult muskellunge is also likely to occur. Further, 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, and that fish similar in size to the juvenile Muskellunge stocked in North Carolina made up more than 60% of the total biomass of their diet. The study also found that great blue herons are most successful when feeding in shallow waters (<0.2 m), habitat that was frequented by juvenile Muskellunge in our study systems. Investigators have explored the notion that exposing hatchery-reared fish to predators or predator stimulation prior to stocking could enhance survival. Although this approach has proven effective in some species (Olla and Davis 1989), it failed to impact juvenile Muskellunge survival (Margenau 1993; Wahl et al. 2012).

Stocking larger fish has been a common strategy for attempting to enhance poststocking survival of juvenile Muskellunge (Margenau 1999). However, literature reports of survival in relation to size are equivocal. A study from Johnson and Margenau (1993) documented 39% higher survival for large (263 mm average) than small age-0 juveniles (202 mm average) in two Wisconsin lakes. Larscheid et al. (1999) found that Muskellunge stocked in a northwestern Iowa lake had higher survival if the fish were held in a hatchery and stocked in spring, as opposed to age-0 juveniles stocked in fall. However, the authors also provide evidence that the length of fish at stocking might not have a significant influence on the overall contribution to the fishery, as a large

cohort of smaller stocked Muskellunge (152 mm average; approximately one-half the size of fish stocked in our study), produced one of the most successful year classes in that lentic system.

Margenau (1999) also studied survival of yearling Muskellunge stocked in the fall (age 18 months, 511 mm average) and found evidence to suggest that the older fish survived better than spring yearlings, with survival to age 5 estimated to be as high as 76% in one experimental lake. Due to increased costs of retaining fish in the hatchery for longer grow-out periods and the equivocal results reported by other studies, the benefits of stocking older, larger Muskellunge to enhance poststocking survival seem uncertain.

Alternatively, managers may want to consider increasing the number of surviving fish simply by stocking more fish. The annual stocking rate 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 using the current stocking rates and estimated poststocking survival 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 fish that are currently stocked in the river to estimate the number of Muskellunge that would need to be stocked in the New River to compensate for the lower survival rates that we observed there. Using this method, approximately 1,650 fish (or roughly 12 times the number of fish currently stocked) would need to be stocked in the New River to achieve the same number of fish/km surviving 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 may still inhibit successful recruitment.

Although high dispersal similar to what we observed has been documented for adult Muskellunge (21.4 km average for 920-1,210 mm fish) over a 3-year study period by Younk et al

(1996), high dispersal has not been found in other juvenile Muskellunge studies. Dispersal of juvenile Muskellunge stocked in a Tennessee River was low, with a maximum documented dispersal of only 9 km by 56 d poststocking, and with an 'alive dispersal' distance of only 1 km (Warren 2013). Juvenile Muskellunge stocked in two lentic systems in Wisconsin only dispersed a maximum of 5.6 km by 34 d poststocking (Hanson and Margenau 1992). It is not clear why we observed such high dispersal distances in our two study systems. Although our study periods (approximately 86 d) were much longer than in Hanson and Margenau (1992) and Warren (2013), the 'alive dispersal' that we observed was still much higher after 6 weeks of tracking the fish; we found average 'alive dispersal' to be 9.3 and 4.7 km (50 and 35 km maximum) on the New and French Broad rivers at only 42 d poststocking.

It is also unclear why we observed longer dispersal distances in the New River than in the French Broad River. Because mortality was higher on the New River than the French Broad 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 a difference in dispersal distance that we observed between fish that died and fish that did not does not suggest a strong linkage. 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 with riffle-run dominated characteristics, whereas the upper French Broad River has a gradient of only 0.5 m/km with few riffle areas (Monaghan 1985), and based on the habitat selection patterns that we observed related to water velocities, stocked Muskellunge could be inclined to move downstream when surrounded by faster-flowing water. However this theory was not supported by observations during high flow events, as we did not find an association between elevated flow and increases in dispersal. During the study periods there were two high-flow events on the New River ($>2,000 \text{ ft}^3/\text{s}$ at USGS site 03161000) and three high-flow events on

the French Broad River ($>3,000 \text{ ft}^3/\text{s}$ at USGS site 03443000; U.S. Geological Survey 2015). We did not detect any increase in dispersal or mortality events during or immediately following elevated flows. The nearshore habitat areas that fish were most often using would likely provide adequate refuge from swift moving water during such events. Regardless, the high dispersal and dam passage observed on the New River are additional factors that could hinder stocking success upstream from the North Carolina-Virginia border in this system.

Finally, the habitats that stocked juvenile Muskellunge occupied in our study - nearshore, shallow, low velocity, with high amounts of cover – suggest that juvenile Muskellunge select similar habitats in both lentic and lotic systems. In a lentic ecosystem, Hanson and Margenau (1992) found that tagged juvenile Muskellunge primarily selected relatively shallow water ($<3 \text{ m}$) with sandy substrate and varying amounts of vegetation, despite the majority of available habitat existing in deeper areas without vegetation. In studies of native age-0 Muskellunge in backwater bays of the St. Lawrence River near Lake Ontario, Murry and Farrell (2007) and Farrell and Werner (1999) found that fish were associated with moderate (20-60%) vegetative cover in shallow, nearshore areas where prey fish were abundant. Further, Wagner et al. (2015) found that age-2 juvenile Muskellunge selected for coarse woody debris of moderate complexity in littoral habitat areas in an Illinois reservoir. Also, our PCA results provide further evidence that juvenile Muskellunge were selective in the type of habitat they used. However, occurrence of the selected habitats was correlated, so Muskellunge may not have been selecting for any specific parameter (distance to shore, depth, or water velocity) individually. The exception to this would be percent cover, which was strongly selected by juvenile Muskellunge and was not correlated with the other habitat variables. Generally, the pattern of habitat association that we observed appears to be consistent for Muskellunge across systems and throughout their life cycle (Cook and Solomon 1987).

The higher mortality observed on the New River compared to the French Broad River might be mediated by differences in habitat availability. Hanson and Margenau (1992) suggested that high survival of stocked juvenile Muskellunge in their study could have been due to the availability of aquatic vegetation, downed trees, and overhanging vegetation that the fish selected. Likewise, the upper portion of the French Broad River contains an abundance of large woody debris, whereas available habitat in the North Carolina sections of the New River is more limited to boulders and ridges of bedrock (Monaghan 1985). Compared to the juvenile Muskellunge on the French Broad River, the fish on the New River associated less with overhanging vegetation in favor of small woody debris and boulders; this contrast in habitat use would likely render stocked juvenile Muskellunge on the New River more susceptible to predation, especially from avian predators like great blue heron. This difference in cover or structure type use is likely due to habitat availability differences; although we did not quantitatively assess habitat availability on the New River, we noticed less overhanging vegetation and large woody debris on the New River than on the French Broad River. Selectivity by Muskellunge in the types of habitat that they use is supported by circumstantial evidence of habitat avoidance on the French Broad River, where there were no fish or tags located in a 2.3 km stretch of river downstream from the second stocking site. Although habitat availability was not quantified in this section of the river, we noticed that it is dominated by more riffle/run characteristics similar to the New River, with fewer deep pools and less overhanging vegetation or large woody debris. Because there were fish stocked upstream and downstream from this area that were located after moving through in both directions, it appears as if the tagged Muskellunge avoided this section in favor of upstream and downstream areas containing more suitable habitat.

Taken collectively, our results suggest that high mortality and dispersal of juvenile Muskellunge immediately following stocking may contribute to the apparent failure of the New River Muskellunge fishery in North Carolina upstream from the Virginia border. The high dispersal

that we observed suggests that fishery managers should expect stocked fish to move downstream, and it may therefore be warranted to consider stocking sites upstream from the actual desired fishery areas. Poststocking dispersal requires careful consideration in systems similar to the New River, where dams are located downstream of stocking sites, because dam passage 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. Fishery managers should therefore carefully consider concentrating stocking efforts in lotic systems with habitat suitable for juvenile Muskellunge.

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Table 1. Sample size, mean, standard deviation, and range for total length and weight of age-0 Muskellunge used in each study site and in the tag retention study.

	N		Mean	Standard Deviation	Range
New River	50	TL (mm)	282.2	12.7	255-325
		Weight (g)	116.7	19.0	82-186
French Broad River	50	TL (mm)	306.5	12.7	277-335
		Weight (g)	138.7	19.5	101-183
Dummy-tagged	15	TL (mm)	289.9	13.7	270-323
		Weight (g)	126.1	21.5	98-178
Control	15	TL (mm)	275.9	13.7	252-298
		Weight (g)	105.9	19.2	78-146

Table 2. Descriptions of cover type categories used for habitat availability and use observations.

Cover Type	Description
None	No cover observed
Boulder	One or more boulder
Emergent Vegetation	Aquatic macrophyte growing from the substrate to beyond the surface of the water
Large Woody Debris	Woody structure >100 mm in diameter and >1 m in length, or combination of woody structure >50 mm in diameter and small sticks, leaves, or other types of submerged or floating debris
Overhanging Vegetation	Brush, tree, limb, or grass <1.5 m above water surface
Small Woody Debris	More than one of sticks, leaves, roots, or other types of submerged or floating debris <25 mm in diameter and <300 mm in length, or a single woody structure >25 mm in diameter and >300 mm in length

Undercut Bank

Horizontal protrusion of bank extending >300 mm away from shore at the surface of the water, or within the water column

Table 3. Survival probabilities for juvenile age-0 Muskellunge stocked in the New and French Broad rivers estimated from Program MARK.

	Survival Probability	Standard Error	95% Confidence Interval	Z_{daily}
New River ('Missing Fish Censored')	0.093	0.04	0.04 - 0.20	0.0010
French Broad River ('Missing Fish Censored')	0.370	0.08	0.23 – 0.54	0.0048
New River ('Missing Fish Died')	0.035	0.02	0.01 – 0.09	0.0004
French Broad River ('Missing Fish Died')	0.253	0.07	0.15 – 0.40	0.0030
New River ('Missing Fish Survived')	0.173	0.05	0.09 – 0.30	0.0020
French Broad River ('Missing Fish Survived')	0.558	0.08	0.41 – 0.70	0.0084

Table 4. Retained component loadings (based on a correlation matrix) from principal component analysis for the French Broad River availability (N) and use (n) data. Significant loadings are shown in bold. The K-S test indicates that the use and availability distributions were significantly different.

N = 842, n = 70	Component 1	Component 2
Distance From Shore	-0.51	0.18
Depth	-0.46	0.38
Water Velocity	-0.50	-0.02
Primary Substrate	-0.35	-0.90
% Cover	0.40	-0.15
Variance Explained	61%	15%
K-S Test (D Statistic)	0.68	0.35
K-S Test (P Value)	<0.001	<0.001

Figure 1. Study area, total search area, stocking sites and tag locations of radio-tagged Muskellunge on the New River during fall of 2013.

Figure 2. Study area, total search area, stocking sites and tag locations of radio-tagged Muskellunge on the French Broad River during fall of 2014.

Figure 3. Cumulative survival estimates for juvenile Muskellunge stocked in the New (NR) and French Broad (FBR) rivers from Program MARK based on three different treatments of fish that disappeared during the study period: censored, treated as mortalities, or considered alive throughout the study period.

Figure 4. Comparison of 'alive dispersal' for juvenile Muskellunge between the New and French Broad rivers.

Figure 5. The total number of times individual fish were observed for each habitat parameter on the French Broad River.

Figure 6. Habitat suitabilities for juvenile Muskellunge in the French Broad River. Sample sizes denoted by N = total availability observations and n = total use observations.

Figure 7. First and second Principal Component Analysis scores for juvenile Muskellunge habitat use and availability on the French Broad River, with descriptions of significant component loadings for each axis. The principal component loadings and sample sizes are given in Table 4.

Figure 8. Comparison between habitat used by juvenile Muskellunge on the New and French Broad rivers. Number of observations for each type of habitat indicated above bars. Note: surface velocity was measured quantitatively on the French Broad River and visually estimated on the New River.

APPENDICES

Appendix A. Locations of the six stocking sites used in the New (fall 2013) and French Broad (fall 2014) rivers.

Site	River	Latitude (N)	Longitude (W)
Upper	New River	36° 29' 56.87"	81° 20' 20.87"
Middle	New River	36° 30' 57.64"	81° 19' 42.31"
Lower	New River	36° 33' 35.60"	81° 21' 09.32"
Upper	French Broad River	35° 13' 03.35"	82° 43' 12.02"
Middle	French Broad River	35° 15' 04.28"	82° 41' 57.53"
Lower	French Broad River	35° 16' 10.11"	82° 38' 10.12"

Appendix B. Individual frequency numbers of tags, length, weight, stocking site, number of live detections, and fate of juvenile Muskellunge at 3 months poststocking on the New River. Fish were stocked on October 11, 2013.

Tag	Frequency (MHz)	Length (mm)	Weight (g)	Stocking Site	Live Detections	Fate	Comments
	150.001	283	120	Middle	2	Recovered	
	150.010	320	173	Upper	10	Mortality	
	150.022	255	82	Lower	0	Mortality	
	150.031	279	118	Middle	0	Recovered	Recovered on land
	150.041	270	96	Upper	7	Disappeared	
	150.051	297	126	Upper	1	Disappeared	
	150.061	280	108	Middle	5	Mortality	Tracked to live great blue heron
	150.069	275	100	Lower	3	Recovered	Fish dead on bottom
	150.080	293	147	Lower	0	Recovered	Recovered on land
	150.090	276	106	Upper	5	Mortality	
	150.101	272	110	Upper	2	Disappeared	
	150.112	271	107	Middle	8	Disappeared	
	150.121	266	93	Upper	4	Recovered	Recovered on land
	150.131	286	116	Lower	1	Recovered	Recovered outside of study area
	150.141	279	109	Middle	5	Disappeared	
	150.152	295	124	Upper	3	Mortality	
	150.161	282	112	Middle	0	Mortality	

Appendix B. Continued

Tag	Frequency (MHz)	Length (mm)	Weight (g)	Stocking Site	Live Detections	Fate	Comments
150.171	290	123	Lower	2	Mortality		
150.181	277	105	Upper	3	Mortality		
150.191	271	94	Lower	1	Mortality		
150.201	268	102	Middle	0	Mortality		
150.211	289	124	Middle	0	Recovered		
150.221	276	101	Lower	3	Disappeared		
150.233	325	186	Upper	9	Alive		
150.241	280	115	Lower	0	Recovered		
150.251	268	105	Lower	0	Recovered		
150.261	279	105	Middle	0	Recovered		Recovered outside of study area
150.273	285	115	Upper	0	Recovered		Recovered on land
150.281	287	139	Upper	2	Recovered		
150.289	276	113	Lower	0	Mortality		
150.302	290	114	Lower	0	Recovered		
150.312	297	133	Upper	1	Disappeared		
150.321	277	111	Lower	3	Disappeared		
150.331	276	105	Middle	1	Recovered		Recovered on land
150.341	275	99	Middle	3	Recovered		
150.351	266	99	Upper	2	Recovered		
150.362	298	133	Middle	9	Mortality		
150.371	290	133	Middle	6	Recovered		
150.382	270	106	Lower	5	Recovered		Recovered on land
150.391	275	115	Lower	4	Recovered		Recovered on land
150.401	296	150	Lower	0	Recovered		
150.410	277	112	Upper	1	Recovered		
150.420	285	125	Middle	1	Recovered		
150.431	277	107	Lower	0	Mortality		
150.440	284	114	Upper	10	Disappeared		
150.451	275	104	Middle	2	Recovered		Recovered on land
150.460	284	122	Middle	3	Recovered		
150.471	300	141	Upper	3	Recovered		Recovered on land
150.480	279	117	Middle	0	Recovered		Recovered outside of study area
150.490	287	119	Upper	5	Alive		

Appendix C. Individual frequency numbers of tags, length, weight, stocking site, number of live detections, and fate of juvenile Muskellunge at 3 months poststocking on the French Broad River. Fish were stocked on October 10, 2014.

Tag						
Frequency (MHz)	Length (mm)	Weight (g)	Stocking Site	Live Detections	Fate	Comments
150.502	303	136	Middle	1	Disappeared	
150.511	301	131	Upper	6	Alive	
150.522	316	157	Lower	0	Disappeared	
150.532	318	155	Middle	8	Alive	
150.541	304	138	Middle	1	Disappeared	
150.551	322	156	Middle	0	Mortality	
150.561	308	138	Lower	4	Alive	
150.572	335	175	Upper	1	Disappeared	
150.581	288	112	Lower	1	Recovered	Recovered outside of study area
150.591	308	131	Lower	1	Recovered	
150.601	316	138	Middle	1	Disappeared	
150.611	293	122	Upper	0	Recovered	
150.619	310	148	Middle	10	Alive	
150.630	290	115	Lower	1	Recovered	
150.641	321	165	Upper	1	Disappeared	
150.650	307	136	Upper	9	Alive	
150.660	290	115	Lower	4	Mortality	
150.670	305	129	Lower	0	Censored	Censored (tag failure)
150.681	307	137	Middle	1	Disappeared	
150.690	315	153	Lower	6	Alive	
150.701	295	126	Lower	4	Recovered	
150.710	325	177	Upper	4	Disappeared	
150.722	295	126	Lower	10	Alive	
150.731	298	112	Upper	1	Recovered	
150.741	301	126	Lower	4	Recovered	
150.751	319	162	Lower	7	Alive	
150.762	303	125	Middle	1	Mortality	
150.771	290	117	Middle	4	Disappeared	
150.781	299	125	Upper	0	Recovered	
150.790	324	169	Upper	0	Recovered	
150.800	312	145	Middle	7	Alive	
150.811	310	150	Middle	4	Mortality	
150.820	277	101	Middle	9	Alive	
150.831	292	114	Lower	1	Disappeared	
150.841	308	139	Upper	9	Alive	
150.850	315	154	Lower	0	Disappeared	
150.860	316	153	Middle	9	Alive	

Appendix C. Continued

Tag Frequency (MHz)	Length (mm)	Weight (g)	Stocking Site	Live Detections	Fate	Comments
150.871	319	162	Lower	0	Disappeared	
150.881	305	131	Upper	3	Recovered	
150.891	296	129	Middle	3	Recovered	
150.901	314	142	Middle	1	Recovered	Recovered outside of study area
150.911	289	111	Upper	11	Alive	
150.921	295	124	Upper	1	Recovered	
150.931	313	150	Upper	0	Recovered	
150.941	325	162	Upper	0	Recovered	
150.951	289	125	Lower	8	Alive	
150.960	317	151	Upper	0	Mortality	Mortality outside of study area
150.972	292	111	Middle	9	Alive	
150.981	329	183	Upper	0	Recovered	
150.991	308	148	Middle	2	Recovered	

Appendix D. Encounter history of tagged juvenile Muskellunge stocked in the New River during fall of 2013. Dots indicate detections within the study area for each tracking period. Dashes indicate non-detection of a fish for that tracking period. Xs indicate the earliest tracking period when mortality of a fish was known. Ds indicate the earliest tracking period when a fish was considered to have disappeared from the study area. Depending on the model we used missing fish were censored, treated as mortalities, or considered to have remained alive throughout the entire study period (see methods).

Tag Frequency (MHz)	New River Bi-weekly Tracking Period						
	1	2	3	4	5	6	7
150.001	•	•	—	X			
150.010	•	•	•	•	•	X	
150.022	X						
150.031	X						
150.041	•	•	•	•	•	•	D
150.051	•	D					
150.061	•	•	•	•	•	X	
150.069	•	X					
150.080	•	X					
150.090	•	•	—	X			
150.101	•	•	D				
150.112	•	•	—	•	•	D	

Appendix D. Continued

Tag Frequency (MHz)	New River Bi-weekly Tracking Period						
	1	2	3	4	5	6	7
150.121	●	X					
150.131	●	D					
150.141	●	●	D				
150.152	●	●	—	X			
150.161	●	X					
150.171	●	●	X				
150.181	●	X					
150.191	X						
150.201	●	—	—	X			
150.211	X						
150.221	●	●	●	D			
150.233	●	●	●	●	●	●	●
150.241	X						
150.251	●	—	—	X			
150.261	●	D					
150.273	●	—	—	X			
150.281	●	X					
150.289	X						
150.302	X						
150.312	●	D					
150.321	●	●	●	D			
150.331	●	X					
150.341	X						
150.351	X						
150.362	●	●	●	●	X		
150.371	●	●	●	●	X		
150.382	●	X					
150.391	●	●	●	X			
150.401	X						
150.410	●	●	X				
150.420	X						
150.431	X						
150.440	●	●	●	●	●	●	D
150.451	●	●	X				
150.460	●	●	●	—	X		
150.471	●	X					
150.480	●	D					
150.490	●	●	●	●	●	●	●

Appendix E. Encounter history of tagged juvenile Muskellunge stocked in the French Broad River during fall of 2014. Dots indicate detections within the study area for each tracking period. Dashes indicate non-detection of a fish for that tracking period. Xs indicate the earliest tracking period when mortality of a fish was known. Ds indicate the earliest tracking period when a fish was considered to have disappeared from the study area. Depending on the model we used missing fish were censored, treated as mortalities, or considered to have remained alive throughout the entire study period (see methods).

Tag Frequency (MHz)	French Broad River Bi-weekly Tracking Period						
	1	2	3	4	5	6	7
150.502	•	D					
150.511	•	•	•	—	•	•	•
150.522	•	D					
150.532	•	•	•	•	•	•	X
150.541	•	D					
150.551	X						
150.561	•	—	—	—	•	•	•
150.572	•	D					
150.581	•	X					
150.591	•	D					
150.601	•	D					
150.611	X						
150.619	•	•	•	•	•	•	•
150.630	•	X					
150.641	•	D					
150.650	•	•	•	•	•	•	•
150.660	•	•	•	X			
150.681	•	D					
150.690	•	•	•	•	•	•	•
150.701	•	•	•	•	X		
150.710	•	•	•	D			
150.722	•	•	•	•	•	•	•
150.731	•	X					
150.741	•	•	•	•	X		
150.751	•	•	•	•	—	•	•
150.762	•	X					
150.771	•	•	•	D			
150.781	X						
150.790	X						
150.800	•	•	•	—	•	•	•
150.811	•	•	—	•	X		
150.820	•	•	•	•	•	•	•
150.831	•	D					
150.841	•	•	•	•	•	•	•

Appendix E. Continued

Tag Frequency (MHz)	French Broad River Bi-weekly Tracking Period						
	1	2	3	4	5	6	7
150.850	●	D					
150.860	●	●	—	●	●	●	●
150.871	●	D					
150.881	●	●	●	—	X		
150.891	●	●	X				
150.901	X						
150.911	●	●	●	●	●	●	●
150.921	X						
150.931	X						
150.941	X						
150.951	●	●	●	●	●	●	●
150.960	●	D					
150.972	●	●	●	●	●	●	●
150.981	X						
150.991	●	X					