Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 9:564–572, 2017
Published with license by the American Fisheries Society
ISSN: 1942-5120 online
DOI: https://doi.org/10.1080/19425120.2017.1381207

ARTICLE

Low Apparent Survival and Heterogeneous Movement Patterns of Invasive Blue Catfish in a Coastal River

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Abstract
Blue Catfish *Ictalurus furcatus* were purposefully introduced into freshwater tributaries to Chesapeake Bay in the past, and populations have subsequently spread to new areas, negatively impacting native communities and causing concern for resource managers. To aid development of management strategies, we implemented a multiyear (2012–2015) tagging study of invasive Blue Catfish in a 40-km stretch of the Potomac River to estimate survival and assess movement patterns. Blue Catfish (*N* = 1,237) were captured by electrofishing and double-tagged to allow us to estimate tag retention rates; we used reward tags to increase reporting rates. Recaptured fish (*N* = 104; 8.4% return rate) were at large for between 2 and 1,208 d. Tag retention rates were 0.88 (SE = 0.045) after 1 year and declined to 0.31 (SE = 0.107) after 2.7 years. The mean minimum distance moved by fish was 24.1 km (range = 0.0–112.6 km). Most (63%) fish displayed downriver movements, but distance moved was unrelated to fish size or days at large. Greater distances were observed among fish that moved downriver (34.4 km) than those that moved upriver (6.7 km). These results suggest high variability in movement behaviors for Blue Catfish inhabiting the tidal Potomac River from freshwater reaches to estuarine habitats. We estimated an annual apparent survival rate of 0.56 (SE = 0.057; Brownie tag-return model) across the study period. This survival rate is lower than survival rates reported from their native range. Long-distance movements of Blue Catfish in the Potomac River indicate that robust, large-scale control measures will be needed to reduce population abundance and minimize negative impacts of this species on native communities.

Intentional releases of nonnative Blue Catfish *Ictalurus furcatus* in Virginia waters during the 1970s and early 1980s were successful in establishing recreational fisheries and resulted in increased abundance and expansion of the 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 areas on the eastern and northern parts of the bay in Maryland (Schloesser et al. 2011). Blue Catfish are omnivorous predators that can grow to large sizes (Graham 1999), characteristics that raise concerns about

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Subject editor: Carl Walters, University of British Columbia, Vancouver

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Received May 2, 2017; accepted September 12, 2017

their increasing abundance and potential negative effects on native aquatic species (Aguilar et al. 2017). Resource managers in Chesapeake Bay are actively working to develop coordinated management strategies for Blue Catfish, which has been designated an invasive species in the region (Invasive Catfishes Task Force 2015). Effective management strategies require an understanding of the biology and ecology of the species in question, such as survival rates and movement patterns, to inform appropriate control measures.

In their native range (Mississippi, Missouri, and Ohio River drainages, all large freshwater river systems), Blue Catfish exhibit variable movement patterns from little to no movement to unidirectional, long-distance movements. Most Blue Catfish exhibit seasonal upstream movements to spawning habitats (spawning migrations) and downstream movements to feeding and overwintering habitats (Graham 1999). In the lower Mississippi River, tagged Blue Catfish were found 5–12 km from their release location after 363–635 d at large; unfortunately, the recapture rate of tagged Blue Catfish was low (1.4%, 3 recaptures out of 222 tagged Blue Catfish), and these results may not be representative of the species throughout its range (Pugh and Schramm 1999). In the Missouri River, 80 large Blue Catfish (mean = 872 mm TL, range = 569–1,260 mm TL) were tagged with radio tags and acoustic tags and followed for 2 years (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 more than 100 km (Garrett and Rabeni 2011). The majority of Blue Catfish (66%) exhibited seasonal movements, shifting upstream to spawning habitats during March–April and downstream to summer–fall habitats during July to October, where they remained during winter months (Garrett and Rabeni 2011). The remaining Blue Catfish did not exhibit seasonal behaviors: some fish resided year-round in small stretches of the river (<30 km), whereas others moved long distances (>100 km) 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 km) and long-range (>689 km) movements were observed throughout the year (Tripp et al. 2011).

In nonnative habitats, and in particular the tidal reaches of estuaries, movements of Blue Catfish are largely unknown. To gain insight about movement patterns of Blue Catfish in nonnative tidal habitats and to estimate annual survival, we employed a tagging study in the Potomac River, Maryland, from 2012 to 2015. The Potomac River is one of the largest tributaries to Chesapeake Bay and contains a variety of suitable freshwater, tidal freshwater, and estuarine habitats for Blue Catfish (Schloesser et al. 2011). 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). 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, personal communication). In addition, in Maryland and Virginia these fish are pursued by recreational anglers, who may use guides to maximize their likelihood of capturing a trophy-size fish. Understanding the 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 nonnative resident.

Understanding movement patterns and seasonal habitat use of introduced Blue Catfish in the Chesapeake Bay region can provide important information for developing fishery management and control programs. Whereas tag returns provide insight into movement patterns, inferring seasonal movements from such studies is difficult because tag returns may occur at irregular intervals. To explore seasonal movement patterns in Blue Catfish populations, we examined data from a spatially explicit standardized trawl survey from the adjacent Rappahannock River. We assumed that changes in trawl catch by river location reflected changes in fish habitat use by region of the river. Movement between these regions could be associated with foraging behaviors or transition to spawning or overwintering areas as documented in native river systems (Garrett and Rabeni 2011) or could be influenced by freshwater discharge and changes in salinity (Edmonds 2006).

We estimated apparent annual survival of tagged adult Blue Catfish in the Potomac River using a Brownie et al. (1985) dead recovery model. Previous estimates of survival for several Virginia tidal rivers from catch-curve analyses estimated annual survival rates between 67.7% and 79.2% (Greenlee and Lim 2011). Using a tagging study that considered recaptures and recoveries, Fabrizio et al. (in press) estimated survival rates for Blue Catfish in the James River, Virginia, and these rates varied between 16.2% and 44.3% annually. Our survival estimates are the only ones for the Potomac River population and are important for informing management strategies for the species.

METHODS

Tagging Blue Catfish.—Sampling was conducted in a 40-km reach of the Potomac River during July–November 2012 and June 2013 (Figure 1). We used both low frequency (<15 pulses per second and < 1 amp) and high frequency (>30 pulses per second and variable current and amps) electrofishing following standard methods to capture adult Blue Catfish (300–1,165 mm TL; Figure 2a). The size range of Blue Catfish that were tagged in this study included mature individuals (>381 mm TL in native habitats; Graham 1999) capable of undertaking directed spawning movements. Blue Catfish were tagged with uniquely coded plastic-tipped dart tags (Hallprint PDS tags) imprinted with a reporting phone

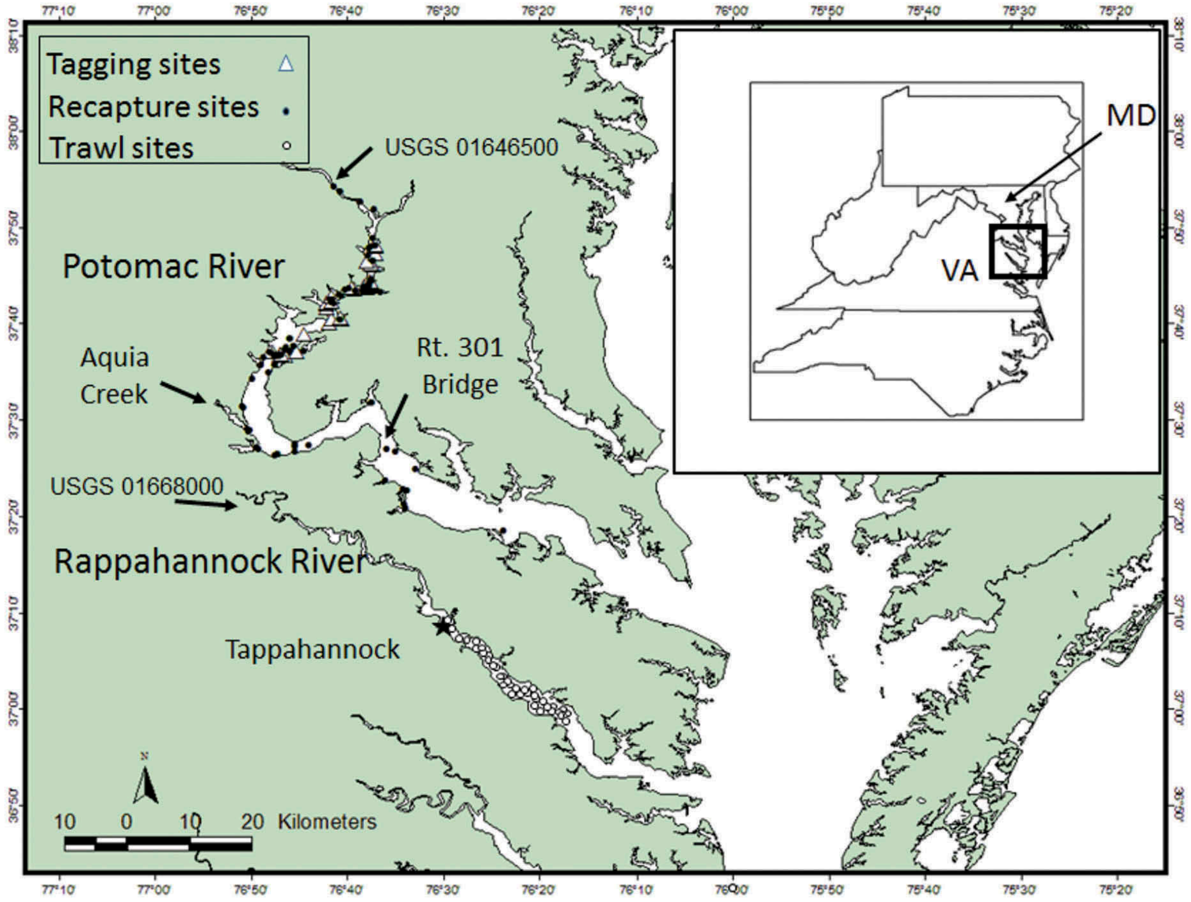

FIGURE 1. Map of tagging sites (open triangles) and recapture sites (filled circles) for Blue Catfish in the Potomac River, Maryland, and trawl sites (open circles) on the Rappahannock River, Virginia, where Blue Catfish are routinely captured by the VIMS (Virginia Institute of Marine Science) Trawl Survey. Tappahannock (black star) marks the uppermost sites sampled by the trawl survey. Also shown are the U.S. Geological Survey (USGS) gauges used for estimating discharge, Aquia Creek, and the location of the U.S. Route 301 bridge.

number and a reward message. All tags were reward tags, and we offered the choice of a hat or a pin. We assumed all encountered tags were reported. The tagging program was advertised widely in traditional and social media outlets. Fishers who reported a tagged fish were asked to remove both tags and report the tag numbers, date and location of capture, fish size, water temperature, fishing depth, and fate of fish (harvest or release). Anglers were also classified as recreational or commercial fishers. To estimate tag retention, all fish were double tagged and retention was estimated with a Cox proportional hazards model (CPH; Cox 1972; Musyl et al. 2011) that included fish length, minimum distance moved, and direction of movement as predictors (Therneau and Grambsch 2000; R Core Team 2016).

Movement of Blue Catfish.—Movement of Blue Catfish was inferred from reports of recapture locations and estimated using the distance between the release location and the reported recapture location. We measured the minimum distance between the two points along the main axis of the river using ArcGIS software (version 9.2; Esri) and note that fish may have moved a greater distance than we report. We tested the effects of fish size, days at large, and direction of movement on the minimum distance moved using a linear model and assuming a lognormal distribution in R. Daily freshwater discharge data (from January 2012 to December 2015) were obtained from USGS gauge 01646500, near Washington, D.C. (Little Falls Pump Station), to investigate the effect of freshwater flow on the relationship between the distance and direction moved by Blue Catfish in the Potomac River.

Due to the inability to discern seasonal movement patterns of Blue Catfish in the Potomac River from the tagging study, we used catch data from a temporally intensive survey in the neighboring Rappahannock River. The trawl data used to examine the spatial distribution of Blue Catfish in the Rappahannock River were collected monthly from 22 sites between the freshwater–saltwater interface (river kilometer 64, measuring from the mouth of the river) downstream to river kilometer 32 (Figure 1; see Tuckey and Fabrizio 2013 for trawl program details). We calculated a monthly index of adult

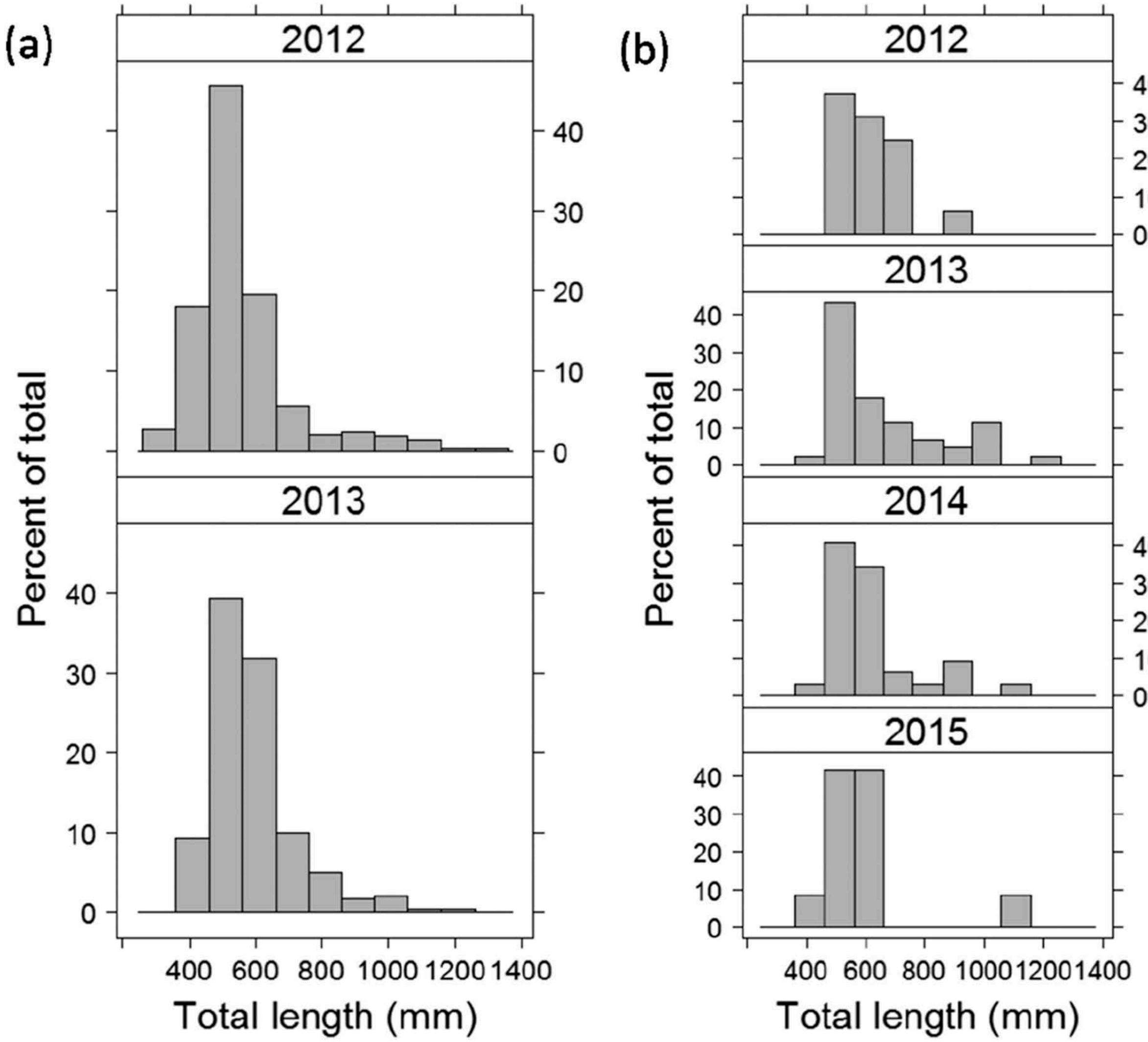

FIGURE 2. Length frequencies of Blue Catfish **(a)** tagged and released in 2012 (*N* = 739) and 2013 (*N* = 498) and **(b)** recaptured in 2012 (*N* = 37), 2013 (*N* = 37), 2014 (*N* = 24), and 2015 (*N* = 6).

Blue Catfish abundance 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 seasonal comparisons of mean abundances among years. Seasonal estimates of mean abundance were then used to identify 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 (using R) to test for the effect of season, discharge, and their interaction on seasonal relative abundance (significance determined at alpha = 0.05). Average monthly discharge for the Rappahannock River was calculated from daily values obtained from USGS gauge 01668000, near Fredericksburg, Virginia. If Blue Catfish exhibit behaviors similar to those observed in their native rivers, then we expect to 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 downriver areas in the Rappahannock River are utilized for foraging and overwintering.

Survival of Blue Catfish.—We implemented the Brownie et al. (1985) dead recovery model 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 as follows: (1) tagged fish are representative of the population, (2) tags are not shed and 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. In addition to considering fish that were harvested and fish that were recaptured then released alive, we also considered models for harvested fish only to examine the sensitivity of model estimates to the fate of the fish. Competing models were compared using Akaike information criterion corrected for small samples sizes (AIC$_c$). We then used the estimate of the tag retention rate 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).

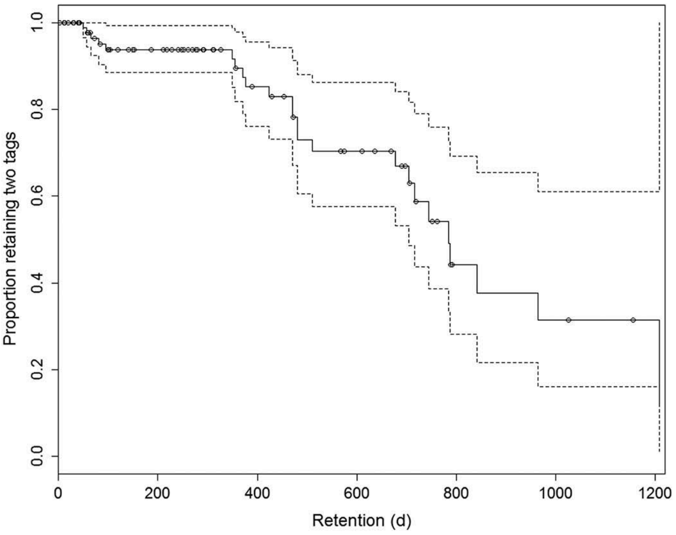

FIGURE 3. Proportion (dotted lines show the 95% CI) of Blue Catfish retaining two tags from 2012 to 2015 in the Potomac River, Maryland.

RESULTS

Tagged Blue Catfish

In 2012 we tagged 739 Blue Catfish ranging in size from 300 to 1,319 mm TL, and in 2013 we tagged 498 Blue Catfish ranging from 374 to 1,165 mm TL (Figure 2a). A total of 104 Blue Catfish were recaptured during the study, which resulted in a tag return rate of 8.4% (92% of tag returns were from the recreational sector). Recaptured Blue Catfish remained at large from 2 to 1,208 d and consisted of fish from a wide range of sizes (390–1,160 mm TL; Figure 2b) that represented the size range of tagged fish (Figure 2a). 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).

There were 33 fish that were recaptured with a single tag during the study, indicating some tag loss. Based on the Cox proportional hazards model and considering only those fish that lost tags during the first year at large, the estimated proportion of Blue Catfish retaining both tags was 0.88 (SE = 0.045; Figure 3). 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; Figure 3).

Movement of Blue Catfish

The mean discharge in the Potomac River differed between tagging years with significantly greater freshwater discharge in 2013 (F = 8.082, P < 0.001; daily mean = 328.7 m^3/s) than in 2012 (252.8 m^3/s; Figure 4). During 2014, freshwater discharge in the Potomac River further 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 rates observed in 2012 (Figure 4). Discharge in the Rappahannock River showed a pattern similar to the Potomac River, with highest discharge observed in 2014 (120.4 m^3/s) and lowest in 2012 (29.9 m^3/s).

Recapture location was not reported for five recaptured fish, resulting in 99 fish that could be evaluated for movement patterns in the Potomac River. The average minimum distance moved for recaptured Blue Catfish was 24.1 km, with a range of 0.0–112.6 km (Figure 5). Thirteen percent of Blue Catfish were recaptured from their release locations for both fish released in 2012 (recaptured 30–1,127 d postrelease) and those released in 2013 (381–789 d postrelease) (Table 1). Most Blue Catfish (63%) were recaptured downstream from the release location, and a greater proportion of Blue Catfish were recaptured downstream in 2013 (75%) than in 2012 (57%; Table 1; Figure 4). The mean minimum 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, and direction accounted for 64% of the variance in the observed minimum distance moved. On average, Blue

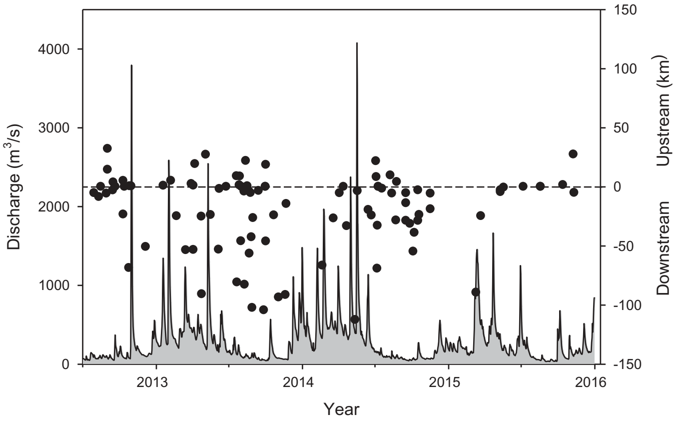

FIGURE 4. Mean daily freshwater discharge (m^3/s) measured at USGS gauge 01646500 on the Potomac River, Maryland, near Washington, D.C. from July 2012 to December 2015, and the distance and direction Blue Catfish moved from the release location (black circles) on the Potomac River.

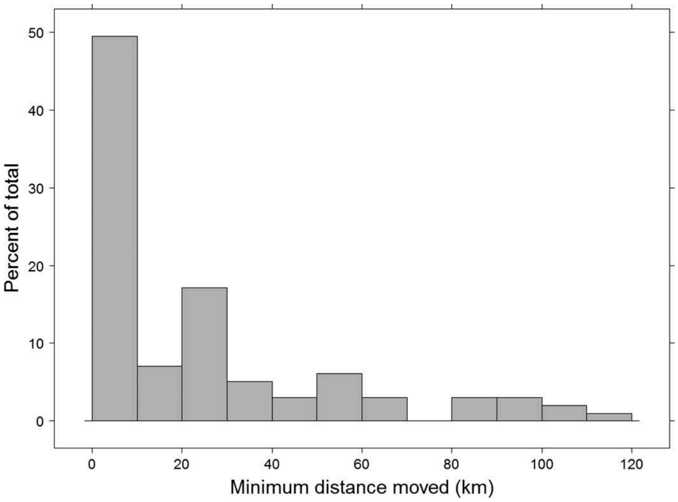

FIGURE 5. The estimated minimum distance Blue Catfish moved from the release locations to the recapture locations reported by recreational anglers and commercial fishers in the Potomac River, 2012–2015.

Catfish moved greater distances downstream (mean = 34.4 km; SE = 3.97) from release locations than upstream from release locations (mean = 6.7 km; SE = 1.53).

We observed high variability in mean-centered relative abundance of Blue Catfish within and among months in the Rappahannock River (Figure 6). There were no significant effects of season (i.e., forage, spawning, and overwintering seasons; $F_{2,\,56} = 0.723$, $P = 0.49$), discharge ($F_{1,\,58} = 0.855$, $P = 0.36$), or the season × discharge interaction ($F_{2,\,54} = 2.36$, $P = 0.104$) on mean-centered abundance of Blue Catfish.

Survival of Blue Catfish

Most models considered for survival estimation were plausible (AIC$_c$ < 2); we chose the time-invariant model for survival, *s*, and recovery rate, *f*, as the best model because it has the fewest parameters (i.e., harvested fish and those released alive). The time-invariant *s* and *f* model also had the lowest AIC$_c$ score among the models fit to the harvested-only subset (Table 2). Survival estimates (adjusted by the single 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 those harvested and those released alive. 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 indicated that overdispersion ($\hat{c}$) was not a problem because the estimate of $\hat{c}$ was close to 1.0 for the group of all recaptured fish ($\hat{c}_{\text{Option 1}} = 1.06$) or less than 1.0 ($\hat{c}_{\text{Option 2}} =$ 0.60) for the harvested-fish-only scenario.

DISCUSSION

Movement of Blue Catfish

Adult Blue Catfish in the Potomac River moved similar (minimum) distances compared to movements of Blue Catfish in their native habitats. The range in salinity that fish were recaptured in in our study indicates that the entire tidal Potomac River, from freshwater habitats to salinities of approximately 12.8‰ (Chesapeake Bay Program 2016), serves as habitat for this species. Additionally, we have observed Blue Catfish in salinities of up to 14.7‰ in the Rappahannock River (Schloesser et al. 2011) and 21.8‰ in the James River, Virginia (Mary Fabrizio and Troy Tuckey, unpublished), suggesting that the Blue Catfish in the Potomac River are likely distributed farther downstream in higher salinity habitats than what we observed from tag returns in this study. The majority of catfish anglers who target Blue Catfish are fishing between Aquia Creek (Figure 1), which is below our release locations, up to and including Washington, D.C. waters (Mary Groves, unpublished). Therefore, the relative differences in reported movements likely resulted from differences in actual downstream movements and is not a result of greater downstream fishing effort.

Trawl catches of adult Blue Catfish were similar across seasons, providing little evidence for seasonal movement patterns. Blue

TABLE 1. Summary of the minimum distance (km) and direction moved from release locations, the number of fish, and the days at large for recaptured Blue Catfish from the Potomac River, 2012–2015.

Release year	Number tagged	Direction of movement	Number recaptured	Minimum distance moved (km)	Days at large
2012	739	Upriver	20	0.4– 2.1	3–1,208
		No movement	9	0.0	30–1,127
		Downriver	38	1.8–93.6	2–1,156
		No information	3		254–712
2013	498	Upriver	4	0.5–18.6	30–842
		No movement	4	0.0	381–789
		Downriver	24	0.8–112.6	31–697
		No information	2		136; 707

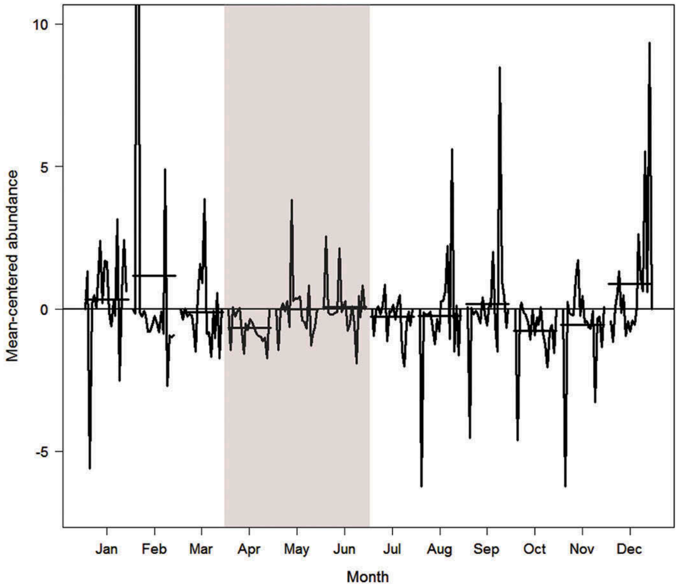

FIGURE 6. Relative abundance index calculated using a delta lognormal model for each month from 1996 to 2015 for adult Blue Catfish (≥381 mm TL) captured by bottom trawl in the Rappahannock River, Virginia. Annual means were subtracted from monthly values to calculate mean-centered abundances. The black horizontal line segments indicate the mean index value by month across years, and the shaded region indicates putative spawning months. The value of the peak that is cut off in February is 29.3.

Catfish may use habitats throughout the river for spawning, including smaller tributaries as has been observed in native habitats (Garrett and Rabeni 2011; Tripp et al. 2011). 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 nonnative estuaries may occur during a different or longer period of time (i.e., April–June does not fully characterize the spawning period of these fish in nonnative habitats). Further study of the maturation process and associated seasonal movements of Blue Catfish in nonnative, coastal rivers is needed.

Survival of Blue Catfish

Blue Catfish survival estimates from the Potomac River were lower than those reported by Greenlee and Lim (2011) for coastal rivers in Virginia but higher than estimates reported by Fabrizio et al. (in press) from the James River. 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, reported in Greenlee and Lim 2011). The total instantaneous mortality rate (from catch-curve analysis of similarly sized Blue Catfish) calculated from 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 higher survival rate in their native system (Tombigbee River) compared with a coastal river estuary (Potomac River). Another explanation for differences is that survival rates vary geographically due to differences in fishing mortality rates and variation in factors contributing to natural mortality rates (e.g., disease, cannibalism, predation, resource limitation). Additionally, because these rates are apparent survival rates, fish may have emigrated from the study area thereby contributing to a negative bias in our estimate. Further work is needed to better understand survival of Blue Catfish in Chesapeake Bay.

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 the dead-recovery model. 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

TABLE 2. A comparison of models used to estimate survival rates of Blue Catfish in the Potomac River, Maryland, from 2012 to 2015. We modeled all recaptures of Blue Catfish regardless of their fate (released or harvested; Option 1) and also 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. Abbreviations are as follows: AIC*c* = Akaike information criterion corrected for small sample size and *k* = the number of parameters. Model selection was based on the lowest ΔAIC*c* score.

Option	Model	AIC*c*	ΔAIC*c*	AIC*c* weight	Model likelihood	*k*	Deviance
1	*s*(.)*f*(.)	938.681	0.000	0.392	1.0000	2	5.3305
	s(*t*)*f*(.)	939.520	0.839	0.257	0.6573	4	2.1469
	s(.)*f*(*t*)	940.288	1.607	0.175	0.4478	5	0.8984
	s(*t*)*f*(*t*)	940.288	1.607	0.175	0.4478	5	0.8984
2	*s*(.)*f*(.)	746.790	0.000	0.517	1.0000	2	3.0217
	s(*t*)*f*(.)	748.155	1.365	0.261	0.5054	4	0.3639
	s(.)*f*(*t*)	749.870	3.080	0.111	0.2144	5	0.0623
	s(*t*)*f*(*t*)	749.870	3.080	0.111	0.2144	5	0.0623

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; Fabrizio et al., in press); 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 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). This assumption is likely overly optimistic and could affect our estimated survival rate (survival rates may be higher than those reported here due to the potentially erroneous assumption of a 100% reporting rate). 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 the 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 the 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 the Potomac River (based on movements we observed). Directed seasonal movements of large Blue Catfish may occur in nonnative habitats, but we were unable to detect these movements in the neighboring Rappahannock River even though we considered 20 years of spatially explicit monthly abundance data. Four reasons may account for our inability to detect seasonal movements: (1) the high abundance of Blue Catfish in nonnative coastal rivers, coupled with the relatively small sample size of captured fish, yields an estimate of seasonal movement with low precision, which does not permit detection of a significant seasonal effect; (2) the behavioral variation among fish is large, and seasonal patterns are not applicable to the population as a whole; (3) the spawning season in the Chesapeake Bay region may be longer than that reported for Blue Catfish in their native range; or (4) a combination of two or more of these reasons.

An additional management implication concerns the consumption of potentially contaminated fish. To protect human health, the Maryland Department of the Environment provides consumption advisories for individual species, including Blue Catfish, which are size and location specific. Movement of Blue Catfish in the Potomac River reduces the effectiveness of these consumption advisories because Blue Catfish captured outside of the advisory area may have accumulated contaminants while they resided within the region of elevated contaminants. For example, the advisory for Blue Catfish in the Potomac River extends from the Route 301 bridge to the District of Columbia and is based on elevated levels of PCBs. Nine Blue Catfish (8.6% of reported tags) that were tagged above the 301 bridge in our study were recaptured below the 301 bridge. Therefore, potential human exposure to elevated PCBs is higher than currently recognized due to downstream movements of fish. We note that our reliance on tag returns from the fishery makes it difficult to discern the true proportion of the population that moves downstream, and provision of such an estimate requires further research.

It is reasonable to consider that movement patterns of Blue Catfish in the Potomac River, one of the largest river estuaries in Chesapeake Bay, may extend to other river systems in the region. For example, there are reports of further range expansion into the low-salinity waters of the upper Chesapeake Bay (the Susquehanna flats; Mary Groves, unpublished), which would permit potential movement into the Susquehanna River. Additionally, the low-salinity waters in the upper bay and the presence of the Chesapeake and Delaware Canal, a 22.5-km waterway that links Chesapeake Bay with Delaware Bay, makes invasion of Delaware Bay a serious possibility.

Lower survival rates in the Potomac River than in native habitats suggest a higher natural mortality rate in nonnative coastal estuaries. However, we do not know the impact of commercial and recreational harvests on the Blue Catfish population in the Potomac River and research is needed to estimate both fishing and natural mortality rates. Long-distance movements of Blue Catfish in the Potomac River indicate that robust control measures will be needed to reduce population abundance and minimize negative impacts of this species on the native estuarine community. Attempts to reduce the abundance of nonnative species in other river systems in the USA have yielded varying results due to compensatory responses in nonnative populations and the potential refuges afforded by the connectivity and complexity of large river systems (Coggins et al. 2011; Franssen et al. 2014; Weber et al. 2016). Additionally, nonnative fish removal programs are expensive and require multiple-year efforts before effects are evident. Prior to investigating mechanical removal methods for Blue Catfish in Chesapeake Bay, investigations into the potential for compensatory responses is warranted. In particular, individual fecundity, spawning frequency, spawning locations, and identification of the spawning period in nonnative habitats are critical data gaps that could inform population dynamics models and help guide management actions.

ACKNOWLEDGMENTS

We are grateful to Branson Williams and Tim Groves (Maryland Department of Natural Resources) for tagging fish. We thank Ross Williams for tagging fish and answering phone calls from anglers reporting tag returns. 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). Two anonymous reviewers provided helpful comments on an earlier version of this manuscript. This paper is contribution number 3666 of the Virginia Institute of Marine Science, College of William and Mary.

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