11-2016

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Recommended Citation
Fabrizio, M. C., Tuckey, T. D., Latour, R. J., White, G. C., Norris, A. J., & Groves, M. (2016) Population Size and Survival Rates of Blue Catfish in Chesapeake Bay Tributaries. Virginia Institute of Marine Science, College of William and Mary. http://doi.org/10.21220/V5KK5D

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Final Report ~ November 2016

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Final Report Submitted to:

National Marine Fisheries Service
NOAA Chesapeake Bay Office
410 Severn Avenue, Suite 107A, Annapolis, MD, 21403

November 2016

Preface

This report comprises two studies conducted from 2012 to 2015 to estimate population size, survival rates, and movements of invasive blue catfish in Chesapeake Bay tributaries. The first study of population-size and survival was conducted in the James River, VA (*Population Size and Survival Rates of Invasive Blue Catfish in Tidal Waters of the James River Subestuary*). The second study on movement and survival of blue catfish was conducted in the Potomac River, the natural boundary between Maryland and Virginia (*Movement Patterns and Survival Rate of Blue Catfish in a Non-Native Habitat Estimated with a Tagging Study*). The Executive Summary of this report provides a synopsis of both studies.

Because methods for the two studies differed, we present the results of our work as two documents, each prepared in the format of a journal article. We intend to submit these documents for publication in the scientific literature, and to communicate the results of this work with fisheries managers in the region as well as at scientific conferences.

Executive Summary

Intentional releases of non-native blue catfish *Ictalurus furcatus* in Virginia waters during the 1970s and early 1980s were successful in establishing recreational fisheries and resulted in the expansion of the abundance and spatial distribution of this species in Chesapeake Bay subestuaries. Blue catfish are considered an invasive species in the Chesapeake Bay region and efforts are underway to manage populations and limit impacts on native communities. However, the biology and ecology of blue catfish in these non-native systems is poorly understood. In particular, little is known of key vital rates (survival, recruitment) and movement of fish, which could aid the development of ecosystem-based models that seek to assess the impact of blue catfish on native resources. In turn, such models can be used to identify and develop effective management strategies. The purpose of this study was to estimate population abundance and survival rates of invasive blue catfish in tidal freshwater habitats of Chesapeake Bay tributaries. We accomplished this by conducting two independent multi-year mark-recapture experiments: one in the James River subestuary, and the other in the Potomac River subestuary.

James River Subestuary: We conducted a three-year experiment (2012-2014) with blue catfish in a 12-km stretch of the tidal James River, near Claremont, VA, to estimate population size and survival rates. We used coded wire tags (CWT) to tag 34,252 blue catfish that ranged in size from 214 to 466 mm fork length from the James River subestuary in a four-week period in July-August, 2012 and 2013. We selected this late-summer period to ensure minimal immigration and emigration of fish to and from the study site; this was a key assumption of the model used to analyze the tagging data. Our use of CWTs is the first application in large (post-juvenile) fish; we used CWTs because a laboratory experiment with 93 blue catfish suggested that tag loss rates were low 14 weeks after tagging, and because the automated CWT injector allowed us to efficiently tag large numbers of fish. Fish were captured in baited traps by a commercial waterman, tagged, and released throughout the study area, ensuring mixing of tagged and untagged fish (another key model assumption). We monitored for recaptures by using a handheld wand detector in 2013; we also monitored a portion of the commercial harvest in 2013 and 2014 to assess recoveries (encounters of dead tagged fish) with an automated tunnel detector, which had a 100% detection rate. We encountered 1,177 recaptures in 2012 and 2013, and 279 recoveries in 2013 and 2014; the size range of recaptured and recovered fish represented the range of sizes of initial releases. No fish was encountered more than two times after release. Observations from 2012-2014 were used to estimate annual survival rates with a Cormack-Jolly-Seber model, whereas observations from 2013-2014 were used to estimate population size with Barker's modification of the robust design model. The Barker modification allowed us to use information from recoveries in 2013-2014. Program MARK was used to fit the model to the data; we modeled heterogeneity in detection probabilities using fishing effort (trap nights) as a covariate, although this was not significant in the final model. We also accounted for individual heterogeneity in detection probabilities using individual random effects in the model. Overdispersion was estimated using the median $\hat{c}$ procedure in MARK and used to adjust the standard error of the estimated population size. The blue catfish population in the study area in 2013 was estimated to be 1.6 million fish (95% confidence interval [CI] adjusted for overdispersion: 926,307 –

2,914,208 fish). The annual apparent survival rate was 0.16 (95% CI: 0.10 – 0.24) in 2012-2013, and 0.44 (95% CI: 0.31 – 0.58) in 2013-2014. These survival rates are apparent rates because fish that emigrated permanently from the study area are considered 'losses'. Emigration from the study area may have been higher in 2012 compared with 2013, or survival may have been lower in 2012 compared with 2013, or a combination of both. Conditions at our study site in the James River were cooler and fresher in 2013 relative to 2012, but it is unclear if environmental conditions contributed to the observed differences in emigration or survival rates. Our estimate of population size is equivalent to a density estimate of 544 fish/ha, which is somewhat higher than previous estimates for the James River subestuary, but within the same order of magnitude. Using this density estimate, and assuming the James River supports similar densities from Richmond to the upriver limit of Burwell Bay, we calculated a population size of 19.8 million fish ranging in size between 214 and 466 mm fork length. This size range of fish includes individuals that are piscivorous and those that are likely to colonize estuarine habitats. The estimate of population size that we present may be biased low if tag loss rates were not negligible (we assumed negligible tag loss rates), but may be biased high if the assumption of population closure was not met in July-August 2013. Further research on the movement ecology of invasive blue catfish in large subestuaries of Chesapeake Bay, such as the James River subestuary, may shed light on connectivity of habitats in subestuaries and adjacent habitats in tributaries to the subestuary. Additional study of the reproductive biology of this species would help to better understand the duration of the spawning period of fish, and factors contributing to the likelihood of fish to undertake long-distance movements.

Potomac River Subestuary: We implemented a multi-year (2012-2015) mark-recapture study of invasive blue catfish in a 40-km stretch of the tidal Potomac River to allow estimation of survival rates and assessment of movement patterns. Blue catfish (N=1,237) were captured by electrofishing and double-tagged with dart tags; fish ranged in size from 300 mm to 1,319 mm total length and were tagged from July to November in 2012, and in June 2013. Dart tags were used because these tags could be readily detected and reported by anglers, and because two-year retention rates of dart tags were reported to be high (96%) in another catfish species. Fish were double-tagged to allow us to directly estimate tag retention for blue catfish; furthermore, we used reward tags to encourage reporting of recaptured fish. We obtained 104 reports of recaptured fish (8.4% return rate, 2012-2015) from anglers and commercial fishers who fished the Potomac River from Washington, DC, to Aquia Creek, which was downriver of our release sites. Fish were at large for 2 to 1,208 days and the size range of recaptured fish represented the size range of tagged fish. Using a Cox proportional hazard model, we estimated tag retention rates of 0.88 (standard error [SE]=0.045) after one year and 0.31 (SE=0.107) after 2.7 years. The mean minimum distance moved by fish was 24.1 km (range: 0 – 112.6 km); 73% of fish moved less than 30 km from the release site and a small portion of the tagged population (13%) was recaptured in the area of release. Most (63%) recaptured fish displayed downriver movements, but distance moved was not related to fish size or days at large. However, direction of movement significantly affected the mean distance moved by fish, such that greater distances were observed among fish that moved downriver (34.4 km) versus those that moved upriver (6.7 km). Together, these results suggest high variability in movement behaviors among individual fish. We conclude that large blue catfish use the entire tidal Potomac River from freshwater reaches to habitats exhibiting salinities of about 12.8 psu.

We used the Brownie model for dead recoveries to estimate the annual apparent survival rate and to investigate overdispersion. The estimated annual survival rate adjusted for tag shedding was 0.56 (SE=0.057), and we found no evidence of overdispersion. This survival rate is similar to that reported here for the James River population from 2013-2014, but lower than that reported by others for blue catfish in the James River, and lower than survival rates reported for blue catfish from their native range. Low survival rates in the Potomac River compared with native habitats suggest a higher natural mortality rate in non-native coastal estuaries. However, we do not know the impact of commercial and recreational harvests on the blue catfish population and research is needed to estimate both fishing and natural mortality. Another possible explanation for our low survival rate estimate is permanent emigration (e.g., movement of fish into tributaries of the Potomac River with no return to the study area); if present, permanent emigration would result in lower estimated survival rates for Potomac River fish. Although we postulated that directed seasonal movements are undertaken by large blue catfish in non-native habitats, we were unable to detect these movements. Four reasons may account for our inability to detect seasonal movements: (1) the high abundance of blue catfish in the Potomac River, coupled with the relatively small sample size of recaptured fish, yields an estimate of seasonal movement with low precision, which did not permit detection of a significant seasonal effect on mean distance moved; (2) the behavioral variation among fish is large, and seasonal patterns are not applicable to the population as a whole; (3) spawning locations are not known and thus we lacked a robust reference location from which to observe movements; and (4) the spawning season in the Chesapeake Bay region is longer than that reported for blue catfish in their native range. Long-distance movements of blue catfish observed in the Potomac River indicate that robust control measures will be needed to reduce population abundance and minimize the potential for negative impacts of this species on the native estuarine community. Furthermore, the fecundity-at-age relationship, spawning frequency, spawning locations, and spawning period in non-native habitats are critical data gaps that would inform population dynamics models and stock assessments and help guide management actions.

Population Size and Survival Rates of Invasive Blue Catfish in Tidal Waters of the James River Subestuary

Mary C. Fabrizio, Troy D. Tuckey, Robert J. Latour, Gary C. White, and Alicia J. Norris

Introduction

The growing abundance of invasive blue catfish *Ictalurus furcatus* in tidal tributaries of Chesapeake Bay has prompted concerns about the ecosystem effects of this large, long-lived omnivore. In the 1970s and 80s, blue catfish were introduced in the James, York, and Rappahannock rivers to establish recreational fisheries in Virginia. This species, which is native to the Mississippi, Missouri, and Ohio river drainages, readily adapted to the tidal tributaries of Virginia and abundance soon increased (Tuckey and Fabrizio 2015). Within the Chesapeake Bay watershed, blue catfish are now found in the Piankatank, Potomac, Patuxent, Nanticoke, Sassafras, and Susquehanna rivers (Schloesser et al. 2011; M. Groves, MD Department of Natural Resources, *pers. comm*.); these occurrences may have been aided by natural events (e.g., flooding) or illegal movement of fish by humans (Figure 1). In addition to freshwater habitats, blue catfish in the Chesapeake Bay region currently occupy mesohaline habitats (Schloesser et al. 2011). Because this is a freshwater species, it is believed that high salinity may impede further range expansion in subestuaries of Chesapeake Bay. However, salinity tolerance and potential for adaptability of blue catfish is unknown; we note that a single individual was recently found in 21.8 psu in the lower James River (Fabrizio and Tuckey, *pers. obs.*), suggesting that acute salinity tolerance is quite high. Within currently occupied habitats, invasive blue catfish have the potential to negatively affect native aquatic organisms such as American shad and freshwater mussels (Brown and Dendy 1961; MacAvoy et al. 2009).

In the Chesapeake Bay region, the Sustainable Fisheries Goal Implementation Team of the Chesapeake Bay Program identified the need to develop a coordinated management plan for blue catfish, but such a plan cannot be advanced without a better understanding of the ecological role of this species (particularly pertaining to the role of predator) and the population size (Invasive Catfish Task Force 2015). The lack of knowledge of the current sizes of the blue catfish populations in tidal tributaries hinders our ability to evaluate potential management measures to control the spread and growth of these populations in the region. Basic knowledge of population size is required to evaluate management alternatives such as directed removals and increased harvests.

The distribution of blue catfish throughout the freshwater and mesohaline reaches of mid-Atlantic slope rivers presents a sampling challenge because of the variation in salinity and physical habitat types, and the accompanying variation in efficiency of a single sampling gear. Currently, fisheries programs at VIMS, Virginia Commonwealth University (VCU), Virginia Tech, Virginia Department of Game and Inland Fisheries (VDGIF), and Maryland Department of Natural Resources (MD DNR) use electrofishing and bottom trawls to sample the freshwater and tidal portions of the major subestuaries, with minor spatial overlap (e.g., low-frequency electrofishing is generally not conducted in salinities exceeding 2 psu). Such sampling can be used to infer changes in spatial distribution and relative abundance of blue catfish from survey-specific CPUE indices (e.g., Greenlee and Lim 2011; Schloesser et al. 2011), but a single estimate of population abundance remains elusive because established surveys use different sampling designs and gears. For example, the VIMS bottom trawl survey is conducted monthly at stations selected randomly from a stratified survey design in the James River from the mouth of the Chickahominy River downstream (east) to the mouth of the James River, whereas the VDGIF electrofishing survey is conducted primarily during summer in the James River upriver from, and including, the area near the mouth of the Chickahominy River. Blue catfish occur throughout the sampled areas of the James River (Figure 1) and are encountered by both gears, but the relative contribution of freshwater and estuarine habitats to the overall production of blue catfish populations is unknown.

Populations of blue catfish in each of the tributaries exhibit differences in annual recruitment (Tuckey and Fabrizio 2015), growth, and mortality rates (Greenlee and Lim 2011); this is evidenced by different age-frequency distributions observed among Virginia rivers (James, Pamunkey, and Rappahannock rivers). Because vital rates appear to differ and because fish from the major tributaries in Virginia do not intermingle, populations are best treated as separate stocks for management purposes (Schloesser et al. 2011). In Virginia, the most abundant blue catfish populations are in the James and Rappahannock rivers, the two systems where blue catfish were first introduced in the 1970s (Figure 2).

The objectives of this study were to estimate the size of the blue catfish population in the tidal freshwater region of the James River and to estimate annual survival rates. We used a three-year mark-recapture study (e.g., Williams et al. 2002; Pine et al. 2003) and analyzed the data using a modification of the robust design (Pollock 1982) developed by Barker (Barker 1997; Kendall et al. 2013). The robust design provides an estimate of the annual survival rate between two or more primary tagging periods, wherein the population is open, and an estimate of population size using observations from the secondary tagging sessions, wherein the population is considered closed (Figure 3). Thus, the robust design combines attributes of open population models, which allow birth, death, immigration, and emigration rates to be nonzero, and closed models, wherein these rates are zero. In the robust design, estimates of survival rates are obtained using the Cormack-Jolly-Seber (CJS) model, whereas estimates of population size are obtained using closed-population models that do not require the assumption of equal catchability (Pollock et al. 1990; Kendall and Pollock 1992). The use of closed-population models to estimate population size is desirable because such estimates are sensitive to the assumption of equal catchability and this assumption is more likely to be met during closure when additions and deletions to the population are negligible. However, the closure assumption is difficult to satisfy unless the period of study is short (e.g., on the order of days or a few weeks); thus, by sampling during restricted weekly sessions (during which closure applies) we relaxed the assumption of homogeneous capture probabilities (Williams et al. 2002). In addition to these assumptions, mark-recapture models assume no tag loss (i.e., 100% tag retention), no tagging-induced mortality, and complete mixing of tagged and untagged animals (Burnham et al. 1987).

To minimize the effect of long-range movement on our marked population during the closed period, we tagged blue catfish during four weeks in July-August (primary periods of the robust design), at the putative conclusion of spawning and when migratory movements were expected to be minimal. The long interval between these periods (approximately one year) allows additions (births, immigration) and deletions (deaths, emigration) to the population. In their native range, large-scale migratory movements occur mainly in spring and fall in response to changing water temperature; in winter, blue catfish are presumed to be predominantly stationary (Graham 1999). Prior to spawning, which occurs between April and early July (Graham 1999), fish may undertake long-range movements to spawning sites. Movements of invasive blue catfish in the James River and elsewhere in the Chesapeake watershed are not well known, although acoustic studies are currently underway (M. Ogburn, SERC; A. Bunch, VDGIF; *pers. comm.*). However, we note that blue catfish in the James River may not exhibit the distinct movement patterns reported for this species in its native range; an 18-month acoustic telemetry study of blue catfish in the upper James River (Jones Neck, Herring Creek, and Powell Creek) indicated little upstream or downstream movement of fish (VDGIF *unpub. data*; Figure 4). Unfortunately, sample size of the acoustic telemetry study was small (N=27), and thus, power to observe long-range movements may have been low. Within each primary period, we tagged and monitored recaptures during four closed sampling sessions (each of these secondary sessions corresponded to about one week). Intervals between the four successive secondary samples were sufficiently short to satisfy the closure assumption. No fish were tagged in the third year, however, recaptures were monitored.

Because the type of tag selected was critical for the success of this study, we conducted a lab-based experiment to determine appropriate tag placement and to estimate tag retention rates prior to implementation in the field. We sought to identify a tag that could be retained at a high rate and that would allow quick and efficient tagging of large numbers of fish (> 1,000 fish per day), which we postulated would be necessary for estimation of population size.

Catfishes, which are scaleless, have been marked with cold and hot brands and various tattoos and pigments; however, all of these methods suffer from problems with visibility and distortion. Individually numbered T-bar anchor tags, which are relatively inexpensive and easy to apply, are associated with high tag-shedding rates in catfishes (90% of tags shed in 3 months, Greenland and Bryan 1974; 24% shed in 6 months, Bodine and Fleming 2014; 50% shed in 8.3 months, Timmons and Howell 1995; 29% shed in 9 months, Buckmeier and Irwin 2000). In one long-term study with T-bar anchor tags in African sharptooth catfish *Clarias gariepinus*, shedding rates after 1 year were 17% (Booth and Weyl 2008). Most North American catfishes are typically tagged with Carlin dangler tags, and shedding rates associated with these tags can vary from 0% shedding in the first year (Travnichek 2004; Michaletz et al. 2008) to annual rates near 30% (23% tag loss rate in channel catfish >305 mm TL, Shrader et al. 2003; 31.4% tag loss rate in flathead catfish, Marshall et al. 2009). We speculate that variation in tag retention rates for the Carlin dangler tag largely reflects variation among taggers and tag placement. Although most externally attached tags can be associated with high or variable tag loss rates (e.g., Mitamura et al. 2006), dart tags appear to exhibit high retention rates. For example, shedding rates of dart tags inserted into the dorsal musculature of the African sharptooth catfish were 2% after one year and 4% after two years (Booth and Weyl 2008). Unfortunately, application of dart tags is time consuming and thus, were not considered in this study in the James River because we wished to tag large numbers of fish.

Other types of tags have been used in catfishes with variable results. Visible implant elastomer (VIE) tags inserted in the cheek were used successfully to mark fingerling blue catfish (~152 mm), with 100% tag retention in 9 months (Zeller et al. 2010). However, in 5.7 months, channel catfish (>280 mm total length) shed 100% of a similar type of tag (visual implant alphanumeric tags; Buckmeier and Irwin 2000). Other internal tags have been used in catfishes including acoustic transmitters and passive integrated transponders (PIT). Although useful for short-term studies (30-40 days; e.g., Hart and Summerfelt 1975), internal tag placement is not warranted for long-term studies because of an unusual phenomenon observed among catfishes: expulsion of tags from the body cavity. African and channel catfish surgically implanted with acoustic transmitters expel their transmitter transintestinally, transdermally, or through the incision site (Summerfelt and Mosier 1984; Marty and Summerfelt 1986, 1988; Baras and Westerloppe 1999). Unlike acoustic transmitters, PIT tags have high retention rates. PIT tags inserted into the dorsal or opercular musculature of flathead catfish exhibited 100% and 98.5% retention rates after 10 months (Daugherty and Buckmeier 2009). Similarly, 97% tag retention was obtained after 1 year for channel catfish tagged in the dorsal musculature (Moore 1992), and 100% retention after 6 months for blue catfish (Bodine and Fleming 2014). Although PIT tags appear to be a good choice, our goal to tag more than 1,000 fish per day rendered this approach impractical and cost prohibitive. In addition, studies where recaptures or resightings are expected to occur several months after release would benefit from high tag-retention rates.

One type of tag that has been used successfully to tag large numbers of small fish and which has a high retention rate is the coded-wire tag (CWT; e.g., Brennan et al. 2007; Hand et al. 2010; Simon and Dorner 2011; Lin et al. 2012; Ashton et al. 2014). Such tags are used routinely to mark hatchery-reared salmonids along the Pacific coast of North America (e.g., Trudel et al. 2009; Weitkamp 2010) and in the Great Lakes (e.g., Adlerstein et al. 2008). Automated tag applicators permit tagging of large numbers of fish (e.g., millions of hatchery smolts are marked annually). We used CWTs to tag blue catfish because of the potential for high tag retention, ease of application, and cost effectiveness. To our knowledge, our use of CWTs in blue catfish represents the first application of these tags in this species and with large (post-juvenile stage) fish.

Methods

Tag Retention and Tag-Induced Mortality

We conducted a tag-induced mortality and tag-retention experiment with blue catfish in the laboratory and monitored tag retention for 3 months prior to implementation of the tagging study in the James River. We captured fish from the James River in January and March 2012 using a bottom trawl (n=93 fish; mean size=322 mm fork length [FL]; range= 284 – 770 mm FL). These fish represented the sizes we proposed to tag in the mark-recapture experiment (see *Mark-Recapture Experiment*, below). Fish were transported to the VIMS Seawater Research Laboratory where they were held in eight 2,500-L aquaria filled with a mix of filtered York River water and freshwater to achieve a salinity of 2.8-3.4 psu; temperature was maintained between 14 and 16°C. Water quality was ensured using a 100-micron mesh-bag filter, a bio-active filter, and UV sterilization. Fish were fed *ad libitum* every other day with squid and pellet feed until fish readily accepted pellets, after which feeding occurred every 2 days with pellets only.

Blue catfish were tagged with CWTs in the dorsal musculature below the dorsal fin and held in the Seawater Laboratory at VIMS for 14 weeks of observation between March and June 2012. To account for tagger variability, three individuals participated in the tag-retention and mortality study. Although the three participants had significant experience with fish tagging and marking, none of the individuals had employed a CWT injector, nor tagged blue catfish. Fish were tagged with a single CWT (n=77) on 20 March and 10 April 2012 on either the left or right side. Each person applied left-side and right-side tags, but left-side tags were applied first (first group), followed by right-side tags (second group) to assess potential changes in tag-retention rates with tagging experience (first group represents novice operators). We used a handheld wand detector (Northwest Marine Technology, Inc.) to confirm tag insertion immediately after tagging and prior to returning fish to the aquaria. Control fish (n=16) were not tagged, but were handled similarly to tagged fish; these fish were used to compare mortality rates among handled and tagged fish and fish that were handled, but not tagged. Fish tagged on 20 March 2012 and control fish were handled and observed at 0, 3, 7, 14, 21, 42, 70, and 98 days post-tagging to assess tag loss and tagging-induced mortality; fish tagged on 10 April 2012 were handled and observed at 0, 3, 10, 17, 24, 31, 56, and 77 days post-tagging. (Table 1). The experiment was terminated on 26 June 2012, when all fish were scanned for tags, removed from tanks, and euthanized in an ice slurry according to an IACUC-approved protocol (The College of William & Mary IACUC-2012-02-24-7720-mcfabr).

Mark-Recapture Methods 2012

Originally, we proposed to use low-frequency electrofishing to capture blue catfish for the mark-recapture study in the James River. However, we learned that blue catfish are unaffected (and therefore, not vulnerable to capture) by the electric current for at least one week following exposure to low-frequency electrofishing (R. Greenlee, *pers. comm.*). This characteristic prevented us from capturing fish on successive days from the same location, which is necessary to meet the sample size requirements and closure assumption of the robust design model. To maximize our sample size, we contracted with a local waterman who fished baited traps for blue catfish from Claremont, VA, in the portion of the James River between the mouth of Upper Chippokes Creek and the mouth of the Chickahominy River (Figure 5); thus, our study area spanned approximately 12 km (total straight-line distance). In this portion of the James River, blue catfish are harvested commercially between June and October.

We coded-wire tagged and released 15,721 blue catfish captured by baited traps set in the James River during a 30-day period in 2012 (8 July - 4 August 2012; Table 2). Two scientists tagged fish simultaneously using two automated CWT injectors (Mark IV tag injector; Northwest Marine Technology, Inc.) from a 21-ft. Carolina Skiff. Blue catfish were supplied from a 3 x 1.2 x 1.2-m net pen lashed to the side of the boat. Prior to tagging, fish were scanned with a handheld wand detector to determine recapture status; if the fish did not have a CWT, then the fish was tagged in the right dorsal musculature; scanned again to ensure tagging success; and gently released. While tagging and releasing blue catfish, the vessel was maintained in a safe position in the river channel for drift releasing of tagged fish throughout the capture area. We measured water depth (m) and environmental conditions (temperature [°C], salinity [psu], and dissolved oxygen [mg/L]) in surface and bottom waters in the central portion of the study area on each sampling day. Also on each day, and just prior to tagging, a random subset of 50 fish was measured; in 2012, fish ranged in length between 214 and 464 mm FL (n=899; left panel, Figure 6) and reflected the availability of fish to the traps. Most of the fish we tagged were greater than 250 mm FL, and this size class represented the majority of fish in the river (VIMS Juvenile Fish Trawl Survey, *unpubl. data*). In 2012, we euthanized recaptured fish in an ice slurry and returned them to the lab for length measurements and dissection of tags. Batch numbers imprinted on the CWTs removed from recaptured fish were later read under a stereoscope to identify release week (unique batch marks were used each week in 2012); unfortunately, we were unable to ascertain batch identity for some of the recaptured fish.

In addition to monitoring recaptures from among the fish sampled by baited traps, thousands of blue catfish are encountered annually by on-going fishery-independent sampling programs in the James River. These programs are the VDGIF electrofishing survey (E. Brittle, A. Bunch, and R. Greenlee), VCU electrofishing survey (G. Garman and S. McIninch), Virginia Tech electrofishing sampling (J. Smith and D. Orth), VIMS gillnet sampling (E. Hilton and P. McGrath), and the VIMS bottom trawl survey (M. Fabrizio and T. Tuckey). Thus, multiple gears are used to intercept blue catfish in the James River, from the upper freshwater reaches near Richmond, VA, to mesohaline habitats at the mouth of the River near Hampton, VA (Figure 5). Although gillnet sampling was restricted to Burwell Bay in spring 2014, blue catfish are abundant in this portion of the James River. We provided handheld detection wands to program scientists who agreed to scan blue catfish for CWTs. These surveys occurred throughout freshwater tidal and estuarine habitats in the James River and expanded our spatial and temporal efforts to encounter previously tagged fish. We requested survey personnel to retain all coded-wire tagged blue catfish that were intercepted during the auxiliary surveys and to provide tagged fish to us for tag retrieval.

Mark-Recapture Methods 2013

In 2013, we implemented a revised tagging strategy whereby tagging week was identified by the unique location of the tag (rather than by the batch mark on the CWT; Figure 7) and removals due to the fishery were monitored. The use of tag location to identify release week (secondary period in 2013) allowed us to observe more than two encounter events per fish because fish were not euthanized for tag removal in 2013. This nonlethal identification method using CWTs has also been employed to identify hatchery origin of Atlantic salmon *Salmo salar* (Goulette and Lipsky 2016). To indicate a fish had been recaptured in 2013, we clipped one of several fins (corresponding to the week of recapture), thereby allowing their release and future recapture (Figure 7). With this approach, we could encounter an individual fish in two or more secondary tagging periods and construct its unique encounter history. In addition, the timing of our mark-recapture experiment in 2013 was adjusted to coincide with the occurrence of larger catches and larger fish in the traps. Based on observations from 2012, we expected to observe larger catches later in summer; therefore, tagging operations commenced on 20 July in 2013, about two weeks later than in 2012. With these changes in place, we tagged 18,531 blue catfish with

CWTs during 16 occasions between 20 July and 16 August 2013 (Table 2). As in 2012, a random subset of the tagged fish (N = 799) was measured prior to tagging; these fish ranged from 247 to 466 mm FL (right panel, Figure 6).

In 2013, we recorded GPS coordinates to track the drift of the boat during release of tagged blue catfish in the James River; these data allowed examination of drift patterns for potential effects on mixing of tagged and untagged fish (a critical assumption of mark-recapture models). To better understand how the release of tagged fish may have affected tag-return rates in 2013, we examined temporal patterns in release locations. To facilitate analysis, we partitioned the study area into approximately equal segments using Claremont, VA, as the mid-point of the area. The upper and lower delineations of river segments corresponded with the extent of the 12-km area fished by the commercial waterman. During the first week, drift releases occurred over the greatest extent of the study area and included upriver and downriver segments (9.7 km; Figure 8). Drift releases in the second (8.4 km) and fourth (7.2 km) week occurred primarily in the downriver section (Figure 8). During the third week, drift releases occurred primarily in the upriver section (6.2 km; Figure 8); thus, released fish were well dispersed among the population in the study area, and presumably well mixed with untagged fish.

We also inspected the waterman's harvest for tagged fish on 11 occasions between 20 July and 25 August 2013 (Tables 2 and 3); we recorded daily effort (trap nights), total weight harvested (kg), the portion of the harvest that was inspected (kg), the number of fish inspected, and the number of fish recovered with CWTs. Harvest inspections occurred during each weekend of the four-week tagging period, two weekdays during which both tagging and harvest inspection occurred (9 and 16 August 2013), and the week following tagging (i.e., multiple weekdays and weekend days in week five). The inspections in the fifth week helped to ensure maximum detection of recovered fish, especially those tagged and released in the fourth week of 2013. To efficiently detect tags among the harvested fish, we used an R9500 tunnel detector (Northwest Marine Technology, Inc.), which automatically distinguished between tagged and untagged fish in the harvest. This process was accomplished at the waterman's land-based catch-processing operation. Prior to implementation, we conducted an experiment with the tunnel detector to determine error rates. False negative rates (i.e., failure to detect a tag) were zero.

Recoveries 2014

Our field efforts in 2014 focused on recovery of tagged fish because no fish were tagged in 2014 (Tables 2 and 3). As permitted by the waterman's schedule, we inspected harvested fish for CWTs on 29 occasions between 7 July and 22 August 2014 (Table 3). We collected information on the size of harvested fish, total weight harvested, weight of fish inspected, number of fish inspected, and fishing effort (pounds/trap-night). The daily commercial catch in 2014 was generally low (< 710 kg), and the waterman allowed us to inspect the entire catch on all dates. Fish harvested in 2014 measured 116 to 463 mm FL (based on a random subset of 2,850 fish).

We used an R9500 tunnel detector to efficiently inspect 41,925 harvested fish (or 15,096 kg). As before, we conducted an experiment with the R9500 tunnel detector to determine tag-detection error rates. The experiment involved a known mixture of tagged and untagged fish; specifically, 4 groups of

10-11 fish with 1, 2 or 3 tagged fish/group. Different tag placements representative of those used in the study (Figure 7) were incorporated in this experiment to assess possible tag detection error due to variability in tag placement. Tunnel detector operators were blind to the total number of tagged fish/group and tag placement. Each of the five operators individually passed four groups of fish through the tunnel detector. As before, false negative detections were zero indicating that all tags were detected. During field operations in 2014, we observed 120 occurrences of false positives – i.e., an untagged fish was identified as a tagged fish. We mitigated this error by confirming the presence of a CWT with a handheld wand detector; 41% of the false positive fish were associated with the presence of metal bits (possibly from the ice or the gear used to harvest and process fish). At the end of the 2014 field season, we repeated the experiment with four groups of fish and four operators and found 100% detection rates with the tunnel detector, an observation consistent with the 100% detection rate reported by Vander Haegen et al. (2002).

Encounter Histories

Encounter histories were used to summarize releases, recaptures, and recoveries (i.e., harvested fish). All recaptures and recoveries were assigned encounter histories using year and week as the temporal increment as appropriate (year for fish released in 2012; week and year for fish released in 2013). We also identified several recoveries that occurred within the week of tagging in 2013.

To construct encounter histories for recaptured or recovered fish, each observation was assigned (1) a disposition, either dead or released alive, (2) the tagging year (based on the CWT location), and (3) the week of recapture or recovery. Some of the fish received more than one CWT, and upon encounter, we could determine if one or more tags was missing and subsequently use this information to assess tag-loss. For example, a fish with a right dorsal CWT and lower caudal fin clip was tagged in 2013 (due to the presence of the fin clip) but the left dorsal CWT was not retained (see Figure 7). Other fish likely lost tags as evidenced by an impression of the coded-wire tag injector on the skin (visible as a faint, round outline); these fish lacked a CWT but appeared to have been tagged due to the presence of the impression. The injector impression was temporary and could be seen on many fish immediately after tagging; we believe that the impression was short-lived, likely lasting no more than one or two weeks.

The structure of the encounter history is determined by the type of mark-recapture model selected for analysis. Encounter histories were constructed using data recorded from released and recaptured fish as described above (e.g., tag placement, release date, and recapture date), and were represented by a series of 0's and 1's, where 0=not encountered and 1=encountered. Typically, the number of columns (or digits in the encounter history) equals the number of unique sampling events during which an encounter may occur. Each encounter history is followed by the number of fish sharing this history (Table 4). Positive numbers indicate the number of fish tagged and released with a given history that are subsequently available for capture. Conversely, negative numbers indicate fish that were removed and are no longer available for capture (these are referred to as 'losses on capture'). For example, an encounter history of 1001 15 indicates that 15 fish shared the following encounter history: fish were captured during the first occasion, not seen on occasions 2 or 3, and seen again on occasion 4. Encounter histories for the Barker model are more complex, using two columns for each occasion where the first column indicates a live encounter (L) and the second column indicates a dead encounter (D). For example, the Barker notation for a four-week secondary period is LD LD LD LD; as before, the L's and D's are replaced with 0's and 1's to indicate 'not encountered' or 'encountered.'

Mark-Recapture Modeling

Fish that were marked and released alive may undergo a variety of fates, depending on the probabilities of survival, harvest, and detection. Fate diagrams are commonly developed in mark-recapture studies as a way to visualize encounter data and to aid in the development of mark-recapture models. In a fate diagram, all possible outcomes for a tagged fish are identified and transitions between fates are assigned model parameters (Figure 9). The population of blue catfish in the James River supports a commercial fishery, thereby necessitating the use of models that allow for both dead recoveries (from the fishery) and live releases of recaptured fish.

We fitted several models to the data, using a modification of the robust design by Barker that allowed consideration of live recaptures and dead recoveries (Barker 1997; Kendall et al. 2013). Three types of encounters are permissible in the Barker live-dead formulation: (1) mark and release of live fish that are subsequently recaptured live; (2) dead recoveries (from the harvest); and (3) resightings, that is, tagged fish that are captured by fishers and released alive. For our study, we will inform the Barker model with the first two types of encounters because resightings were not applicable to this study.

The Barker robust design in Program MARK (White and Burnham 1999) was used to estimate detection probabilities, population size in 2013, annual survival rates, and tag recovery rates for blue catfish from the James River. This likelihood can be considered in three parts: the closed-captures portion for estimating population size and detection probabilities, the Cormack-Jolly-Seber (CJS) portion from live recaptures, and the dead recovery portion from dead recoveries. The closed period occurred in 2013 (with 4 secondary occasions); thus, fish tagged in 2013 and recaptured in 2013 provided information on population size at the beginning of 2013. The 2012 releases and recaptures were used to estimate survival rates using the open-population CJS model estimators.

Secondary periods in 2012 were collapsed to a single period because we were unable to construct full encounter histories for 140 fish tagged in 2012 and observed again in 2012, 2013, or 2014 (this was due to 140 unreadable tags). Although no estimates of population size could be computed for 2012 (because robust-design data types require two or more secondary encounter occasions within each primary session), encounter histories for fish tagged in 2012 could be used to estimate survival rates. To do this, the 2012 captures were pooled into a single secondary occasion and a dummy secondary occasion was added that consisted of zero entries in the encounter history to satisfy the software requirement. Likewise, because there were no live tagging events in 2014, two dummy secondary occasions were used to represent 2014. We note that neither of the secondary occasions in 2014 showed live encounters. Thus, simplified encounter histories comprised 12 columns, the first two representing 2012, the third through the tenth representing each of the four weeks in 2013, and the eleventh and twelfth representing 2014 (Table 4). Further modification of these encounter histories was necessary to satisfy the software requirements of MARK and to properly implement the Barker model.

Dead encounters in the Barker robust design data type are assumed to occur only in the interval between primary sessions. Thus, all tags detected during harvest were coded as dead encounters for the intervals between 2012 and 2013, 2013 and 2014, and post-2014. Fish that were harvested during the closed-capture period in 2013 had dots inserted into their encounter history for any secondary occasions after they were harvested. Dots in the encounter history are treated as if the probability of detecting an untagged fish, *p*, equals 0, which is the case when the fish are removed from the population. The robust design assumption of closure during the secondary occasions is clearly violated when fish are removed by harvesting (which occurred in 2013). However, because the population size estimated is the size on the first occasion of 2013, these removals lead to individual heterogeneity in the detection probabilities and do not affect the estimate of population size directly.

As with all mark-recapture models, assumptions are necessary for proper inference (Burnham et al. (1987). The usual assumptions that apply to this study are: (1) marked fish are representative of the population of fish about which one seeks mortality information; (2) initial handling, marking, and holding do not affect survival rate; (3) the numbers of fish released are exactly known; (4) marking (tagging) is accurate and no marks (tags) are lost or misread; (5) all releases and recaptures occur in brief time intervals, and recaptured fish are released immediately; (6) the fate of each fish, after any known release, is independent of the fate of any other fish; (7) with multiple lots (or other replication), the data are statistically independent over lots; (8) statistical analyses of the data are based on the correct model; (9) captured fish that are rereleased have the same subsequent survival and capture rates as fish alive at that site which were not caught, i.e., capture and rerelease do not affect their subsequent survival or recapture; and (10) all fish (in the study) of an identifiable class (e.g., size or replicate) have the same survival and capture probabilities; this is an assumption of parameter homogeneity. Assumptions 1–5 relate to study planning, field procedures, and generality of the desired inferences; these assumptions are not generally correctable via statistical analysis. The effect of tag loss (assumption 4) is to bias survival estimates low (Arnason and Mills 1981; Pollock 1981) and to decrease precision of survival rate estimates from CJS models (Arnason and Mills 1981); however, if survival rates are not high, then estimates of tag loss can be used to adjust survival rates (e.g., Fabrizio et al. 1997; Pollock et al. 2007). Assumptions 6-7 relate to the stochastic component of the models; and assumptions 8–10 relate to model structure. We used the median $\hat{c}$ procedure (see below) to correct for overdispersion, including individual heterogeneity (assumption 10) and lack of independence of tags (assumption 6).

The parameters of the Barker robust design are shown in Table 5, along with an explanation of parameters that were fixed (i.e., not estimated from the data). The closed-captures portion of the likelihood is joined to the Cormack-Jolly-Seber (CJS) likelihood via the detection probabilities. That is, the CJS likelihood estimates the probability of a fish being detected one or more times during the secondary occasions within a primary occasion, and commonly denoted as *p** in robust design models. The closed-captures initial detection probabilities relate to *p** as $p^* = 1 - \prod_t (1 - p_t)$. That is, the product of 1 – *p* values is the probability of never encountering a fish during the secondary occasions, so that 1 minus this product is the probability of encountering a fish 1 or more times during the primary occasion. Thus the *p* parameters in the closed-captures likelihood are also influenced by the CJS detection probabilities via *p**. The CJS portion of the likelihood is joined to the dead recoveries portion of the likelihood via the annual survival rates.

Population sizes are computed as derived parameters based on the closed-captures portion of the likelihood, using the Huggins (1989, 1991) and Alho (1990) approaches. Effectively, the number of unique fish seen one or more times (commonly denoted as M_{t+1} is divided by the probability of being observed one or more times to estimate *N*: $\hat{N} = M_{t+1} \Big/ 1-\prod_t (1-p_t)$.

Because we did not have valid secondary occasions during 2012 and 2014, population sizes cannot be estimated for these primary sessions. Also because live encounters did not occur during secondary occasions in 2014 and because there were no new releases in 2014, the survival estimate for 2013 is confounded with the inestimable *p** value for 2014 and the survival estimate in 2014. Further, the survival rate for 2014 is confounded with the recovery rate for 2014, and so cannot be estimated unless additional constraints are provided. As a result, even though there are 6 parameters in the model, only 4 are actually estimable. Because of this confounding, the model with survival in 2013 equal to survival in 2014, and recovery rate in 2013 equal to recovery rate in 2014 is the most appropriate model to consider for estimating survival. Thus, a survival estimate is obtained for 2012–2013, and an annual survival estimate that is the same for 2013–2014 and 2014–2015.

Confidence intervals for probabilities *S*, *r*, and *p* are computed with a logit transformation, where logit(θ) = log[θ/(1 − θ)]; here, *S* is the annual survival probability, *r* is the probability that a tag is recovered given that the fish has died, and *p* is the detection probability of untagged fish (see Table 5 for description of these parameters). Confidence intervals for *S, r*, and *p* are computed on the logit scale and then transformed back to the real scale.

Confidence intervals for *N* are computed assuming a lognormal distribution on the number of animals never captured (f_0), with $\hat{N} = \hat{f}_0 + M_{t+1}$, where M_{t+1} is the number of animals captured at least once during the primary period. The following equations describe the procedure:

$$\hat{f}_0 = \hat{N} - M_{t+1}$$

$$\text{LCI} = \hat{f}_0 / C + M_{t+1},$$

$$\text{UCI} = \hat{f}_0 / C + M_{t+1}, \text{ and}$$

$$C = \exp\left\{1.96 \times \sqrt{\log_e\left[1+\left(\frac{SE(\hat{N})}{\hat{f}_0}\right)^2\right]}\right\}.$$

Models Considered - All the models considered had the following fixed parameters because these parameters are not estimable without a full robust design. Detection probability *p* for the 2012 primary session was fixed to one because this parameter is not identifiable from a single secondary occasion, with the dummy encounter *p* fixed to zero. Both *p* values for the 2014 primary session were fixed to zero. All the parameters concerning fidelity were fixed to 1.

The last *S* and *r* are confounded, and only the product, *S*(1 – *r*), is estimable. Further, *S* for 2013–2014 is also confounded from the lack of an estimate of *p* from 2014. For the three *S* and three *r* parameters, only four estimable quantities are possible because of no new releases in 2014. Therefore, three models were considered with various constraints (Table 6).

The notation (year1, year2=year3) denotes that the first year was estimated separately, with year 2 and year 3 set equal. The motivation for fixing the last two years for *S* or *r* was that the harvest rates or the inspection of harvested fish was approximately the same for 2013 and 2014, whereas these values were different for 2012 (no harvested fish were inspected).

Only three models were considered for detection probabilities in 2013: those in which a separate *p* was estimated for each secondary session – denoted *p*(secondary session) – and those in which *p* was constant across secondary sessions – denoted *p*(.). Recapture probabilities were assumed equal to initial capture probabilities in all cases. However, to account for individual heterogeneity in detection probabilities, an extension of the model *p*(secondary session) was considered where a normally distributed random effect is added to logit(*p*) on the logit scale for each individual, i.e., $p_i = \frac{1}{1+\exp\left(-\left[\text{logit}\,(\bar{p}) + z_i\right]\right)}$, where z_i is a normally distributed random variable with mean zero and standard deviation σ_p. The likelihood is integrated numerically over the normal distribution so that σ_p can be estimated.

Effort measured as the number of trap nights for each of the secondary occasions was used as a covariate to model time variation in *p* estimates (Table 7). The individual random effects model was also used with the effort models. We note that traps were fished from either downriver or all sections of the river on alternate days so that any biases associated with spatially-varying effort were not confounded with time.

Assessing Goodness-of-Fit - The confounding of the *S* and *r* parameters precludes evaluating lack of fit for this portion of the model. However, extra-binomial variation may exist within the closed-captures portion due to individual heterogeneity and lack of independence of captures. The logit normal model described above provides strong evidence of individual heterogeneity, but additional extra-binomial variation may be present. Therefore, we used the median $\hat{c}$ procedure in MARK to assess the extent of overdispersion in the closed-captures portion of the likelihood. We extracted just the 2013 live captures from the data, and the median $\hat{c}$ procedure on the Huggins closed captures model with individual random effects (described above). The median $\hat{c}$ procedure estimates the amount of extra-binomial variation to generate a value of *c* that produces data with half of the fish greater than the observed $\hat{c}$, and half with values less than the observed $\hat{c}$. Logistic regression is used to estimate this median value.

We generated 3 estimates of $\hat{c}$ to assess the amount of variation as this is a Monte Carlo procedure. For each estimate, we used a total of 22 points on the *x* scale, with 50 simulations at each point. Each run took approximately 10 hours on a 12-thread machine dedicated to these jobs. The 3 values were 1.46, 1.48, and 1.50, giving both a mean and median value of 1.48, with the standard error of the mean of 0.013. The $\hat{c}$ = 1.48 was then applied to the full Barker model.

Results

Environmental Conditions in 2012 and 2013

Compared with 2012, average environmental conditions in surface and bottom waters in 2013 were significantly cooler ($F_{surface}$ = 44.08, P<0.01; F_{bottom} = 50.20, P<0.01), fresher ($F_{surface}$ = 108.76, P<0.01; F_{bottom} = 75.15, P<0.01), and more oxygenated ($F_{surface}$ = 15.54, P<0.01; F_{bottom} = 44.71, P<0.01) (Figure 10). The lower temperature and salinity conditions at our study site in 2013 reflected the higher mean discharge in the James River in that year (Figure 11). Dissolved oxygen conditions in our study exceeded 3.3 mg/L at all times and thus were not likely to have affected the distribution of blue catfish (Figure 10).

Tag Retention and Tag-Induced Mortality

We observed mortalities among laboratory-held tagged fish, ranging from 2 to 5 mortalities per tank, with an average mortality rate of 15.5% (SE=0.0666; Table 1); however, none of the control fish experienced mortality, suggesting that the tagging procedure rather than handling may have caused mortality in captive blue catfish. Higher tag-retention rates among fish from the second group (Table 1) are attributed to the increased experience with tagging and handling techniques. Overall, fish from the second group (which were tagged by staff that had gained experience) generally had greater tag retention rates (0.818 to 1.000) than fish from the first group (0.333 to 0.800; Table 1). We believe that these higher tag retention rates (near 100%) were obtained in the field experiment in the James River because we implemented a rigorous training protocol prior to tagging operations in 2012 and 2013.

In the field, we noted the presence of a circular mark and the absence of a CWT in seven putative recaptures in 2012 (7 out of 930 fish or about 0.7% tag loss). We believe this represents a conservative assessment of tag loss because the circular mark was not likely to remain visible for long periods of time. In 2013, we noted tag loss in 4 fish (out of 402 recaptures and recoveries or about 1% tag loss); these fish had been released in 2013 with multiple CWTs, but were recaptured or recovered with a single tag. Our observations from the laboratory study and from the field suggest minimal or negligible tag loss rates for CWTs so we did not adjust estimates of population size or survival rates for tag loss.

Releases (2012 and 2013)

Fish marked and released in 2013 were, on average, 10.4 mm larger than those marked and released in 2012 (N_{2012}=899, $mean_{2012}$ = 280.2 mm FL, SE_{2012} = 0.896; N_{2013}=799, $mean_{2013}$ = 290.6 mm FL, SE_{2013}=0.924). Although statistically significant (F=65.37, P<0.01), the 10.4 mm increase observed in 2013 is not likely to be biologically significant given the broad, overlapping ranges of fish size used in this study (Figure 6). We believe that the increase in mean size of fish marked and released in 2013 was due to increased culling efficiency in 2013 relative to 2012: in 2013, the waterman employed an assistant to aid in the sorting of fish and improve the accuracy of the culling procedure. As evidence of this, we note that in 2013, the mean length of fish provided for tagging (290.6 mm) was significantly greater than that of harvested fish (260.9 mm; F=249.83, P<0.01).

Recaptures (2012 and 2013)

In 2012, we encountered 930 previously tagged fish that measured 241 to 430 mm FL (mean = 288.0; SE = 0.783; n=928 and excludes fish recaptured in the release week). The range of sizes of recaptured fish was similar to that of fish at time of release (214-464 mm FL; Figure 12); the difference in mean size of fish at time of release and time of recapture was 7.8 mm (fish recaptured in 2012 were significantly larger than fish released in 2012; F=43.27, P<0.01). This represents a statistically significant result (due to large sample sizes), but is not likely a biologically meaningful one given the size distributions observed (Figure 12). As expected, fish tagged in the later weeks represented a smaller proportion of recaptured fish due to shorter times at-large and fewer opportunities for encounter. Number of recaptures during the fourth week were low because fish tagged in week four were vulnerable to recapture for a maximum of only four days.

We observed 247 recaptures during 2013 that ranged in size from 253 mm to 398 mm FL (mean=301.8; SE = 1.820; N=245 and excludes fish recaptured in week of release); with the exception of 28 fish, all of the fish recaptured in 2013 were released alive after obtaining length measurements. Fish tagged in 2012 and recaptured in 2013 (N = 27) were observed throughout the 2013 tagging period, and represented a relatively small proportion of the total recaptures (10.6%; Table 8). Of the 2013 releases, fish released in weeks one (48.8%) and two (37.8%) comprised the majority of recaptured fish, which were observed in week three of 2013 (Table 8). The majority [98.2%] of 2013 releases that were recaptured had no fin clip, indicating they were first-time recaptures, and none were recaptured more than twice after release.

Recoveries (2013 and 2014)

In 2013, we scanned 10,797 fish for CWTs during 11 occasions, and recovered 193 previously tagged fish (Table 3). The size range of 2013 recoveries from the harvest was 246-462 mm FL, whereas harvested fish measured 152-463 mm FL (based on a random subset of fish measured each day; N = 525). Note that substantially smaller fish were present among the harvested fish. The mean size of fish harvested in 2013 was 260.9 mm FL (SE=1.459). Although fish tagged in 2012 comprised a relatively small proportion (5.7%) of recoveries in 2013, we observed them among harvested fish throughout the study period in 2013. Similar to what we observed during tagging operations, fish tagged in weeks one (34.7%) and two (40.4%) in 2013 comprised the majority of recoveries in 2013. None of the tagged fish were encountered more than twice after release, either during field operations on the water or among the harvested fish (i.e., fish were captured, tagged, and encountered once or twice more).

We processed the entire commercial catch on 29 days between 7 July and 22 August 2014 and inspected 41,925 fish, among which we detected and recovered 86 tagged fish (272-483 mm FL) (Table 3). The mean size of fish harvested in 2014 was 242.2 mm FL (N=2,849), which was significantly less than the mean size of fish harvested in 2013 (260.9 mm FL; N=525; difference in means=18.7 mm; F=82.14, P<0.01). Fish released in 2013 comprised the majority (75.6%) of fish recovered in 2014, which may be due to the shorter period of time at liberty relative to fish released in 2012 (and hence, greater survival). We recovered tagged fish throughout the inspection period, but no tagged fish were recovered on three of the days (30 July, 1 August, and 11 August 2014). The lower recoveries observed in 2014 may be due to the lower overall fishing effort that occurred in that year during July-August (effort_{2013} = 1,324 trap nights; effort_{2014} = 1,052 trap nights).

Recoveries from Auxiliary Surveys

Additional sampling (441 events; 6,149 fish checked for tags) was conducted by various agencies and institutions between July 2012 and December 2014 (Table 9); these events encompassed both open and closed periods. Despite incorporating multiple gear types (trawl; low-frequency electrofishing; and gill nets) and sampling multiple habitats (within, upstream, and downstream of the study area near Claremont, VA), only one coded-wire tagged blue catfish was encountered. The single fish was recaptured by the VIMS trawl survey in the James River on 26 April 2014, about 26 km downriver of the downstream boundary of our tagging area. This fish had been tagged and released in the first tagging week (7 July-13 July) of 2012. The extremely low recovery rate we observed among other surveys was quite surprising because the sampling gears used in these surveys are highly effective at capturing blue catfish. This was also surprising because some of these surveys occurred within our study area (electrofishing, trawl). In particular, the trawl survey operated monthly and year-round within and downriver of the study area; this was the only survey to intercept a tagged fish. Such low recoveries suggest a large population size, differential availability to the gears (commercial traps versus survey gears), or both.

Population Size and Survival Rate

Eight models were fitted to the data using the Barker robust design, and simple models with only 5 to 7 parameters provided the poorest fits (Table 10). The median $\hat{c}$ procedure produced an estimate of $\hat{c}$ = 1.48, with a standard error of 0.013. Nearly all of the model weight of 99.3% was associated with the model {*S*(year1,2=3) *r*(year1,2=3) *p*(year2*secondary) Random Effects)}. Therefore, there was no need for model averaging. Parameter estimates corrected for $\hat{c}$ from the Barker robust design are shown in Table 11.

The population estimate for the 2013 closed captures primary occasion was $\hat{N}$ = 1,639,830 with a standard error of 403,156 and 95% confidence interval of 1,021,680 – 2,638,900 when not corrected for $\hat{c}$ = 1.48. When corrected, the standard error was 490,460 and the 95% confidence interval was 926,307 – 2,914,208. These confidence intervals are based on a lognormal distribution.

The probability of detecting an untagged fish during each of the four secondary occasions in 2013 was quite low: 0.001-0.002 (Table 11); although these probabilities were not significantly different, the point estimates declined with time.

The estimated annual apparent survival rate in 2012-2013 was 0.16 (SE=0.035), with a 95% confidence interval of 0.10 to 0.24 (Table 11). The estimated survival rate in 2013-2014 and 2014-2015 was significantly greater: 0.44 (SE=0.070), with a 95% confidence interval of 0.31 to 0.58. These are apparent rates because fish may have emigrated from the study area, thereby contributing to 'losses'.

Discussion

In July-August 2013, tidal freshwater habitats along a 12-km stretch of the James River near Claremont, VA, supported about 0.9 to 2.9 million invasive blue catfish, with a 'best' estimate of population size of 1.6 million fish. Our study area encompassed 3,017 ha; 1.6 million fish in this area of the river equates to a density of 544 blue catfish/ha. This density estimate is in the same order of magnitude of previous estimates for blue catfish in the James River, though our estimate is somewhat higher. A three-day mark-recapture study conducted by the VDGIF in Powell Creek, a tributary to the James River, yielded an estimate of 338 blue catfish/ha in 2014 (Bunch et al. 2015). The VDGIF study used low-frequency electrofishing to sample fish in July 2014. Another approximation of the density of blue catfish in the upper James River near Charles City, VA, is based on low-frequency electrofishing sampling in 2012, 2013, and 2014; this study yielded a mean estimate of 315 blue catfish/ha with a 95% confidence interval of 289-340 fish/ha (G. Garman, VCU, *pers. comm*.). We emphasize that high densities of blue catfish are typically observed in the James River near Upper Chippokes Creek; our estimate of density for blue catfish (544 fish/ha) may reflect the fact that this portion of the river was part of our study area.

Using our estimate of density (544/ha), and assuming equal densities throughout habitats in which blue catfish are commonly and routinely captured in the James River (36,385 ha from Richmond to the upriver limit of Burwell Bay), we estimate 19.8 million blue catfish in this system. We note that blue catfish are also captured in VIMS fisheries surveys further downriver in the James River subestuary near Burwell Bay and Newport News (the single blue catfish captured at 21.8 psu was taken from an area near Newport News). This lower portion of the river exhibits mean annual bottom salinities between 4.6 and 7.6 psu (mean observed from 2005 to 2015); however, in some months, salinities as high as 15.1 psu were recorded from these habitats so we omitted this portion of the river from the calculation above (i.e., these areas were excluded from the estimate of 36,385 ha). Due to the potential for highly fluctuating salinities, we are uncertain if these lower areas of the James River are regularly occupied by blue catfish. Thus, we used the upriver limit of Burwell Bay to represent a conservative estimate of the downriver extent of the blue catfish population in the James River. In addition, our estimate of population size applies to the population of blue catfish that ranges in size from about 240 to 460 mm FL. These fish represent the portion of the population in the James River that is vulnerable to capture by the trap fishery (though we note that the trap fishery also includes fish of smaller size as evidenced by the mean sizes we observed in 2013 and 2014: mean $size_{2013}$ = 260.9 mm FL, mean $size_{2014}$ = 242.2 mm FL). These fish also represent the sizes vulnerable to capture by bottom trawl (VIMS Juvenile Fish Trawl Survey, *unpubl. data*) and electrofishing (Greenlee and Lim 2011); it is likely that this size range of fish represents a sizeable portion of the total biomass of blue catfish in the James River. We also note that our tagging study in the James River included blue catfish >300 mm FL, which is the size at which individuals begin to include fishes in their diet (Schloesser et al. 2011). In addition, blue catfish >300 mm FL are more common among those fish that colonize new habitats in the mesohaline portion of the river (Fabrizio et al. *unpublished ms.*). Thus, our estimates of population size include that portion of the population of blue catfish that may be piscivorous and may participate in colonization of estuarine habitats.

Because some of the tagged blue catfish may have experienced tag loss, our estimate of population size is likely to be biased low and to be less precise than what we report. Field-based and laboratory evidence for tag loss suggests such rates are low or negligible. Our estimate of tag-induced mortality (15.5%) from laboratory-held fish may overestimate true rates in the field because we handled fish multiple times (to examine fish for tag retention) which may have stressed captive fish. We believe these rates were associated with the multiple handling events and not the presence of the tag. We did not adjust our estimates of population size by tag loss rates or tag-induced mortality because of the short duration (14 weeks) of the lab experiment and the small number of possible observations of tag loss from fish released in the James River. Further research on tag loss and tag-induced mortality rates is warranted if future studies are pursued with blue catfish tagged with CWTs.

Our estimate of the population size of blue catfish depended on extremely low estimates of the mean *p* value; all of our estimates of *p* were $\leq$ 0.0022. Such small values may not produce a reliable population estimate, particularly given that the σ_p estimate is 1.05. The resulting distribution of the probabilities of individuals being captured one or more times is quite skewed. We observed a declining pattern in the probability of detection of untagged fish (i.e., *p*) in 2013, which likely mirrored the pattern in effort: effort declined from 168 trap-nights in week 1 to 113 trap-nights in week 4 (Table 7) and was used as a covariate to model *p*. However, the decline in *p* was not significant. We found no evidence of heterogeneity in *p* associated with fish size: the range of sizes of recaptured fish was similar to the range of sizes of marked fish in the James River. Thus, size-based movement was not likely occurring in this population at this time (July-August 2013). Further evidence for this is the extremely low recovery rate (0.02%) of blue catfish from among more than 6,000 fish scanned for CWTs throughout the freshwater and mesohaline habitats of the James River. We observed a single tagged fish, which moved downstream from the point of release. Surveys for tagged blue catfish occurred year round, with multiple (and highly effective) gears, from broad spatial areas that included and extended beyond our study site, yet only a single fish was encountered.

One of the assumptions of the robust design is that the population remains closed during the secondary periods; in our case, this requires making the assumption that fish remained in the study area during the four-week period of tagging in 2013. If fish emigrated permanently from the area or if fish colonized our study area from adjacent habitats in the James River, Chickahominy River, or Upper Chippokes Creek, then our estimate of population size will be biased high. We conducted our sampling during a time when long-range movements of blue catfish were thought to be minimal (i.e., post-spawning, in summer). Habitat conditions in our study area in 2013 were fresher and cooler than in 2012, which may have decreased the likelihood of permanent emigration, although we note that the effects of environmental conditions on invasive blue catfish movements are unknown. In general, the movement ecology of blue catfish within the James River system is largely unknown and it is possible that blue catfish move to tributaries such as Upper Chippokes Creek and remain there for extended periods of time (e.g., greater than one month); in this manner, they may have been unavailable to the traps. We recommend further study of habitat use and movement of blue catfish in large subestuaries such as the James River.

Although not possible to quantify with certainty, the total number of tagged fish removed by commercial harvesting was likely to be comparable to the total number of recaptures that we observed during our study in 2012 and 2013 (N=1,177). Because we inspected the harvest during only 11 occasions in 2013, it was not possible to calculate the total number of tagged fish recovered in 2013 without making assumptions about the daily rate of recoveries and the proportion of recoveries from the 2012 releases versus the 2013 releases. We considered this possibility, but abandoned the approach due to the high variability in daily catch and recovery rates. Fishery removals are a potentially large source of uncertainty that must be acknowledged in the interpretation of estimates of population size and survival rates. The closure assumption may have been invalid if fishery removals during the secondary occasions of 2013 were non-negligible; in this case, our estimate of population size would be biased high. Although we did not inspect the harvest for removals on each of the 2013 secondary occasions, we did account for known removals during those times (using the dot designation in the closed-capture portion of the model). In contrast to the effect of fishery removals on estimates of population size, the CJS estimates of survival rates are not likely to be affected by fishery removals (because the population is 'open' to losses). Thus, the higher apparent survival rates observed in 2013-2014 relative to 2012-2013 suggest that a greater proportion of fish remained in the area in 2013-2014. Fish may have remained in the area because they did not emigrate (or if they did, they returned in the following year), or because they simply experienced higher survival rates, or both. With the exception of a single fish, the lack of observations of blue catfish from multiple auxiliary surveys in the James River suggests that these fish may not undertake extensive movements; however, our examination of movement of invasive blue catfish in the Potomac River does not support this hypothesis. Further research to understand the relative proportion of the population that undertakes long-distance movements is warranted.

One of the motivating questions for this study concerned the level of removal (e.g., harvest) required to reduce the density of blue catfish populations in tributaries of Chesapeake Bay. The feasibility and efficacy of using blue catfish fishery removals to reduce abundance in coastal tributaries is not known. An estimate of the amount of surplus production associated with each stock and the harvest level that can be sustained is needed to assess the likelihood that removals due to the fishery will be effective in controlling the spread of this invasive species. In addition, we currently lack knowledge of how and when individuals colonize new areas and factors associated with the down-estuary range expansions observed in coastal tributaries. Changes in spatially-explicit abundances have been postulated to be associated with environmental factors; in particular, river flow and precipitation in the watershed are thought to affect blue catfish movements and range expansion in tidal tributaries of Chesapeake Bay (Edmonds 2006). Further research could help to understand habitat use and the magnitude of fish movement; in particular, examination of the partial migration strategy (e.g., Jonsson and Jonsson 1993; Kerr et al. 2009) for this species could elucidate the role of movement in maintaining population abundance and in realizing range expansion.

Acknowledgments

We thank Mr. R. Neal Leatherwood and his assistant, Daniel, for their interest in this research and dedicated effort to provide fish for this study. We are grateful to Geraldine Vander Haegen and others at Northwest Marine Technology for providing use of the R9500 tunnel detector in 2013 and 2014; this loan greatly expedited our screening of fish for coded-wire tags. We thank Chris Bonzek for assistance with database creation and management. University and agency scientists conducting fishery-independent surveys in the James River provided valuable assistance by scanning blue catfish for CWTs; we are grateful to Greg Garman and Steve McIninch (VCU electrofishing survey), Eric Brittle, Aaron Bunch, and Robert Greenlee (VDGIF electrofishing survey), Patrick McGrath (VIMS gill-net survey), Joseph Schmitt (VA Tech electrofishing survey), and Hank Brooks, Aimee Comer, Christopher Davis, Rebecca Hailey, James Harrison, Jennifer Greaney, Emily Loose, and Wendy Lowery (VIMS Juvenile Fish Trawl Survey). Finally, none of this work could have been realized without the able assistance of dozens of VIMS staff, students, and volunteers in the field. We thank Sarah N. Mahlandt and Christi Linardich for their valuable contribution as summer field assistants in 2012; Beth Dzula, Sayer Fisher, Andrew Friedrichs, Carol Paulson, and Dominique Thomas in 2013; and Shirley Chu, Andrew Friedrichs, Ben Lanning, Matt Oliver, and Manisha Pant in 2014. Others who lent a much-appreciated, helpful hand in the field during the tagging experiment were: Diana Belcher (VIMS, summer field assistant), Hank Brooks (VIMS, Recruitment Surveys Program), Andre Buchheister (VIMS, Ph.D. student), Melanie Chattin (VIMS, ChesMMAP/NEAMAP), Aimee Comer (VIMS, Recruitment Surveys Program), Theresa Davenport (VIMS, M.S. student), Alison Deary (VIMS, Ph.D. student), Robert Fitchett (VIMS, summer field assistant), Emilie Franke (NOAA), Carissa Gervasi (VIMS, M.S. student), Cassie Glaspie (VIMS, M.S. student), Jennifer Greaney (VIMS, Recruitment Surveys Program), Rebecca Hailey (VIMS Recruitment Surveys Program), Mark Henderson (VIMS, Ph.D. student), Virginia Hewitt (VIMS, summer field assistant), Wendy Lowery (VIMS, Recruitment Surveys Program), Leonard Machut (VIMS, Recruitment Surveys Program), Benjamin Marcek (VIMS, Ph.D. student), Cindy Marin Martinez (VIMS, M.S. student), Danielle McCulloch (VIMS, staff), Taylor Moore (VIMS summer field assistant), Vaskar Nepal (VIMS, Ph.D. student), Ryan Norris (VIMS, Recruitment Surveys Program), Lauren Nys (VIMS, M.S. student), Kristen Omori (VIMS, M.S. student), Ryan Schloesser (VIMS, Ph.D. student), David Shields (VIMS, summer field assistant), Diane Tulipani (VIMS, Ph.D. student), Andrew Turner (NOAA), Margaret Walker (VIMS, REU student), Dixon Wilde (volunteer), and Megan Wood (VIMS, Ph.D. student). This study was funded by the National Oceanic and Atmospheric Administration, Chesapeake Bay Office (Award Number NA11NMF4570222).

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Table 1. Number and size (fork length [FL], mm) of blue catfish tagged with CWTs in 2012 and used to estimate tag retention rates and tag-induced mortality. Group refers to the group of fish tagged first by novice taggers and second by experienced taggers. The tag retention rate is calculated as the quotient of (the final number of fish with tags) and (the number of fish tagged minus the number of mortalities). The mean tag retention rate was 0.796 (n=8 replicates; SE = 0.0750) and the mean mortality rate was 0.155 (SE=0.0666). In addition, 16 control fish were maintained alongside tagged fish in tanks D (n=8) and E (n=8); these fish were handled, but not tagged. None of the control fish experienced mortality. The total number of fish held was 93 (77 tagged; 16 control).

Tank	Group	Mean FL (mm)	Size Range (mm)	# of Fish Tagged	# of Mortalities	Final # of Fish with Tags	Tag Retention	Mortality
A	1	370	300-619	8	2	2	0.333	0.250
B	1	356	304-580	10	0	7	0.700	0
C	1	383	315-770	10	5	4	0.800	0.500
D	2	322	288-434	7	0	6	0.857	0
E	2	316	289-431	7	0	6	0.857	0
F	2	316	284-350	11	2	9	1.000	0.182
G	2	306	297-324	11	0	9	0.818	0
H	2	319	296-384	13	4	9	1.000	0.308
Total		322	284-770	77	13	52	0.796	0.155

Table 2. Dates and duration of sampling activities for the blue catfish mark-recapture study in the James River, VA, 2012-2014.

Year	Activity	Dates	Duration
2012	Mark	8 July – 4 Aug	4 weeks
	Recapture	9 July – 4 Aug	4 weeks
2013	Mark	20 July –16 Aug	4 weeks
	Recapture	20 July – 25 Aug	5 weeks
	Recovery	21 July – 25 Aug	5 weeks
2014	Recovery	7 July – 22 Aug	6 weeks

Table 3. Summary of tagging and inspection events by year for the blue catfish mark-recapture study in the James River, VA. Fish were tagged with coded-wire tags. An inspection event refers to the inspection of the commercial harvest for coded-wire tagged fish. Recaptures are fish encountered during the tagging operations (total=1,176); recoveries are dead encounters from the harvest (total=279). The total number of recaptures and recoveries is 1,456. The total number of harvested fish was estimated by converting the waterman's daily catch (in pounds) to numbers using an established fork-length-to-weight relationship for blue catfish from Chesapeake Bay tributaries ($W = 4.77X10^{-6}L^{3.14}$; T. Tuckey and M. Fabrizio, *unpubl. data*), we estimated).

Year	Number of Occurrences		Number of Fish					
	Tagging	Inspection	Tagged	Inspected	Recaptured in 2012	Recaptured in 2013	Recovered in 2013	Recovered in 2014
2012	19	0	15,721	0	930	27	11	21
2013	16	11	18,531	10,797	-	220	182	65
2014	0	29	0	41,925	-	-	-	-
Total	35	40	34,252	52,722	930	247	193	86

Table 4. Simplified encounter histories for blue catfish from the James River, VA. Fish were tagged with coded-wire tags in 2012 and 2013 and encountered in 2012, 2013, and 2014. Encounter histories are a series of 0's and 1's, with 0 indicating not observed and 1 indicating observed for each tagging or recapture event in the study (each week). In the Barker data type, two columns are used: the first records information (0, 1) for live fish, and the second pertains to dead recoveries (0, 1) for a given sampling event. The simplified histories below were used to prepare encounter histories for analysis with the Barker robust design. The column titled 'number of fish' indicates the number of tagged blue catfish that shared a given encounter history; a negative number indicates fish were euthanized; these are treated as 'losses on capture' as described in Cooch and White (2016).

Encounter history	Number of fish
101000000000	-13
100100000000	4
100010000000	-5
100001000000	1
100000100000	-4
100000010000	4
100000001000	-5
100000000100	2
100000000001	21
100000000000	14784
100000000000	-878
001100000000	14
001011000000	1
001010100000	2
001010000000	45
001001000000	16
001000101000	1
001000100000	51
001000010000	13
001000001000	22
001000000100	23
001000000001	23
001000000000	6063
000011000000	13
000010100100	3
000010100000	64
000010010000	19
000010001100	1

000010001000	30
000010000100	44
000010000001	23
000010000000	5397
000000110000	3
000000101000	3
000000100100	17
000000100001	7
000000100000	3792
000000001100	16
000000001001	12
000000001000	2813

Table 5. Parameters used in the Barker robust design model to estimate population size, survival rates, detection probabilities, and tag recovery rates for blue catfish in the James River, VA.

Model parameter	Description
S(year)	Annual survival between primary sessions, with one additional survival rate estimated post-2014.
p(year*occasion)	Detection probability of untagged fish during each of the secondary occasions. The detection probability for 2012 is not identifiable from the closed-capture portion of the likelihood because there is only one secondary occasion, and this parameter is not part of the Cormack-Jolly-Seber or dead recoveries portion of the likelihood. To allow us to use the 2012 releases for estimation of survival, we fixed the first *p* parameter in 2012 to 1, conditioning on capture during 2012 and indicating that the captured fish were released. Only 4 *p* parameters were estimated for the 2013 secondary occasions based on the closed-captures model. The *p* parameter was fixed to 0 for the dummy secondary occasion in 2012, and also for the two dummy secondary occasions in 2014. Note that all the models considered assumed that $p = c$, i.e., that initial detection probabilities (*p*) were the same as recapture probabilities (*c*). Thus, for these models, *p* is the probability of capturing a fish regardless of whether it had been previously tagged.
c(year*occasion)	Probability of capturing (recapturing) a tagged fish that was marked during the same primary occasion. Only 3 recapture probabilities during 2013 are estimable, and all the models considered assumed that $c = p$, i.e., that recapture probabilities (*c*) were the same as initial detection probabilities (*p*).
r(year)	Probability that the tag is recovered given that a fish has died.
R(year)	Probability that a fish is encountered alive between primary occasions, and remains alive to the next primary occasion. All *R* parameters were fixed to zero.
R'(year)	Probability that a fish is encountered alive between primary occasions, but dies before the next primary occasion. All *R'* parameters were fixed to zero.
F(year)	Fidelity of fish to the study area between primary sessions. These parameters were fixed to 1 because they are not estimable.
a'(year)	Probability of a fish remaining in the study area between primary sessions. These parameters were fixed to 1 because they are not estimable.
a''(year)	Probability of a fish that has temporarily emigrated from the study area between primary sessions has returned to the study area. These parameters were fixed to 1 because they are not estimable unless *a'* is <1, i.e., fish have to be allowed to leave temporarily in order to return.

Table 6. Barker robust design models used to estimate population size in 2013, survival rates, detection probabilities, and tag recovery rates for blue catfish in the James River, VA.

Model	**Number of parameters for *S* and *r***
{*S*(.) *r*(.)}	2
{*S*(.) *r*(year1, year2=year3)}	3
{*S*(year1, year2=year3) *r*(year1, year2=year3)}	4

Table 7. Commercial fishing effort (trap-nights) in the James River near Claremont, VA, in 2012-2014; this effort relates to the fish provided for tagging and does not include harvest effort when no fish were provided or observed in this study. For 2013, information from week 5 was pooled with week 4 (because no fish were tagged in week 5).

	2012	**2013**				**2014**
	Weeks 1 - 4	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Weeks 1 - 6**
Trap-nights	570	168	140	132	113	692
# Fish inspected		1848	1566	1872	5511	41,925

Table 8. Number of blue catfish recaptured by year (and week in 2013) from the James River, VA. Fish were tagged with coded-wire tags. Shaded boxes represent data used in the model to estimate population size. For 2013, information from week five was pooled with week four (because no fish were tagged in week 5).

Release Year	Recaptured in 2012	Recaptured in 2013				Recaptured in 2014
		Week 1	Week 2	Week 3	Week 4	
2012	930	13	5	4	5	21
2013	-		45	117	58	65

Table 9. Effort expended by gear and number of blue catfish inspected for coded wire tags in auxiliary surveys in the James River in 2012-2014. *The VIMS/VDGIF survey occurred only in September of each year; **the VIMS trawl survey occurred monthly. Surveys spanned the area from Richmond, VA, to the James River Bridge near Newport News, VA. All fish $\geq$ 240 mm FL were scanned for CWTs. Number of sites sampled are individual locations (electrofishing or trawls) or number of sets (gill net).

Agency	Gear	Begin Date	End Date	Number of Sites Sampled	Number of Fish Scanned for CWTs
VCU	Electrofishing	Aug 2012	Oct 2012	7	284
VDGIF	Electrofishing	Jul 2012	Jul 2012	2	145
VIMS/VDGIF*	Electrofishing	Sep 2012	Sep 2013	12	935
VCU/VIMS	Electrofishing & trawls	Oct 2012	Oct 2012	12	321
VA Tech	Electrofishing	May 2013	Jun 2013	14	658
VIMS **	Trawl	Aug 2012	Dec 2014	316	2,720
VIMS	Gill net	Mar 2014	May 2014	78	1,086
TOTAL				**441**	**6,149**

Table 10. Model selection results for blue catfish using the Barker robust design in Program MARK. Model selection was based on quasi-AIC (QAIC) values corrected for small sample sizes, with $\hat{c}$ =1.48; k is the number of parameters; *S, r,* and *p* are defined in Table 5.

Model	$QAIC_c$	$\Delta QAIC_c$	QAIC Weights	k	-2log(*L*)
{*S*(year1,2=3) *r*(year1,2=3) *p*(year2*secondary) Random Effects)}	38016.036	0	0.9927	9	56237.09
{*S*(year1,2=3) *r*(year1,2=3) *p*(year2*secondary)}	38025.860	9.824	0.0073	8	56254.59
{*S*(.) *r*(year1,2=3) *p*(year2*secondary)}	38072.828	56.792	0	7	56327.06
{*S*(year1,2=3) *r*(year1,2=3) *p*(year2 effort) Random Effects)}	38202.295	186.259	0	7	56518.67
{*S*(year1,2=3) *r*(year1,2=3) *p*(year2 effort))}	38212.057	196.021	0	6	56536.08
{*S*(.) *r*(.) *p*(year2*secondary)}	38244.681	228.645	0	6	56584.36
{*S*(year1,2=3) *r*(year1,2=3) *p*(year2 constant) Random Effects)}	39070.086	1054.050	0	6	57805.96
{*S*(year1,2=3) *r*(year1,2=3) *p*(year2 constant)}	39079.331	1063.295	0	5	57822.61

Table 11. Parameter estimates from the minimum $QAIC_c$ model {*S*(year1,2=3) *r*(year1,2=3) *p*(year2*secondary) Random Effects)}. Standard errors and confidence intervals are corrected for overdispersion with $\hat{c}$ = 1.48. Logit-based confidence intervals (CI) use the logit transformation to produce the upper (UCI) and lower (LCI) 95% bounds.

			Logit-based CI	
Label	**Estimate**	**SE**	**LCI**	**UCI**
S 2012–2013	0.16164	0.03528	0.10374	0.2431014
S 2013–2014 & 2014–2015	0.4433	0.06987	0.31375	0.5810567
r 2012	0	0	0	0
r 2013 & 2014	0.01667	0.00181	0.01347	0.0206145
σ_p 2013	1.05122	0.15515	0.74712	1.3553197
p 2013 Occasion 1	0.00223	0.00102	0.00091	0.0054475
p 2013 Occasion 2	0.00200	0.00092	0.00082	0.0049015
p 2013 Occasion 3	0.00140	0.00064	0.00057	0.0034303
p 2013 Occasion 4	0.00103	0.00047	0.00042	0.0025270

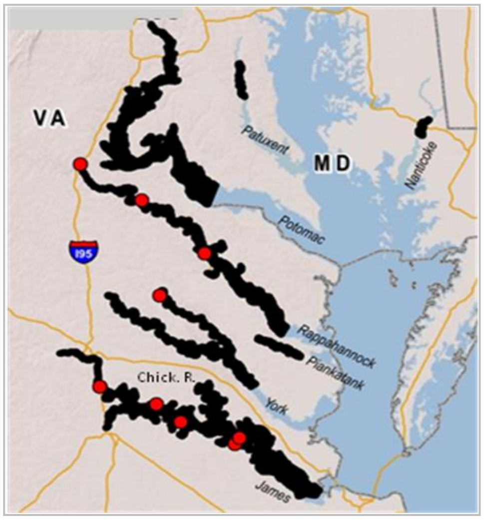


Figure 1. Stocking locations (red dots) and occurrence of blue catfish (black dots) in tributaries of Chesapeake Bay based on electrofishing and bottom trawl surveys from 2003-2008 (from Schloesser et al. 2011); ‘Chick. R.’ refers to the Chickahominy River.

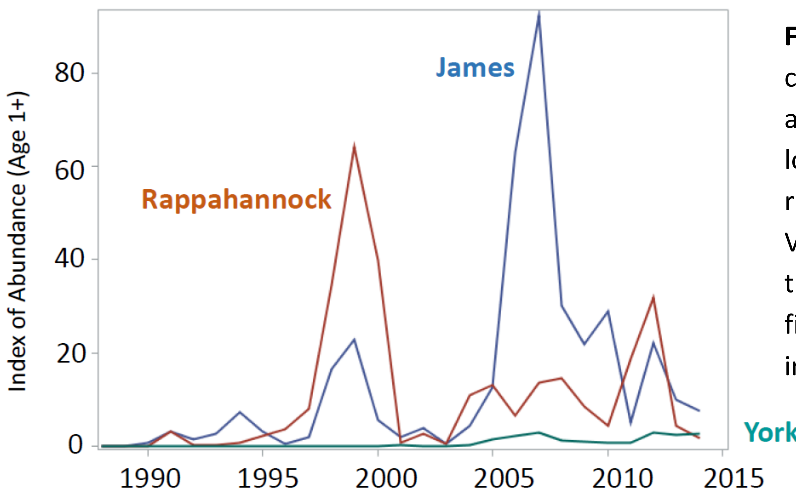


Figure 2. Relative abundance of blue catfish in tributaries of Chesapeake Bay; abundance was estimated using a delta-lognormal index and samples from a random stratified survey conducted by VIMS from 1988-2013 using a bottom trawl (Tuckey and Fabrizio 2015). Only fish age-1 and older were included in this index.

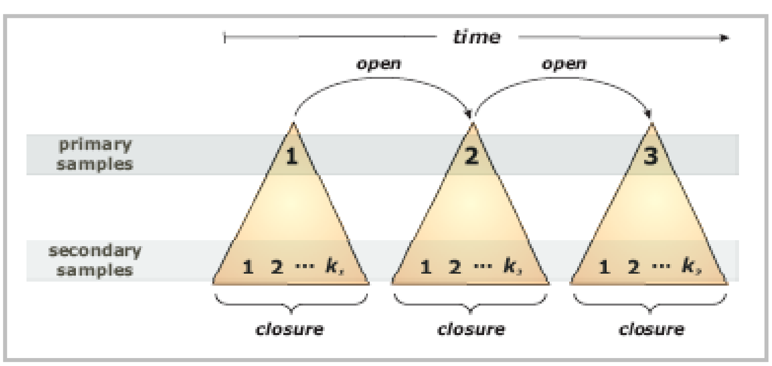


Figure 3. Relationship between the primary (open) and secondary (closed) sampling periods in the robust design (Pollock 1982). We marked and released fish during 4 occasions within the secondary period (k=4 secondary samples, equivalent to weeks in our study); figure from Kendall (2010).

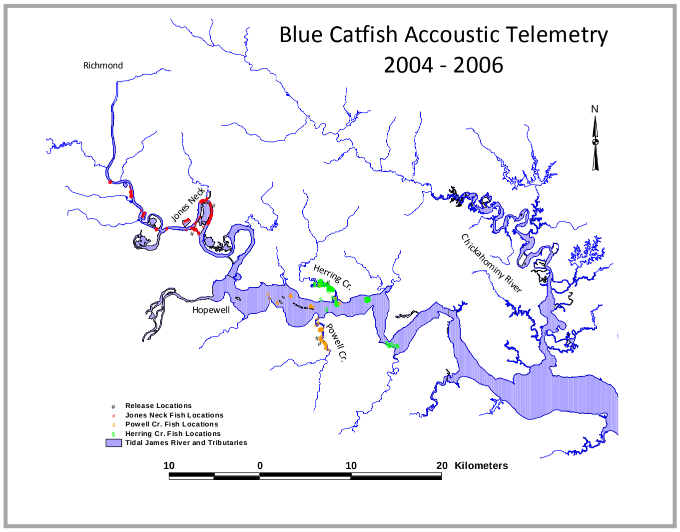


Figure 4. Release and detection locations of 27 blue catfish tagged with acoustic transmitters in the upper James River, VA. Image from VA Department of Game & Inland Fisheries.

Figure 5. Location of mark-recapture study of blue catfish in the James River, VA (red dashed area); inset depicts the Chesapeake Bay, with arrow pointing to the James River study site. The river flowing south into the James River is the Chickahominy River. Image adapted from T. Saxby and K. Boicourt, IAN, Univ of MD Center for Environmental Science.

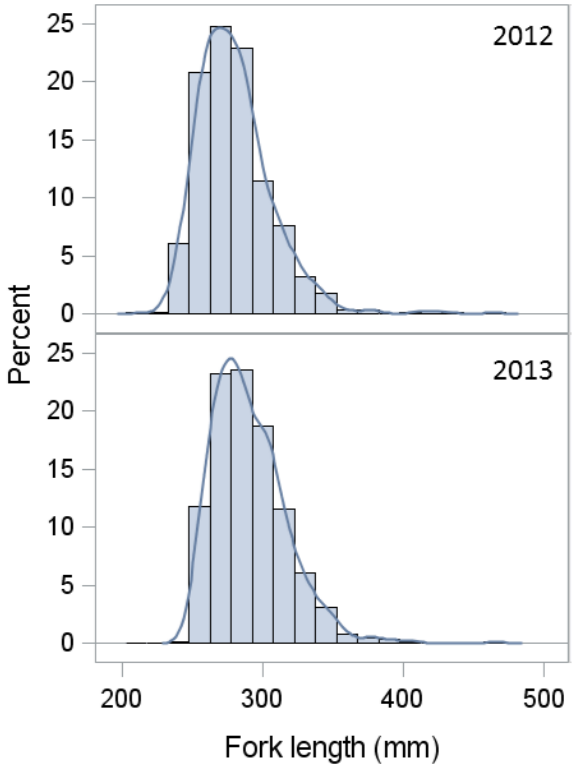
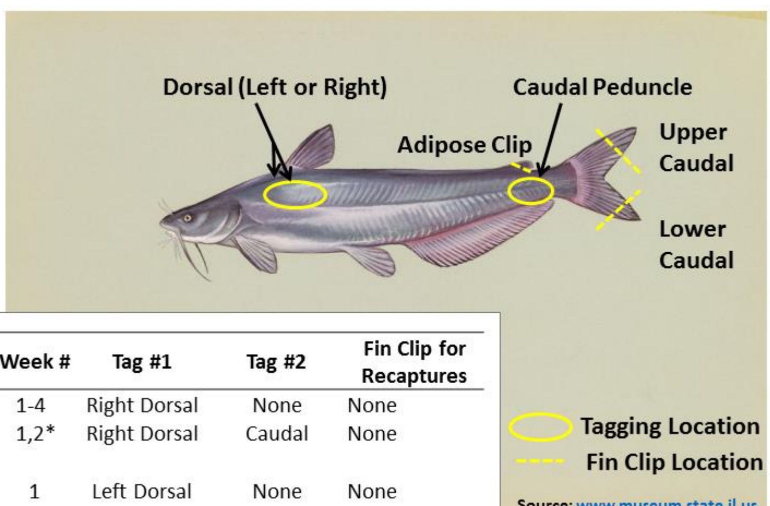


Figure 6. Length-frequencies of blue catfish marked and released in 2012 and 2013 in the James River, VA (n=899 in 2012; n=799 in 2013; total = 1,698). The solid line is a kernel density fit to the frequencies.



Year	Week #	Tag #1	Tag #2	Fin Clip for Recaptures
2012	1-4	Right Dorsal	None	None
2012	1,2*	Right Dorsal	Caudal	None
2013	1	Left Dorsal	None	None
2013	2	Left Dorsal	Caudal	Upper Caudal
2013	3	Left Dorsal	Right Dorsal	Lower Caudal
2013	4	Caudal	None	Adipose

* Used only with fish recaptured on 13 and 16 July 2012

Figure 7. Tag placements for blue catfish marked with coded wire tags and released in 2012 and 2013 in the James River, VA. Also shown are fin clip locations used in 2013.

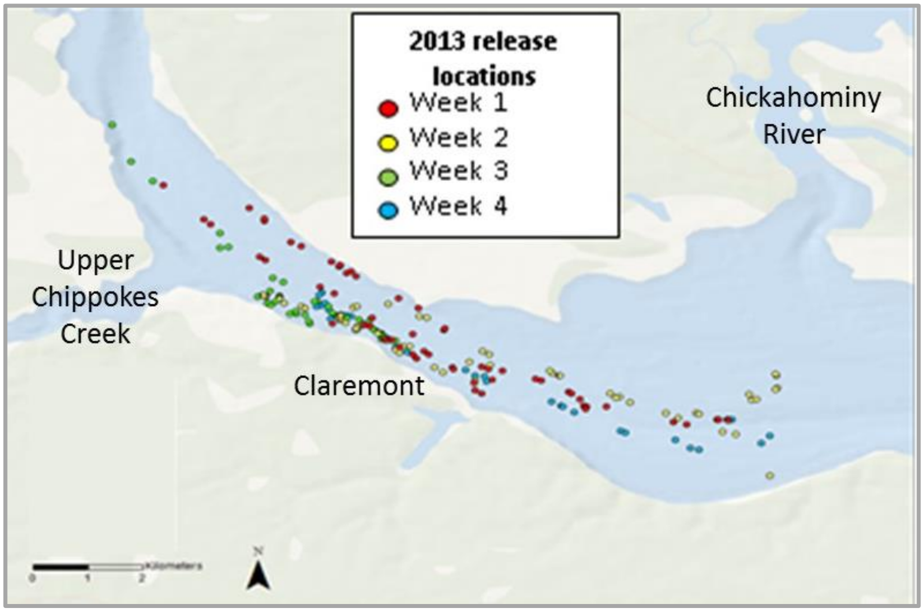


Figure 8. Release locations for blue catfish tagged in the James River, VA, in July-August 2013. Fish were not released in areas that were too shallow to allow safe maneuvering of the vessel. Releases occurred as the vessel drifted with the prevailing tide and currents.

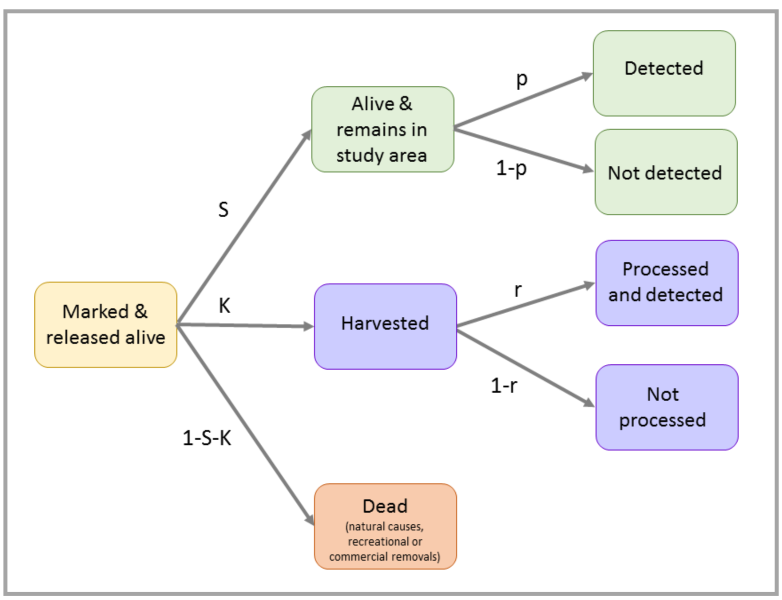


Figure 9. Fate diagram for blue catfish marked and released in the James River, VA, in 2012 and 2013. This figure reflects live encounters and dead recoveries (Cooch & White 2014), where:

S=probability an individual survives the year;

K=probability an individual is harvested;

p=probability of being recaptured (or detected);

r=probability of being recovered.

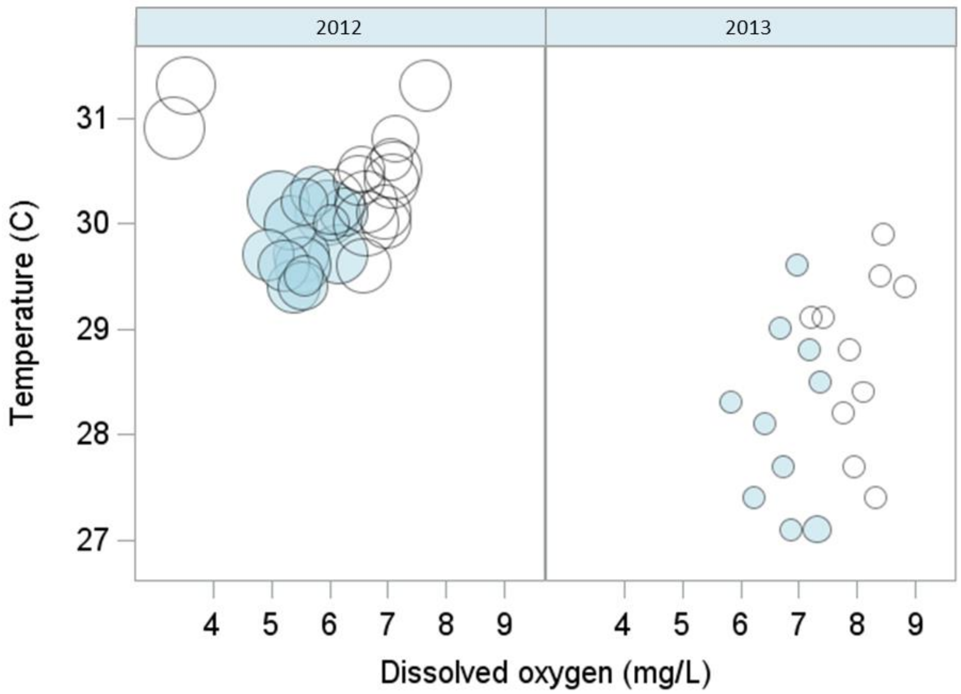


Figure 10. Surface (○) and bottom (●) temperature (°C), dissolved oxygen (mg/L), and salinity (psu) conditions in the James River near Claremont, VA, in July-August 2012 and 2013. The size of the bubbles reflects salinity, with larger bubbles indicating higher salinities. The range of salinities in 2012 was 0.4 to 1.0 psu in surface waters and 0.4 to 1.5 psu in bottom waters (n=15); the range of salinities in 2013 was 0.1 to 0.1 in surface waters and 0.1 to 0.2 in bottom waters (n=10).

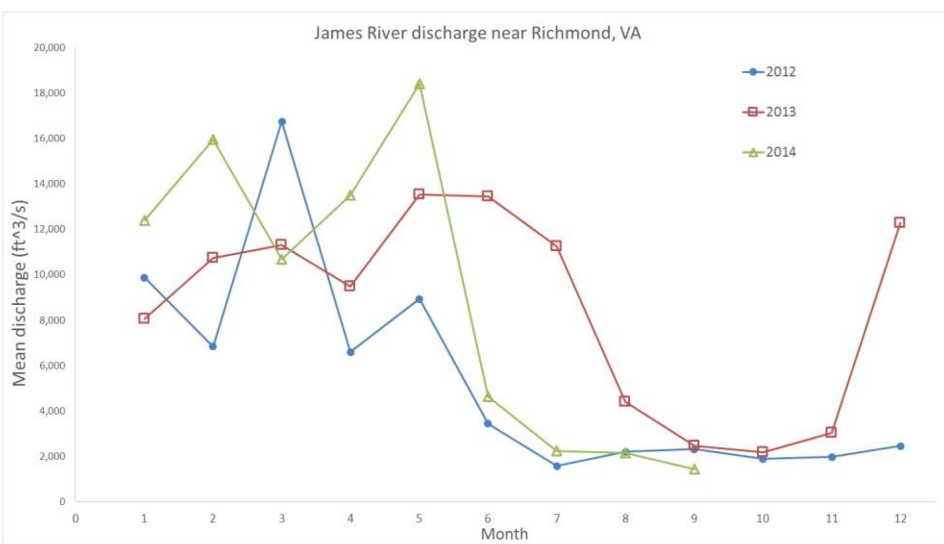


Figure 11. Mean monthly discharge (cubic feet per second) in the James River, VA, in 2012, 2013, and 2014. Data are from USGS gauge near Richmond, VA.

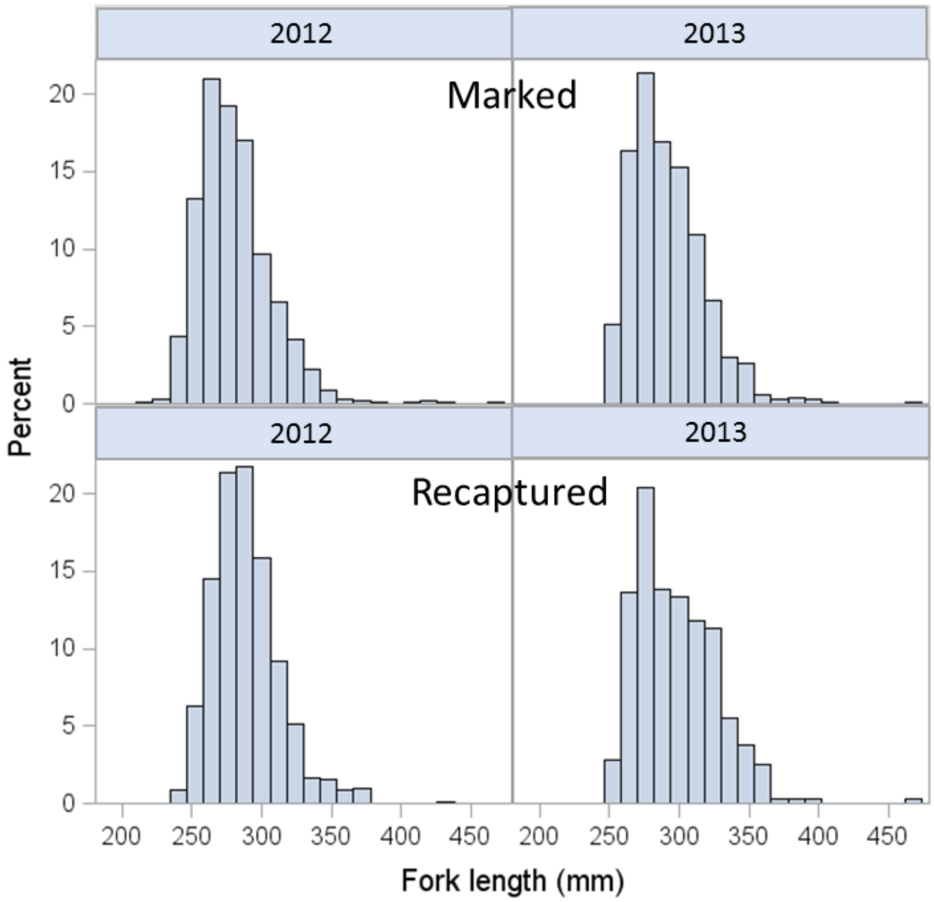


Figure 12. Length-frequencies of blue catfish marked and released in 2012 (N=899) and 2013 (N=799) in the James River, VA (total=1,698). Bottom panels show length-frequencies of recaptured and recovered blue catfish in 2012 (N=928) and 2013 (N=397) (total=1,325).

Movement Patterns and Survival Rate of Blue Catfish in a Non-native Habitat Estimated with a Tagging Study

Troy D. Tuckey, Mary C. Fabrizio, Alicia J. Norris, and Mary Groves

Introduction

Intentional releases of non-native blue catfish *Ictalurus furcatus* in Virginia waters during the 1970s and early 1980s were successful in establishing recreational fisheries and resulted in the expansion of the abundance and spatial distribution of this species in Chesapeake Bay tributaries (Schloesser et al. 2011). Blue catfish are now found in watersheds throughout the Virginia and Maryland portions of Chesapeake Bay, including watersheds in which the species was not intentionally stocked, such as the tributaries to the eastern part of the bay in Maryland (Schloesser et al. 2011). Blue catfish are omnivorous predators that can grow to large sizes (Graham 1999), raising concern about their increasing abundance and potential negative effects on native aquatic resources. Blue catfish are considered an invasive species and efforts are underway to manage populations and limit impacts on native communities. However, the biology and ecology of blue catfish in these non-native systems is poorly understood. In particular, little is known of key vital rates (survival, recruitment) and movement of fish, which could help to identify and develop effective management strategies.

In their native range (Mississippi, Missouri, and Ohio River drainages), blue catfish exhibit multiple movement patterns that vary from little to no movement to unidirectional, long distance movements. However, most blue catfish exhibit seasonal upstream movements to spawning habitats (spawning migrations) and downstream movements to feeding and overwintering habitats. In a simple mark-recapture experiment in the lower Mississippi River, tagged blue catfish were found 5 – 12 km from their release location after 363 – 635 d at large; because the recapture rate of tagged blue catfish was low (1.4%, 3 recaptures out of 222 tagged blue catfish), only limited information could be obtained from this study (Pugh and Schramm 1999). In the Missouri River, 80 large blue catfish (mean TL = 872 mm, range: 569 – 1,260 mm TL) were tagged with radio tags and acoustic tags and followed for two years (40 fish each year; Garrett and Rabeni 2011). Of the 24 blue catfish that were consistently relocated over the span of a year, migratory patterns ranged from little movement to directed movements spanning > 100 river kilometers (rkm; Garrett and Rabeni 2011). The majority of blue catfish (66%) exhibited seasonal movements, shifting upstream during March/April to spawning habitats, and downstream to summer/fall habitats during July to October. The remaining blue catfish did not exhibit seasonal behaviors: some fish resided in small stretches of the river (< 30 rkm), whereas others moved long distances (> 100 rkm) during times other than the spawning period (Garrett and Rabeni 2011). Movements of acoustically tagged blue catfish in the upper Mississippi River were similar to those observed in the Missouri River; in the Mississippi River, both short range (1.3 rkm) and long range (> 689 rkm) movements were observed throughout the year (Tripp et al. 2011).

In non-native habitats, and in particular the tidal reaches of coastal estuaries, movements of blue catfish are largely unknown. To gain insight about movement patterns of blue catfish in non-native habitats and to estimate annual survival, we employed a tagging study in the Potomac River, MD, from 2012 to 2015. The Potomac River is one of the largest tributaries to Chesapeake Bay and contains a variety of habitats suitable for blue catfish. Blue catfish were first reported in the Potomac River in 1987, although the origin of blue catfish in the Potomac River is unknown (Jenkins and Burkhead 1993; Schloesser et al. 2011). In the Potomac River blue catfish reside in freshwater, tidal freshwater, and estuarine habitats (Schloesser et al. 2011). Blue catfish support a commercial fishery in the Potomac River, and in 2015, 524.5 metric tons were harvested with an estimated dockside value of US$1.7 million (Martin Gary, Potomac River Fisheries Commission, *pers. comm*.). Because the river forms the boundary between Virginia and Maryland, these fish are pursued by recreational anglers from both states; in addition, fishing guides are sometimes used by Potomac River anglers to maximize their likelihood of capturing a trophy-size fish. Understanding movement patterns and survival rate of adult blue catfish in the Potomac River is important to achieving effective management of the species as a fisheries resource and in reducing negative impacts of this non-native resident.

The method chosen for tagging or marking blue catfish is not trivial. Catfishes, which are scaleless, have been marked with cold and hot brands and various tattoos and pigments; however, all of these methods suffer from problems with visibility and distortion and cannot be used to individually identify marked fish (that is, these are batch marks). Individually numbered T-bar anchor tags, which are relatively inexpensive and easy to apply, have been associated with high tag shedding rates in catfishes (90% of tags shed in 3 months, Greenland and Bryan 1974; 50% shed in 8.3 months, Timmons and Howell 1995; 29% shed in 9 months, Buckmeier and Irwin 2000). However, in one long-term study with T-bar anchor tags in African sharptooth catfish *Clarias gariepinus*, shedding rates after one year were 17% (Booth and Weyl 2008). Most North American catfishes are typically tagged with Carlin dangler tags, and shedding rates associated with these tags can vary from 0% shedding in the first year (Travnichek 2004; Michaletz et al. 2008) to annual rates near 30% (23% tag loss rate in channel catfish *Ictalurus punctatus* >305 mm TL, Shrader et al. 2003; 31.4% tag loss rate in flathead catfish, Marshall et al. 2009). We speculate that variation in tag retention rates for the Carlin dangler tag largely reflects variation among taggers and tag placement. Dart tags were also inserted into the dorsal musculature of the African sharptooth catfish and shedding rates of 2% after one year and 4% after two years were observed (Booth and Weyl 2008). Thus, these tags provide a combination of relatively easy application and high retention rates.

Other types of tags developed more recently have been used in catfishes, with variable results. Passive integrated transponder (PIT) tags inserted into the dorsal or opercular musculature of flathead catfish *Pylodictis olivaris* exhibited 100% and 98.5% retention rates after 10 months (Daugherty and Buckmeier 2009). Similarly, 97% tag retention was obtained after 1 year for channel catfish tagged in the dorsal musculature (Moore 1992). Visible implant elastomer (VIE) tags inserted in the cheek were used successfully to mark fingerling blue catfish (~152 mm), with 100% tag retention in 9 months (Zeller and Cairns 2010). However, all of the visual implant alphanumeric tags (similar to VIE tags) were shed in 5.7 months from channel catfish (Buckmeier and Irwin 2000). Although useful for short-term studies

(30-40 days; e.g., Hart and Summerfelt 1975), internal placement of tags (such as acoustic transmitters) is not warranted for long-term studies because of an unusual phenomenon observed among catfishes: expulsion of tags from the body cavity. African catfish *Heterobranchus longifilis* and channel catfish surgically implanted with acoustic transmitters expel their transmitter transintestinally, through the incision site, or transdermally (Summerfelt and Mosier 1984; Marty and Summerfelt 1986, 1988; Baras and Westerloppe 1999).

In summary, externally attached tags can be associated with high or variable tag loss rates (e.g., Mitamura et al. 2006), whereas tags placed intramuscularly (e.g., PIT tags) appear to be better retained. We conclude that studies where recaptures or resightings are expected to occur several months to years after release would benefit from the higher tag retention rates associated with placement of small tags within the dorsal musculature (but not in the peritoneal cavity). For this reason, we tagged blue catfish with dart tags, which can be readily identified by anglers. Furthermore, because reporting rates are typically low in fisheries tagging studies, we used reward (dart) tags to maximize reporting rates by anglers; this is a standard approach used to increase the number of resightings (recaptured fish released alive) or recoveries (harvested fish) from anglers. Dart tags were imprinted with the reward notice and a phone number to call to report information. Additionally, to assess tag shedding rates, we double-tagged each blue catfish prior to release.

Although information from tag returns will provide insight into movement patterns, seasonal movements will be difficult to infer from these data because tag returns may not occur at regular frequencies over prolonged time periods. Therefore, we used data from the VIMS Juvenile Fish Trawl Survey (trawl survey) from the neighboring Rappahannock River to discern seasonal changes in relative abundance of blue catfish in Chesapeake Bay tributaries; we assume that seasonal changes in local abundance reflect changes due to movements associated with spawning, foraging, and use of overwintering habitats. We also investigated freshwater flow in the Potomac and Rappahannock rivers as freshwater may alter the salinity gradient and thereby influence the distribution (Edmonds 2006) and abundance of blue catfish.

Finally, we estimate apparent annual survival of adult blue catfish using Brownie et al. (1985) dead recovery models. A previous study in Virginia tidal rivers estimated annual survival from catch curve analysis of otolith-based ages and found annual mortality ranging from 20.8% to 32.3% (Greenlee and Lim 2011). There are no published survival estimates from the Potomac River though such estimates may help in the development of effective management strategies.

Methods

We tagged commercially and recreationally-sized blue catfish (≥ 300 mm TL) in the Potomac River captured during targeted efforts using a Smith Root SR-18 electrofishing boat. Most fish were captured using low frequency electrofishing (LFE <2 amps), which is well suited to the capture of blue catfish. Some blue catfish were collected in shallow-water habitats using standard (high-frequency) electrofishing settings for ambient conductivity.

Blue catfish were collected and tagged from a 40-km stretch of the Potomac River from 17 July to 14 November 2012, whereas in 2013 tagging occurred between 21 and 26 June 2013 (Figure 1). Tagging efforts in 2012 resulted in 739 tagged blue catfish ranging in size from 300 to 1,319 mm TL and in 2013, 498 blue catfish were tagged ranging in length from 374 to 1,165 mm TL (Figure 2). The size range of blue catfish that were tagged in this study included mature individuals (> 381 mm TL; Graham1999) capable of undertaking directed spawning movements.

Fish were double-tagged in the left dorsal musculature with two dart tags (one white and one yellow, Hallprint™). Each tag contained a unique numeric sequence, a phone number, and notice of a reward for reporting each tag. Informative posters were distributed at fishing piers, boat ramps, and tackle supply stores in MD and VA to inform the public of the project and to encourage participation of anglers and commercial fishers. Additionally, the tagging project was advertised on social media platforms, as well as the MDDNR website, and there were also two interviews (one newspaper and one radio, M. Groves, *pers. obs.*) that provided further coverage of the project. Fishers who reported catching a tagged fish were asked to remove both tags and report the date of capture, location of capture, tag numbers, tag colors, status of caller (recreational or commercial fisher), size of fish, water temperature, depth, and the disposition of the tagged fish (either harvested or released).

Tag retention was estimated with a Cox proportional hazard (CPH) model that included fish total length, minimum distance moved, and direction moved as predictor variables that could possibly affect tag retention (Cox 1972; Musyl et al. 2011). We modeled the loss of only one tag because loss of both tags is not discernable. Models were fitted with the *survival* package in R (R Core Team 2016; Therneau and Grambsh 2000).

Movement of Blue Catfish

Movement of blue catfish was inferred from reports of recapture locations from recreational anglers and commercial fishers. We estimated the distance between the release location and the reported recapture location by measuring the minimum distance between the two points along the main axis of the river using ArcGIS software (Esri, 9.2). Reported distances are considered the minimum distance moved, i.e., fish may have moved a greater distance than we report. The direction of movement from the release site (i.e., upstream or downstream) was also recorded. To investigate the effect of freshwater flow on the relationship between the distance and direction moved by blue catfish in the Potomac River, daily freshwater flow data (from January 2012 to December 2015) were obtained from USGS Gauge # 01646500, near Washington, D.C. (Little Falls Pump Station). Daily flow rates (m^3/s) were compared with the distance and direction moved by blue catfish as reported by tag returns in the Potomac River.

Due to a lack of abundance data to identify seasonal movement patterns of blue catfish in the Potomac River, data collected by the VIMS trawl survey, a year-round, monthly survey that assesses fish abundance in the neighboring Rappahannock River was used. The trawl survey collects samples from 22 sites each month, distributed from the mouth of the Rappahannock River (river kilometer 0) to the freshwater interface 64 km upstream, near the town of Tappahannock, VA (for full details of the survey gear, area sampled, and methodology see Tuckey and Fabrizio 2013). Blue catfish are routinely captured from Tappahannock downstream to about river kilometer 32, which serves as the estuarine-most limit of their distribution in the Rappahannock River (Figure 1). We calculated a monthly index of abundance for mature adult blue catfish ≥ 381 mm TL collected between rkm 32 and 64 and from 1996 to 2015 using a stratified mean based on the delta lognormal model. We centered the monthly estimates by subtracting the annual mean to remove the strong annual signal in the data (increase through time) and allow comparisons among years. Seasonal estimates of abundance were then modeled to characterize potential blue catfish movement behaviors (e.g., spring spawning from April to June, summer/fall foraging from July to November, and overwintering from December to March); we used generalized linear models to test for the effect of season and flow (and their interaction) on relative abundance. Average monthly flow data in the Rappahannock River were obtained from USGS Gauge #01668000, near Fredericksburg, VA. Data were analyzed in R and plotted with package *visreg* (Breheny and Burchett 2016; R Core Team 2016). If blue catfish exhibit behaviors similar to those observed in their native rivers, then we should observe a decrease in abundance in spring as blue catfish move upriver to spawn, and an increase in blue catfish abundance during summer, fall, and winter as these areas are utilized for foraging and overwintering.

Survival of Blue Catfish

We implemented the Brownie et al. (1985) dead recovery models to estimate the annual survival rate of blue catfish in the Potomac River using Program MARK (White and Burnham 1999). Assumptions of this study are: (1) tagged fish are representative of the population, (2) tagging does not affect survival, (3) the capture of a tagged fish is independent of whether it has one or two tags, (4) reported tags are correctly assigned to year of recapture, and (5) all tagged fish within a cohort have the same annual survival rate and recovery rate (i.e., survival and recovery rates are homogeneous). Although we requested anglers and commercial fishers to remove both tags from fish before releasing them, some anglers released tagged blue catfish with their tags intact; following Bacheler et al. (2008), we chose to treat those fish as if the tags had been removed. We also modeled harvested fish only (by excluding those that were released alive) to examine the sensitivity of model estimates to the fate of the fish. Competing models were compared using AIC. We then used the estimate of the tag retention rate obtained through CPH models (above) to adjust survival estimates (Pollock et al. 1990); variance estimates for the adjusted survival rates were obtained using the delta method (Henderson and Fabrizio 2014).

Results

One-hundred and four blue catfish were recaptured during the study resulting in a tag return rate of 8.4%. Recaptured blue catfish remained at-large from 2 to 1,208 days and consisted of fish from a wide range of sizes (390 – 1,160 mm TL; Figure 3) that represented the size range of those that were tagged (Figure 2). Most recaptured blue catfish were captured in 2012 and 2013 (N=37 fish each year), and fewer were recaptured in 2014 (N=24) and 2015 (N=6).

Thirty-three fish were recaptured with a single tag during the study. Based on the Cox proportional hazard model and considering only those tags lost during the first year at large, the estimated proportion of blue catfish retaining both tags was 0.88 (SE = 0.045; Figure 4). The tag retention rate declined over time and by the end of the study, the proportion retaining both tags declined to 0.31 (SE = 0.107).

Flow and Movement of Large Blue Catfish

Flow conditions in the Potomac River differed between tagging years with greater freshwater flow in 2013 (mean flow = 328.7 m^3/s; USGS Gauge # 01646500) compared with 2012 (252.8 m^3/s; Figure 5). During 2014, freshwater flow in the Potomac River increased to a mean of 357.4 m^3/s before returning to a level in 2015 (262.3 m^3/s) that was similar to flow rates observed in 2012 (Figure 5). Flow in the Rappahannock River showed a similar pattern compared with the Potomac River with highest flow observed in 2014 (120.4 m^3/s) followed by 2013 (73.6 m^3/s), 2015 (51.9 m^3/s), and 2012 (29.9 m^3/s).

Recapture location was not reported for 5 recaptured fish, resulting in 99 fish that could be evaluated for movement patterns. The average minimum distance moved for recaptured blue catfish was 24.1 rkm with a range of 0 rkm to 112.6 rkm (Figure 6). Thirteen percent of blue catfish were recaptured from their release locations and days at large for these fish ranged from 30 to 1,127 d for fish released in 2012, and 381 to 789 d for releases in 2013 (Table 1). Most blue catfish (63%) were recaptured downriver from the release location and a greater proportion of blue catfish were recaptured downstream in 2013 (75%) compared with 2012 (57%; Table 1; Figure 5). The distance moved by blue catfish was not related to fish size ($F = 0.045$, $P = 0.83$), or days at large ($F = 0.081$, $P = 0.78$), however the direction of movement was a significant ($F = 84.24$, $P<0.001$) determinant of the minimum distance moved; direction accounted for 64% of the variance in the observed minimum distance moved. Blue catfish moved greater distances downstream (mean = 34.4 rkm, SE = 3.97) from release locations than upstream from release locations (mean = 6.7 rkm, SE = 1.53). The majority of catfish anglers who target blue catfish in the Potomac River are fishing between Aquia Creek on the Virginia side, which is downriver of release locations, up to, and including, Washington, D.C. waters (M. Groves, *pers. obs.*). Therefore, the relative differences in reported movements likely resulted from differences in actual downriver movements.

Results from the twenty-year time series of blue catfish relative abundance estimates (mean-centered) in the Rappahannock River indicate high variability within and among months (Figure 7). We found no significant interaction between season and flow on the relative abundance of blue catfish ($F_{2,54} = 2.36$, $P = 0.104$; Figure 8). Main effects of season (i.e., forage, spawning, and overwintering seasons) and flow on relative abundance estimates were not significant (Season: $F_{2,56} = 0.723$, $P = 0.49$; Flow: $F_{1,58} = 0.855$, $P = 0.36$) with mean relative abundance during spawning months (mean= -0.320, SE = 1.148) similar to abundances observed during forage (mean = -0.059, SE = 1.148) and winter months (mean = 0.047, SE = 1.182).

Survival of Large Blue Catfish in the Potomac River

The time-invariant model for survival, S, and recovery rate, *f,* was best supported by the recapture data (i.e., harvested fish and those released alive), as well as the data from harvested fish only (Table 2). Survival estimates (adjusted by the one-year estimate of tag shedding rate, 0.12) were 0.58 (SE = 0.067) for harvested fish only and 0.56 (SE = 0.057) for all recaptures, including harvested and released fish. Tag recovery rates, *f*, were 0.046 (SE = 0.0056) for harvested and released fish and 0.034 (SE = 0.001) for harvested fish only. Tests for the goodness of fit of the two models indicate that overdispersion ($\hat{c}$) was not a problem because the estimate of $\hat{c}$ was close to 1.0 for the all-recaptured-fish scenario ($\hat{c}_{\text{Option 1}} = 1.06$), or less than 1.0 ($\hat{c}_{\text{Option 2}} = 0.60$) for the harvested-fish-only scenario.

Discussion

Movement of Large Blue Catfish

Compared with movements of blue catfish in their native habitats, large (> 300 mm TL) blue catfish in the Potomac River moved similar (minimum) distances. Some individuals appeared to not move at all, despite several years at large, while others moved more than 100 kilometers. In particular, in our study, 13% of tag returns were from the area of release, and 73% of fish moved less than 30 rkm from the release site. In the Missouri River, 34% of tagged blue catfish moved less than 30 rkm during a two-year study (Garrett and Rabeni 2011). Fish in our study were recaptured upstream and downstream of release locations throughout the year indicating that blue catfish may occupy habitats in the tidal Potomac River from freshwater regions to areas exhibiting salinities of approximately 12.8 psu (Chesapeake Bay Program 2016). We have observed blue catfish in salinities up to 14.7 psu in the Rappahannock River (Schloesser et al. 2011) and 21.8 psu in the James River, VA (Fabrizio and Tuckey, *pers. obs.*), suggesting that in the Potomac River, blue catfish may occur in higher salinity habitats down river of those from which we observed tag returns. However, we note that scientific surveys in the lower Potomac River (from the Governor Harry Nice Memorial Bridge [State Route 301] to the mouth of the river) are lacking, and although recreational and commercial fishers have reported landings of blue catfish from the lower Potomac River (e.g., from Breton Bay near Leonardtown, MD), these catches tend to be associated with the mouth of tributaries and embayments to the Potomac River. Thus, we do not know the spatial distribution of blue catfish in these reaches, nor do we understand the role of these higher salinity habitats. For example, blue catfish may use higher salinity areas as feeding areas or as movement corridors; habitat use of blue catfish is critical to understanding the potential for further spatial expansion and future increases in abundance.

Assessment of seasonal movements of blue catfish using tag-return data is challenging because returns do not occur at regular time intervals. Therefore, we examined seasonal relative abundance of blue catfish in the neighboring Rappahannock River to infer what we would expect to observe in the Potomac River. For the years examined (1996 - 2015), mean relative abundance was similar among seasons, most likely due to the high, year-to-year, variation in monthly abundance estimates. Although our model was not significant, relative abundance decreased during spawning months when river flows were high, whereas relative abundance increased during forage and overwintering months suggesting that blue catfish move upstream (or into Potomac River tributaries) to spawn. It is possible that fish move upstream from our study area to spawn, but these movements may be offset by non-spawning individuals that move downstream to tidal estuarine habitats (such as our study area). Alternatively, blue catfish may use habitats throughout the river for spawning. Another explanation for our inability to observe a significant decline in relative abundance during the putative spawning period is that spawning of blue catfish in these non-native estuaries occurs during a longer period of time (i.e., April-June does not fully characterize the spawning period of these fish). Further study of the maturation process and seasonal movements of blue catfish in non-native, coastal estuaries is needed. Such studies are currently underway in MD and VA.

Survival of Large Blue Catfish in the Potomac River

Blue catfish survival estimates from the Potomac River were lower than those reported by Greenlee and Lim (2011) for coastal rivers in Virginia. We estimated an apparent survival rate of 0.56 per year, which is equivalent to a total instantaneous mortality rate (Z) of 0.58 per year, whereas total instantaneous mortality estimates from catch-curve analysis of electrofishing data ranged from 0.23 to 0.39 per year (converted from total annual mortality, A, reported in Greenlee and Lim 2011). The total instantaneous mortality rate (from catch curve analysis) calculated from data in Kelley (1969) indicates a Z of 0.49 per year in the Tombigbee River, Alabama (annual survival rate of 61%). Even though blue catfish in Alabama support significant commercial and recreational fisheries, they exhibit a lower total mortality rate in their native system compared with a coastal estuary. Another explanation for differences in Z is that total mortality rates vary geographically due to differences in fishing mortality rates and variation in factors contributing to natural mortality rates (e.g., diseases, cannibalism, predation, resource limitation). All of these estimates of Z assume a closed population (and unit stock), an assumption which may have been violated in all of these studies, including this study. For example, significant emigration of blue catfish would result in positive bias in estimates of total mortality rates.

Relying on tag returns from recreational anglers and commercial fishers adds complexity to modeling efforts by introducing issues that were not accounted for, or accommodated by, the design of the study. For example, instead of returning both tags from a recaptured fish as designed and requested, some anglers released the fish alive with one or both tags. In doing so, the newly released fish no longer fit the *a priori* design of dead-recovery models. In this case, the live releases can be handled in one of two ways. One approach, used by Bacheler et al. (2008), is to model the tags and assume that a recaptured fish ‘died’ when first reported by anglers. An advantage of this approach is that information from the recaptured fish can be used in parameter estimation. The alternative -- excluding recaptured fish that were released with one or more tags -- reduces the number of recaptures available to use in modeling efforts, but maintains the intended design of the study. More sophisticated mark-recapture models can be used to address these types of multiple sightings, and some surveys employ such designs (e.g., Henderson and Fabrizio 2014), however, our study was short in duration and data limitations do not support the consideration of more complex models. Therefore, we employed both options (including fish that were released alive, and excluding them from the model) to estimate apparent survival rates. Including all fish in the model resulted in a slightly lower apparent annual survival estimate and a smaller standard error compared with the approach that included only those fish that were harvested. This difference was minor and does not affect management implications.

The tag return rate for our study was low, but greater than that observed in other blue catfish tagging studies (Pugh and Schramm 1999). Possible reasons for lower tag return rates in older studies (Pugh and Schramm 1999) is the lack of publicity and outreach efforts, or the lack of rewards for returned tags. The tag reporting rate for the Potomac River fish is unknown, thus, we assumed that all encountered tags were reported, that is, we assumed the notification of reward was sufficient to motivate angler and commercial fisher reporting. We have reports of angling companions who captured a tagged blue catfish but did not report it; some anglers who did report a recaptured fish and its tag number indicated that a tag from another fish was recovered but then lost. Thus, because reporting rates were less than the assumed 100%, survival rates are likely to be higher than those reported here. One assumption of mark-recapture models that we were able to address was that of negligible tag shedding. Tag shedding rates by blue catfish in this study were fairly high (0.12 in first year, increasing to 0.69 after about 2.7 years) and demonstrate that dart tags are not a suitable marking method for long-term studies of this species. If dart tags are used, tag shedding rates should be estimated and the study duration should be short (< 1 year) to reduce complications associated with tag loss. For this reason, we do not recommend dart tags for study of survival rates of large blue catfish.

Management Implications

Managing the blue catfish fishery in the Potomac River requires consideration of the entire population in this tidal subestuary as a single unit because movement occurs at a large spatial scale such that localized depletion is unlikely. Other ictalurids, such as flathead catfish (*Pylodictis olivaris*), can suffer from localized overfishing due to restricted movements in their native range (Pugh and Schramm 1999), but that does not appear to be the case with blue catfish in this tributary of Chesapeake Bay. In the Potomac River, blue catfish may remain in the tidal freshwater and estuarine habitats throughout the year. In their native habitats, most blue catfish (66%) exhibit seasonal movements in spring, possibly associated with spawning, and downstream movements in summer and fall to their foraging habitats (Garrett and Rabeni 2011). These directed seasonal movements may be undertaken by large blue catfish in non-native habitats, but we were unable to detect these movements. Four reasons may account for our inability to detect seasonal movements: (1) the high abundance of blue catfish in the Potomac River, coupled with the relatively small sample size of recaptured fish, yields an estimate of seasonal movement with low precision, which did not permit detection of a significant seasonal effect on mean distance moved; (2) the behavioral variation among fish is large, and seasonal patterns are not applicable to the population as a whole; (3) spawning locations are not known and thus, we lacked a robust reference location from which to observe movements; and (4) the spawning season in the Chesapeake Bay region is longer than that reported for blue catfish in their native range.

Low survival rates in the Potomac River compared with native habitats suggest a higher natural mortality rate in non-native coastal estuaries. However, we do not know the impact of commercial and recreational harvests on the blue catfish population and research is needed to estimate both fishing and natural mortality. Long distance movements of blue catfish in the Potomac River indicate that robust control measures will be needed to reduce population abundance and minimize the potential for negative impacts of this species on the native estuarine community. Furthermore, investigations into individual fecundity, spawning frequency, spawning locations, and identification of the spawning period in non-native habitats are critical data gaps that would inform population dynamics models and stock assessments and help guide management actions.

Acknowledgments

We are grateful to Branson Williams, Tim Groves, and Ross Williams (MDDNR) for tagging fish. We also thank the many recreational anglers and commercial watermen that participated in the study. This study was funded by the National Oceanic and Atmospheric Administration, Chesapeake Bay Office (Award Number NA11NMF4570222), and the Virginia Marine Resources Commission (multiple awards).

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Table 1. Summary of the distance (km) and direction moved (km) relative to release location, number of fish, and days-at-large of recaptured Blue Catfish from the Potomac River, 2012 - 2015.

Release year	Number tagged	Direction of movement	Number recaptured	Distance moved (km)	Days-at-large
2012	739	Upriver	20	0.4 - 32.1	3 - 1,208
		No movement	9	0	30 - 1,127
		Downriver	38	1.8 - 93.6	2 - 1,156
		No information	3	NA	254 - 712
2013	498	Upriver	4	0.5 - 18.6	30 - 842
		No movement	4	0	381 - 789
		Downriver	24	0.8 - 112.6	31 - 697
		No information	2	NA	136, 707

Table 2. A comparison of models used to estimate survival rates of Blue Catfish in the Potomac River, MD, from 2012 to 2015. We modeled all recaptures of Blue Catfish regardless of their fate (released or harvested; Option 1) and only those that were harvested (Option 2). Model descriptions include effects for survival (s) and recovery rate (f), where (.) indicates a constant rate and (t) indicates a time-varying rate. AICc and ΔAICc are Akaike's information criterion corrected for small sample size; No. Par. is the number of parameters. Model selection was based on the lowest ΔAICc score.

Option	Model	AICc	ΔAICc	AICc Weight	Model Likelihood	No. Par.	Deviance
1	s(.)f(.)	520.403	0	0.35452	1	2	2.9451
	s(t)f(.)	522.667	2.2639	0.1143	0.3224	4	1.1862
	s(.)f(t)	523.993	3.5903	0.05889	0.1661	5	0.4963
	s(t)f(t)	523.993	3.5903	0.05889	0.1661	5	0.4963
2	s(.)f(.)	746.79	0	0.46542	1	2	3.0217
	s(t)f(.)	748.155	1.365	0.2352	0.5053	4	0.3639
	s(.)f(t)	749.87	3.0797	0.09979	0.2144	5	0.0623
	s(t)f(t)	749.87	3.0797	0.09979	0.2144	5	0.0623

Figure 1. Location of tagging sites (△) and recapture sites (•) of blue catfish in the Potomac River, MD and the region of the Rappahannock River where blue catfish are routinely captured by the VIMS Trawl Survey (★). Tappahannock is as far upriver as the trawl survey samples and the lower star is located 32 km from the mouth of the Rappahannock River where it meets Chesapeake Bay.

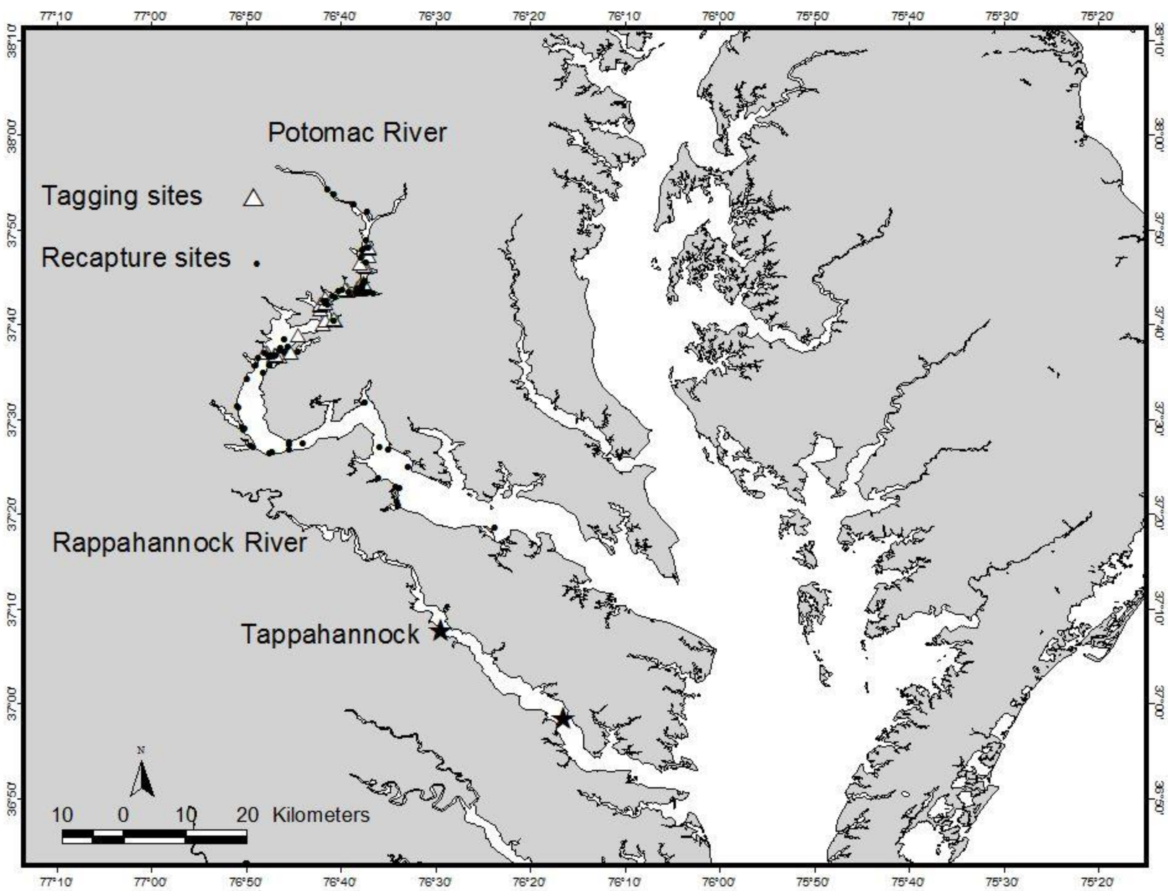

Figure 2. Length frequencies of blue catfish tagged and released in 2012 (N = 739) and 2013 (N = 498) in the Potomac River, MD.

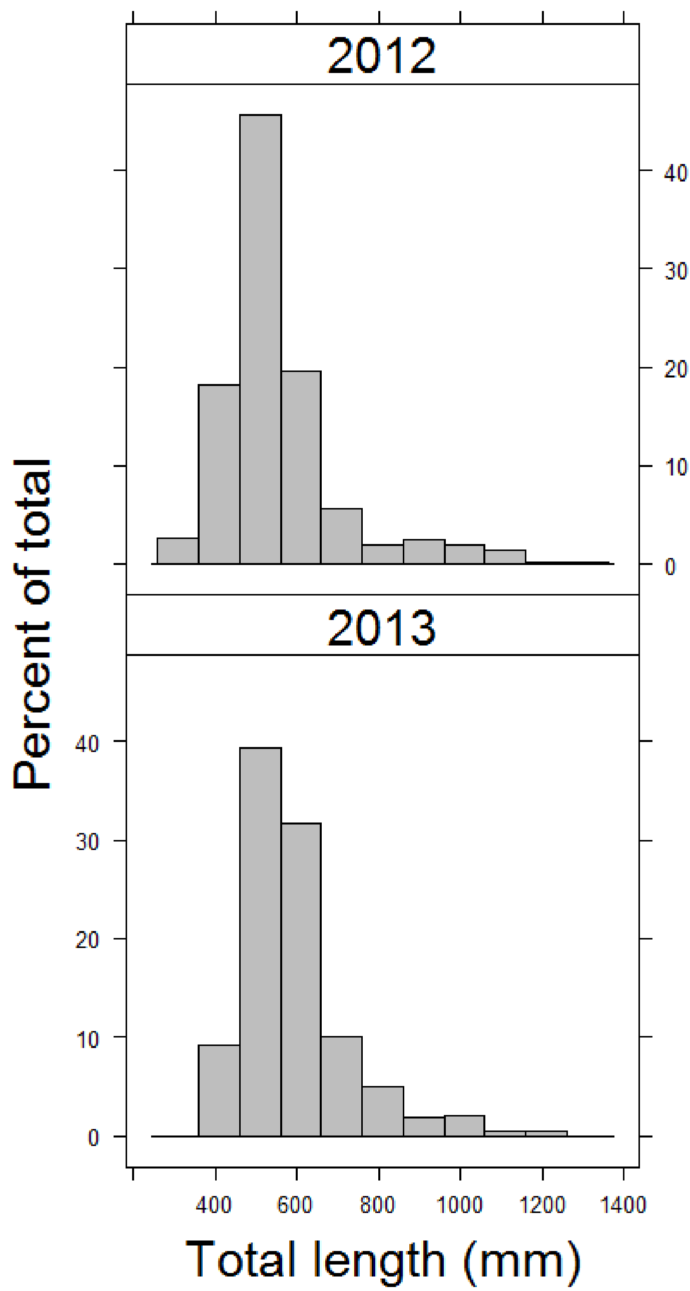

Figure 3. Length frequencies of recaptured blue catfish in 2012 (N = 37), 2013 (N = 37), 2014 (N = 24), and 2015 (N = 6) from the Potomac River, MD.

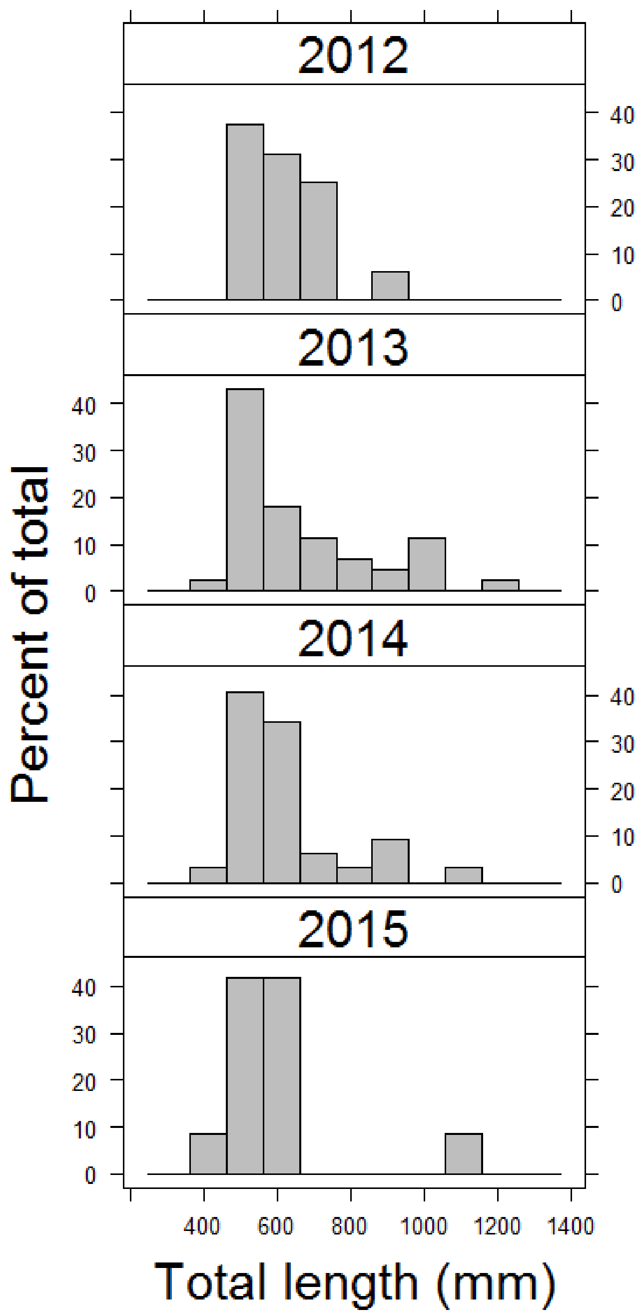

Figure 4. Proportion (and 95% C.I.) of blue catfish retaining two tags from 2012 to 2015 in the Potomac River, MD.

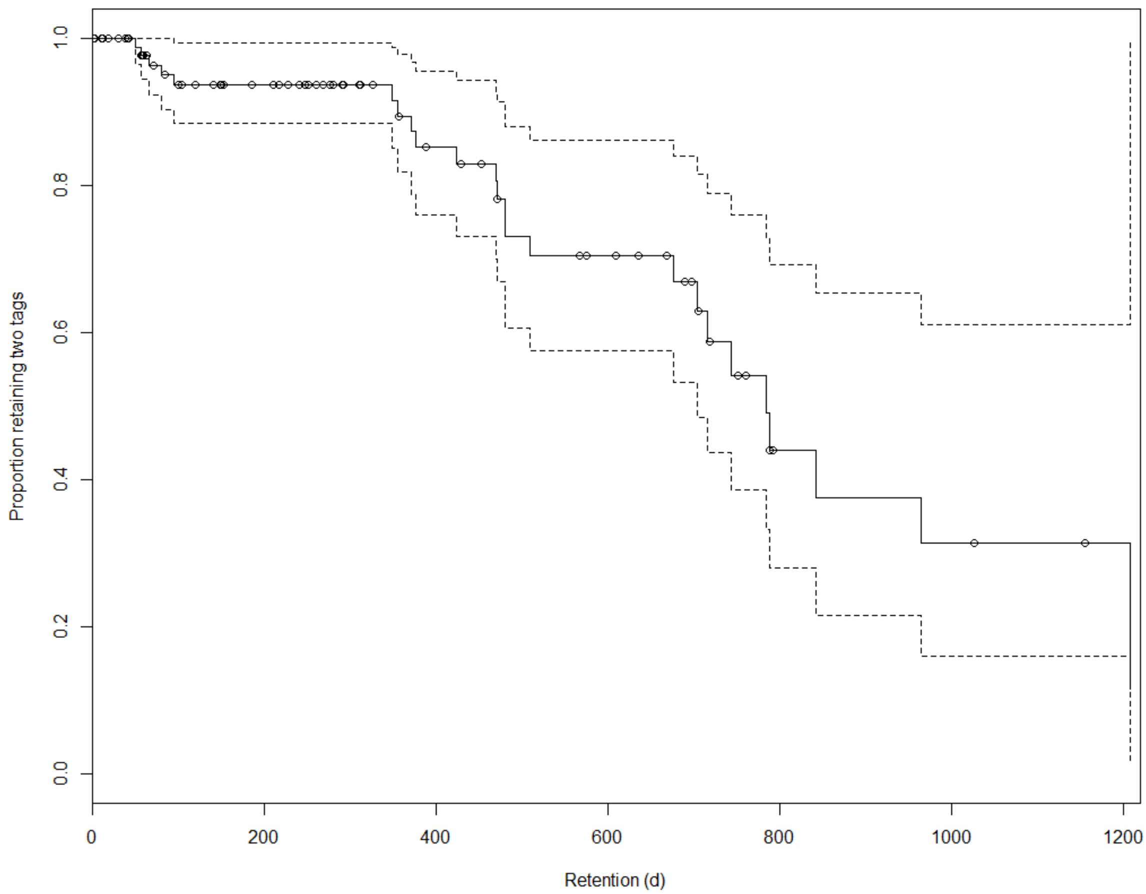

Figure 5. Daily freshwater discharge (m^3/s) measured at USGS Gauge # 01646500 near Washington, D. C. from July 2012 to December 2015, and the distance and direction blue catfish moved from the release location (filled circles, river kilometers, rkm) on the Potomac River, MD.

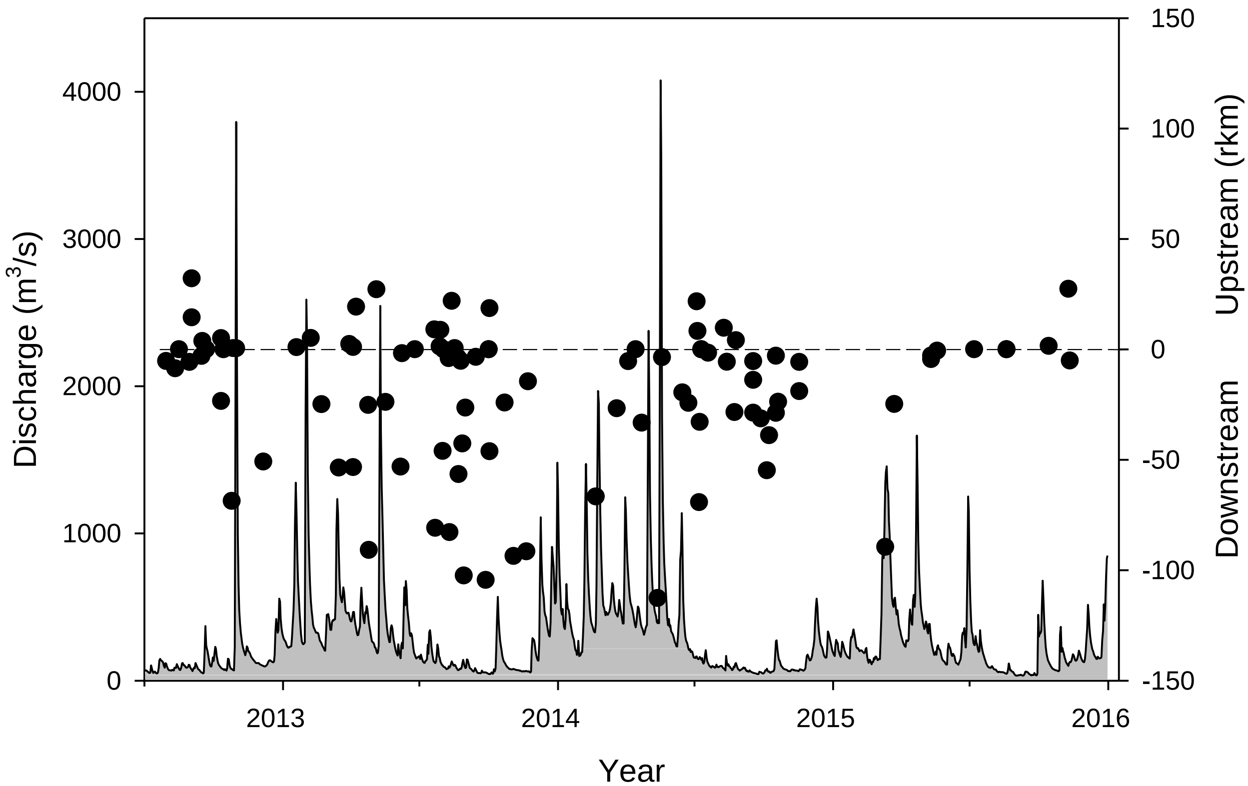

Figure 6. The estimated minimum distance blue catfish moved (river kilometers, rkm) from release locations to recapture locations reported by recreational anglers and commercial fishers in the Potomac River, 2012 – 2015.

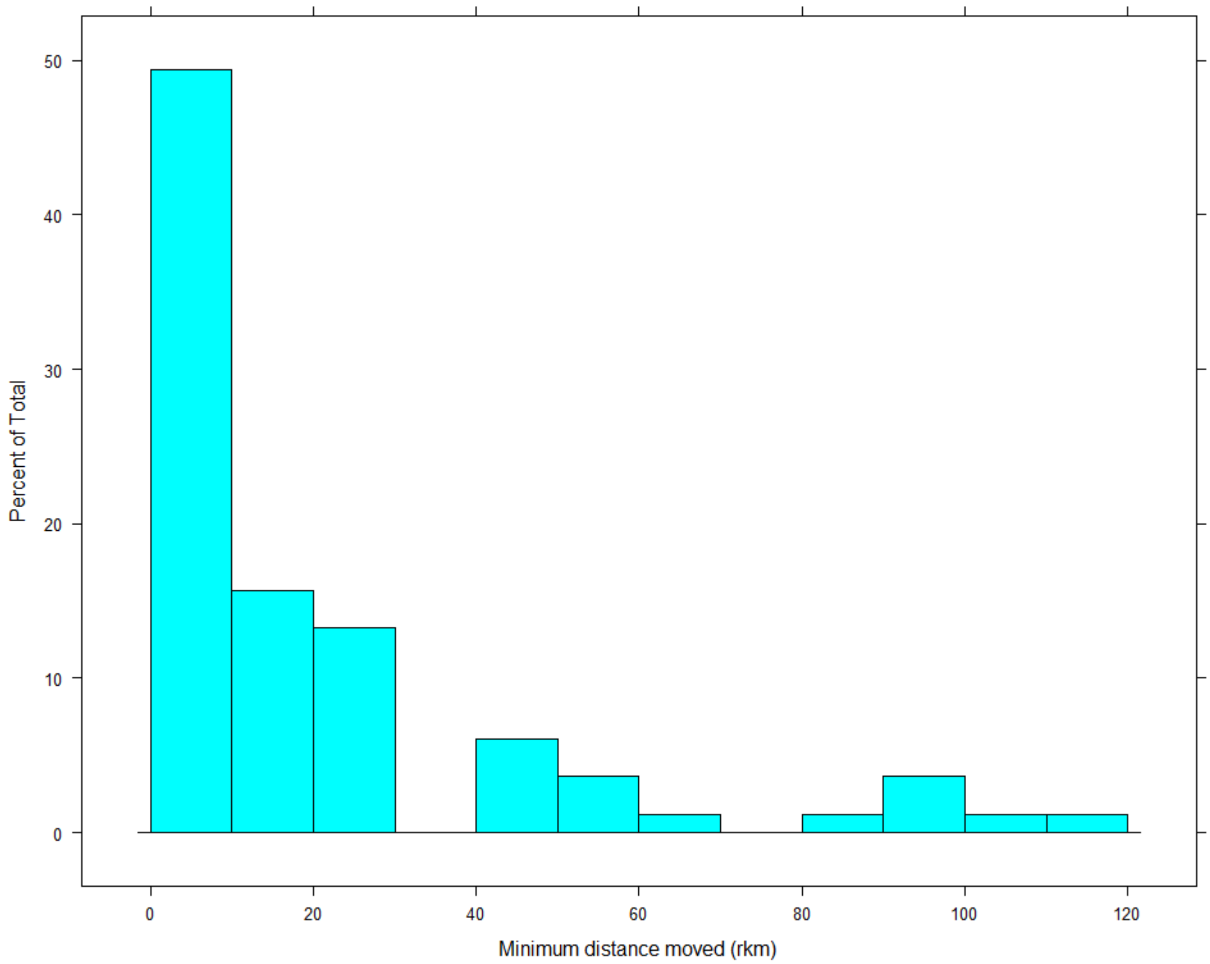

Figure 7. Relative abundance index calculated using a delta lognormal model for each month from 1996 to 2015 for adult blue catfish (≥ 381 mm total length) captured by bottom trawl in the Rappahannock River, VA. Annual means were subtracted from monthly values to calculate mean-centered abundance. Black lines indicate the mean index value by month across years.

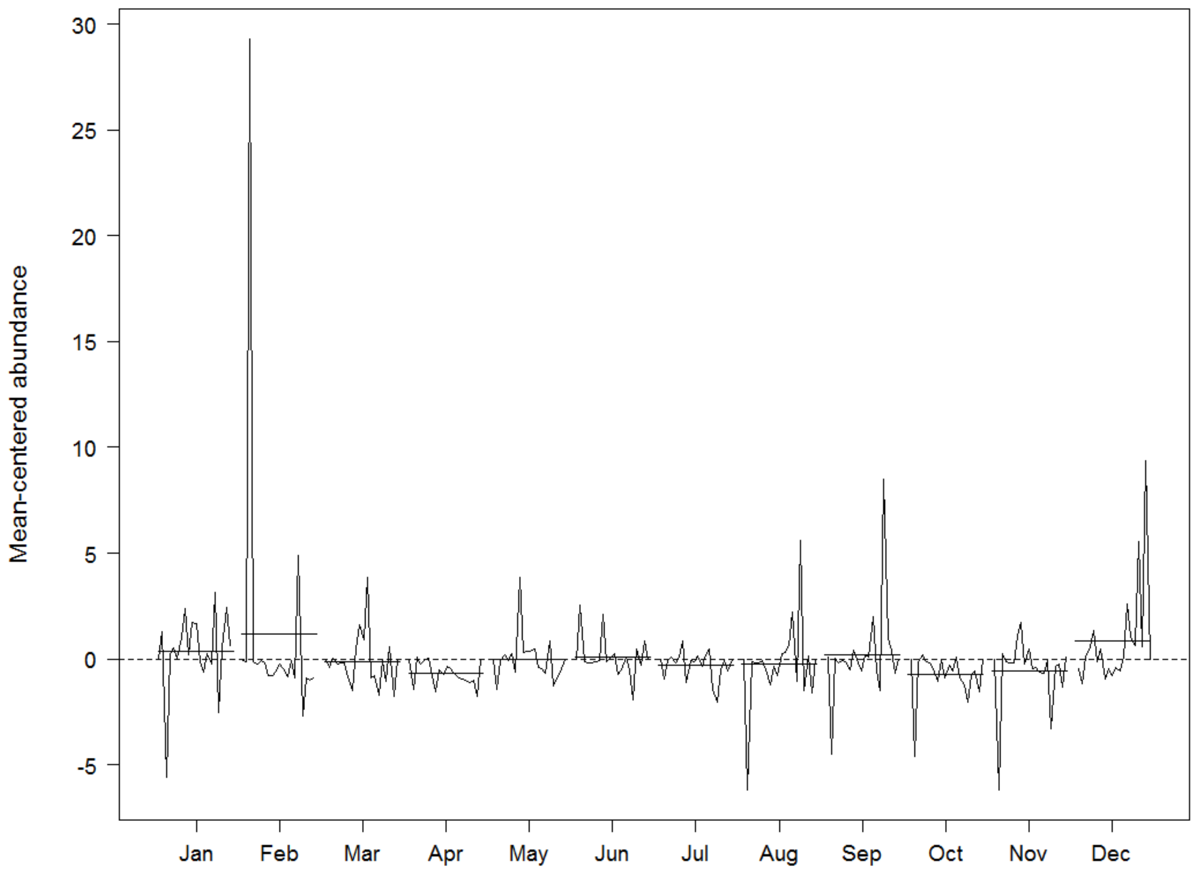

Figure 8. Effect of the interaction of river discharge (m^3/s) and season (Forage: July - November, Spawn: April -June, Winter: December - March) on the relative abundance of blue catfish in the Rappahannock River from 1996 to 2015.