Natural Mortality and Size Structure of Introduced Blue Catfish in Virginia Tidal Rivers

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Abstract: In the 1970s and 1980s, blue catfish (*Ictalurus furcatus*) were introduced to the tidal rivers of Virginia. Current abundances and uncertainty about population characteristics of blue catfish generated concern for other economically important and imperiled species. We estimated natural mortality and size structure of blue catfish for four tidal river systems (i.e., James, Mattaponi, Pamunkey and Rappahannock). Using common empirical estimators with pooled data from the period 2002–2016, we calculated five estimates of natural mortality. Proportional size distributions were used to examine changes in size structure over time. Maximum observed age of 25 years indicated mature populations. Estimated mean instantaneous natural mortality (*M*) from five empirical estimators ranged from 0.13–0.19 in the four rivers. Temporal trends in size structure differed among rivers, likely due to differences in stocking timing and riverine productivity. Proportions of memorable and trophy size blue catfish appear to have recently declined in three of four rivers, but size-structure indices demonstrated continued viability of the James River trophy fishery. This study provides blue catfish mortality estimates to support development of future stock assessment models and management strategy evaluations. Understanding the size structure of these populations will help resource managers gauge the prevalence of large blue catfish relative to historical conditions and provide information on angling opportunities and size-based trophic interactions.

Blue catfish (*Ictalurus furcatus*) are native to the drainages of the Gulf of Mexico from the Mobile to the Rio Grande basins, extending south to Guatemala (Jenkins and Burkhead 1994, Boschung and Mayden 2004). This species has been widely introduced outside its historical range, and now ranges from Atlantic coastal rivers to California with confirmed introductions in 19 U.S. states (Moyle 1976, Jenkins and Burkhead 1994, Graham 1999, Fuller and Neilson 2017). Within the introduced range, blue catfish has been implicated in the declines of native fishes (Grist 2002, Homer and Jennings 2011, Schloesser et al. 2011). Blue catfish generate concern due to their large size (Stauffer et al. 2016) and piscivorous feeding habits at large sizes (Edds et al. 2002, Eggleton and Schramm 2004, Schmitt et al. 2017). While studies have reported blue catfish predation on imperiled or other economically important species (Bonvechio et al. 2011, Aguilar et al. 2017, Schmitt et al. 2017), heavy predation on other non-native species also occurs (Bonvechio et al. 2011, Mitchell 2015).

Blue catfish were introduced in Virginia tidal rivers from the mid-1970s to mid-1980s via intentional stockings by Virginia Department of Game and Inland Fisheries (VDGIF; Jenkins and Burkhead 1994). Stockings occurred in the James, Rappahannock,

and York river systems, but blue catfish have since expanded to all major Virginia tributaries of the Chesapeake Bay and as far north as the Susquehanna River (Greenlee and Lim 2011, Schloesser et al. 2011). Not only has the distribution of blue catfish expanded, populations have become large enough to justify a targeted removal (Greenlee and Lim 2011, Trice and Balazik 2015, Fabrizio et al. 2017). Consumption of American shad (*Alosa sapidissima*), American eel (*Anguilla rostrata*), and blue crab (*Callinectes sapidus*) occurs when and where prey species are abundant and prevalence of these diet items increases with blue catfish size (e.g., >60 cm TL; Moran et al. 2016, Schmitt et al. 2017). This has generated concern for these species in these systems because large, introduced catfishes have been implicated in species declines in other systems (Bart et al. 1994, Moser and Roberts 1999, Dobbins et al. 2012).

Blue catfish in the tributaries of the Chesapeake Bay present a complicated management scenario with numerous conflicts occurring among stakeholders. Blue catfish now provide recreational and commercial fishing revenue to the region (Orth et al. 2017) including trophy blue catfish angling on the James River. Conflicts exist among commercial fishers, as traditional fishers using nets and traps believe management agencies are not ensuring fairness

by only permitting commercial electrofishing to a single boat or addressing their perception that electrofishing is reducing their gear effectiveness and catch. Recreational fishers often do not share the same values and goals (e.g., Wilde et al. 1998, Churchill et al. 2002), and Hyman et al. (2017) reported that blue catfish anglers had different objectives at Kerr Reservoir, Virginia-North Carolina. Commercial and recreational fisher conflicts often arise due to fear of opportunity losses due to activities of the other sector (Arlinghaus 2005). In addition, managing to sustain or otherwise support these fisheries may hinder conservation efforts for other species, as large blue catfish are highly piscivorous (Moran et al. 2016, Schmitt et al. 2017). Further, increases in blue catfish abundance have occurred concurrently with declines in native white catfish (*Ameiurus catus*) likely due to competitive interactions (Schloesser et al. 2011). Differing strategies for blue catfish management among resource management agencies have generated frustration among stakeholders and a lack of a unified approach to managing blue catfish throughout the Chesapeake Bay watershed. To aid in development of strategic management plans based on robust stock assessments, life history traits should be estimated for established introduced populations rather than extrapolated from data in the native range (Sakaris et al. 2006, Rypel 2014).

The purpose of this study was to estimate population characteristics for introduced blue catfish in four Virginia tidal rivers. Specifically, our objective was to estimate instantaneous rates of natural mortality (*M*) for blue catfish in these systems, as no published estimates exist. In addition, we wanted to examine trends in size structure over time. Since the late 1990s, blue catfish in these systems have expanded rapidly and reached large sizes, and we anticipated that natural mortality would be low. These tidal systems were stocked with blue catfish at different points in time; therefore, we hypothesized that maximum size and proportional size distribution (PSD) metrics for given river systems would peak in the temporal order in which blue catfish were introduced.

Study Area

The Chesapeake Bay watershed drains 165,800 km², including six states and the District of Columbia (Chesapeake Bay Fisheries Ecosystem Advisory Panel 2006). The coastal plain in Virginia features several large, tidal rivers that drain into and make up part of the Chesapeake Bay estuary. Within the Virginia portion of the watershed, three major Chesapeake Bay tributaries include the James, York, and Rappahannock rivers. The York River is formed at the confluence of two large tributaries, the Mattaponi and Pamunkey rivers. Blue catfish were stocked beginning in 1974 in the Rappahannock River and later in the James (1975) and Mattaponi River (1985). The species was never stocked in the Pamunkey Riv-

er, but was first detected there in 1988 likely due to colonization from the Mattaponi River.

Methods
Data Collection

From 2002–2016, Virginia Department of Game and Inland Fisheries (VDGIF) collected blue catfish from all four study rivers using low-frequency boat electrofishing. A boat-mounted electrofisher (9.0 GPP, Smith-Root, Inc., Vancouver, Washington) was operated at 15 pulses sec⁻¹ DC current, allowing two netters from the electrofishing boat and two each in two additional chase boats to capture stunned fish. Larger individuals (>60 cm TL) were netted exclusively by a single chase boat to reduce sampling bias towards large individuals by other boats. Due to the extremely high densities of smaller individuals encountered during sampling, gear saturation was a concern. The primary chase boat and electrofishing boat focused on capture of smaller individuals in an effort to reduce sampling bias towards large individuals.

Sampling events generally occurred in August, but blue catfish were also collected in July and September in some years. Water temperature during sampling ranged from 23.6–32.9 °C, as low-frequency electrofishing is more efficient at temperatures >18 °C (Bodine and Shoup 2010). Sampling sites were within the freshwater to oligohaline zones and were used by Greenlee and Lim (2011). A subsample of fish collected were weighed (g) and measured for total length (cm) and retained for otolith extraction at each site. All remaining blue catfish were measured to the nearest cm. Because larger, older blue catfish were not represented in low-pulse samples on the Rappahannock River, additional fish were collected for age analysis using high-frequency electrofishing (120 pulses sec⁻¹) to supplement sample sizes in select years (2002, 2004, 2005, 2007 and 2009). Subsampling procedures for otoliths changed during the study period. From 2002–2004, VDGIF scientists collected a random sample of otoliths using a number per size group subsampling protocol. After 2004, fish were segregated into two size groups (<60 or ≥60 cm TL) and fish were randomly selected for otolith sampling from each group. Fish ≥60 cm TL were aged disproportionately to their abundance to improve understanding of variability in growth for larger fish. Otoliths (lapilli) were processed using the protocol developed by Buckmeier et al. (2002) with modifications described by Greenlee and Lim (2011). Ages were assigned as whole numbers.

To examine changes in size structure over time, we examined data from the Virginia Angler Recognition Program (VARP). Anglers can submit an application for an award upon catching a blue catfish weighing 13.6 kg (30 lb) or 96.5 cm (38 in). We summarized length and weight data from reported awards for the James, Mat-

taponi, Pamunkey, and Rappahannock rivers from 1990–2015 and determined the maximum reported length and weight for each river in each year. These data provided additional information on temporal trends in blue catfish sizes with additional years in which biological data was not collected via electrofishing.

Natural Mortality Estimation

We estimated M using five empirical estimators (Table 1). These estimators use a number of parameters including growth variables, maximum age and weight, and temperature data. Growth in length was described using the von Bertalanffy growth function $L_t = L_\infty$ $(1 - e^{-k(t-t_0)})$ to estimate average maximum length (L_∞), the Brody growth coefficient (k), and the x-intercept (t_0; Haddon 2011) for each river using length-at-age data from 2002–2016. Temporal and individual variability in growth were not considered in this study, as we were interested in a general average. We assumed a lognormal error distribution because variability in length-at-age increases with age (Quinn and Deriso 1999). Growth parameters were estimated using a Bayesian approach in JAGS 4.2.0 (Plummer 2015) using the R2jags package (Su and Yajima 2015) in R 3.1.3 (R Core Team 2015) specified with uninformative priors. Examination of traceplots provided evidence for model convergence (Gelman et al. 2013). To avoid spurious estimates and model fitting errors from taking the logarithm of 0, parameters L_∞, k and t_0 were bound within the intervals [1,144.8 cm], (0,2 yr^{-1}] and [–2,0 yr), respectively. Bounding L_∞ at an upper limit of 144.8 cm limited the parameter to a maximum of the world record length for the species.

Attempts to parameterize the von Bertalanffy weight-at-age model yielded over-estimates of average maximum weight (W_∞) due to the rapid growth of cohorts produced in the years immediately following introduction. Therefore, we substituted the maximum observed weight from low-frequency electrofishing surveys for W_∞ (Maceina and Sammons 2016) to solve for M using Djabali et al. (1993) and Lorenzen (1996) estimators. We estimated

Table 1. Empirical estimators used to estimate average natural mortality (M) for blue catfish in four Virginia tidal rivers over the period 2002–2016. L_∞ (cm), k and t_0 are parameters of the von Bertalanffy growth model, τ is the average water temperature, T_{max} is the maximum age and W_∞ is average maximum weight from growth modeling (or maximum observed weight).

Source	Equation
Pauly 1980	$M = 0.9849 L_\infty^{-0.279} k^{0.6543} \tau^{0.4634}$
Hoenig 1983	$M = 4.31 T_{max}^{-1.01}$
Djabali et al. 1993	$M = 0.8598 W_\infty^{-0.0302} k^{0.5280}$
Jensen 1996	$M = 1.5k$
Lorenzen 1996	$M = 3.00 W_\infty^{-0.288}$

mean water temperature from 1 July 2002 to 30 June 2016 using temperature data collected monthly from multiple stations within the main stem of each river (Chesapeake Bay Program 2017). Water temperature was averaged by month for the 14-year period for each station; we then estimated the mean for each river from respective water quality stations. Raw water temperature data had missing observations; therefore, summarizing by month and station reduced spatial and seasonal biases.
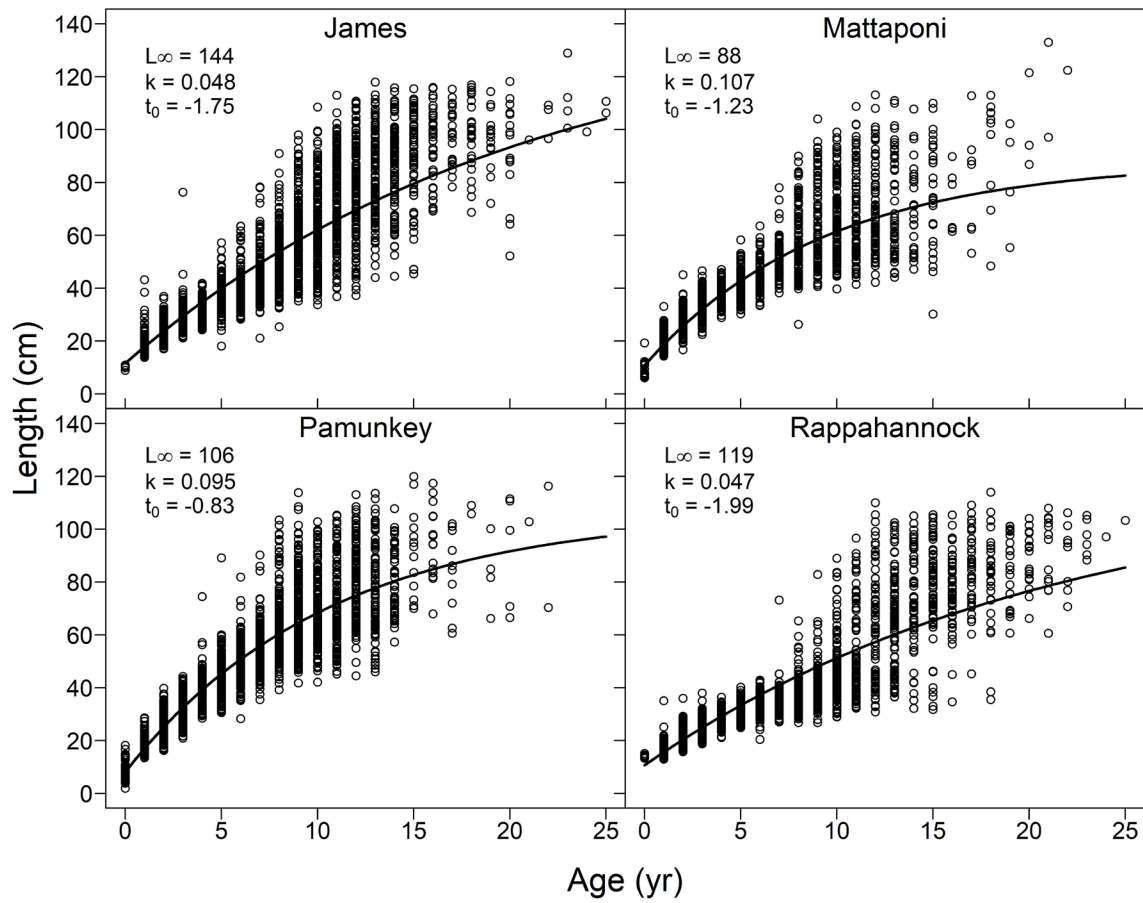
Estimation of Trends in Size Structure

We explored trends in size structure using raw length observations, PSD indices and reported maximum size from trophy anglers. Differences in relative frequency of length observations were compared across years using length-frequency plots. We assessed trends in size structure using PSD indices (Neumann et al. 2012). The published PSD length categories for blue catfish are stock ($\geq$30 cm), quality ($\geq$51 cm), preferred ($\geq$76 cm), memorable ($\geq$89 cm), and trophy ($\geq$114 cm; Gabelhouse 1984). Confidence intervals (95%) on PSDs were estimated from a binomial distribution for PSD, PSD-P, and PSD-M using the Clopper and Pearson (1934) method in the binom package (Dorai-Raj 2015) in R 3.1.3 (R Core Team 2015). Simultaneous incremental PSD confidence intervals were estimated using a multinomial distribution and the MultinomialCI package (Villacorta 2015) in R 3.1.3 (R Core Team 2015). We examined the significance of trends in PSD, PSD-P, and PSD-M over time using Spearman's rank correlations ($\alpha = 0.05$) for each river. In addition, we evaluated trends in annual maximum reported length and weight in VARP awards program data using Spearman's rank correlations ($\alpha = 0.05$) for each river.

Results

A total of 121,578 blue catfish was collected from 2002–2016 in the James, Mattaponi, Pamunkey, and Rappahannock rivers using low-frequency electrofishing. Total lengths ranged from 2–133 cm. A total of 9650 fish were assigned ages using otoliths, with ages ranging from 0–25 years. Maximum observed ages from 2002–2016 varied by system with older observed ages in the James and Rappahannock rivers (25), compared to the York tributaries (22). Maximum observed weight from low-frequency electrofishing was highest in the Mattaponi River and lowest in the Rappahannock River (Table 2). Average water temperature (τ) during the 14-year period was 17.3, 17.1, 17.0 and 16.5 °C for the James, Mattaponi, Pamunkey, and Rappahannock rivers, respectively. Bayesian growth models fit the data from the four rivers well (Figure 1) and the priors used in the models facilitated the capture of the general growth pattern, despite the odd time-varying growth patterns (Greenlee and Lim 2011).

Figure 1. Observed blue catfish length-at-age for four Virginia tidal rivers from 2002–2016. Black lines represent predicted length-at-age from fitted Bayesian von Bertalanffy growth models. Numerical data provide parameter estimates from the fitted von Bertalanffy growth model.

Table 2. Parameters for estimation of average instantaneous natural mortality (*M*) using published empirical estimators for blue catfish in four Virginia tidal rivers over the period 2002–2016. Parameters are defined as T_{max} = maximum observed age, W_{max} = maximum observed weight in electrofishing surveys, *L_∞ = average maximum length, *k is the Brody growth coefficient, *t_0 = theoretical age when length equals zero, and τ = average annual water temperature. * indicates parameter came from the von Bertalanffy growth model.

| Parameter (unit)	James	Mattaponi	Pamunkey	Rappahannock
T_{max} (yr)	25	22	22	25
W_{max} (kg)	34.6	39.5	31.2	22.8
L_∞ (cm)*	144	88	106	119
k (yr^{-1})*	0.048	0.107	0.095	0.047
t_0 (yr)*	−1.75	−1.23	−0.83	−1.99
τ (°C)	17.3	17.1	17.0	16.5

Table 3. Estimates of average instantaneous natural mortality (M) of blue catfish for four Virginia tidal rivers from 2002–2016.

Estimator	James	Mattaponi	Pamunkey	Rappahannock
Pauly 1980	0.13	0.24	0.21	0.13
Hoenig 1983	0.17	0.19	0.19	0.17
Djabali et al. 1993	0.13	0.19	0.18	0.13
Jensen 1996	0.07	0.16	0.14	0.07
Lorenzen 1996	0.15	0.14	0.15	0.17
Mean	0.13	0.19	0.18	0.13
Range	0.07–0.17	0.14–0.124	0.15–0.21	0.07–0.17

Natural mortality was relatively similar across all four river systems, but some differences were evident. The largest *M* estimates were from the York tributaries, whereas the older populations in the James and Rappahannock rivers had lower estimates of *M* (Table 3). The observed range of *M* estimates was the same in the James, Rappahannock and Mattaponi rivers (0.10), but smaller for the Pamunkey River (0.06).
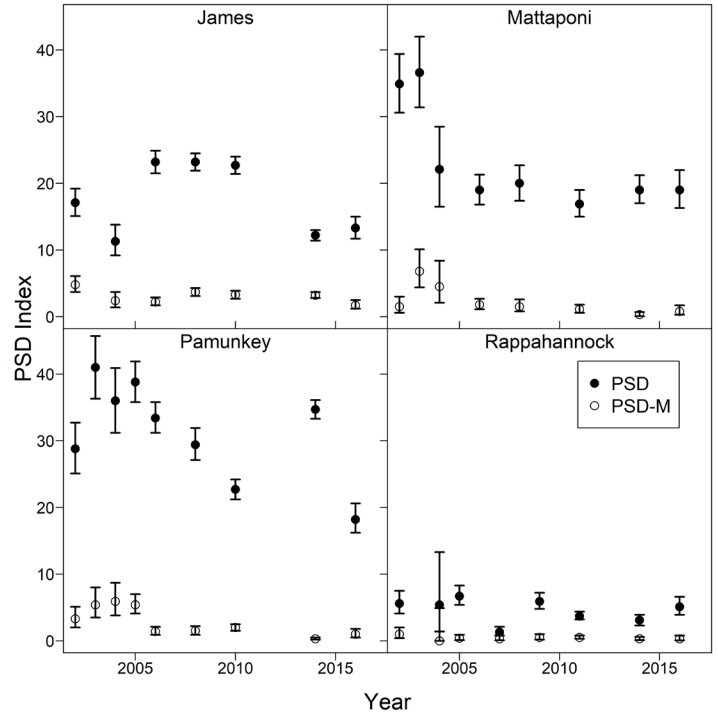
Length-frequency plots (Figure 2) show variable trends in size structure over time. However, the York tributaries (i.e., Mattaponi and Pamunkey rivers) appear to have the greatest proportions of fish
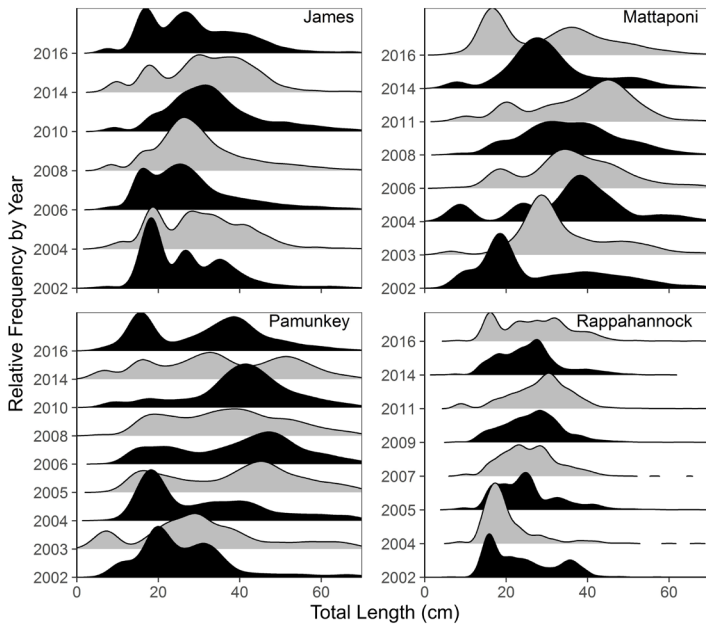
Figure 2. Blue catfish relative length frequency over time in four Virginia tidal rivers. Total length was truncated at 70 cm to enhance detail at more common sizes.

Figure 3. Proportional size distribution (PSD) indices over the period 2002–2016 with error bars (95% confidence intervals) for blue catfish in four Virginia tidal rivers. Symbols represent indices PSD and PSD-M.

longer than 40 cm. The Rappahannock River had the lowest proportion of fish longer than 40 cm. Fish sizes appeared to increase in the early 2000s and decline more in later years (Figure 3); the pattern is most evident in the York tributaries. The James River appears to have stabilized for fish <70 cm with some random fluctuations due to recruitment variability. Occasionally, we observed strong year classes move through the population over time (Figure 2).

Spearman's rank correlations on size-structure indices showed significant negative trends in size structure over the study period in the York tributaries. Spearman's rank correlation of PSD-P and year was significant for the Mattaponi ($\rho = -0.90$, $P = 0.005$) and Pamunkey ($\rho = -0.80$, $P = 0.014$) rivers, but not the James ($\rho = -0.43$, $P = 0.35$) and Rappahannock rivers ($\rho = -0.48$, $P = 0.243$). We found similar trends for PSD-M with significant declines in the proportion of memorable-length fish in the Mattaponi ($\rho = -0.74$, $P = 0.046$) and Pamunkey ($\rho = -0.80$, $P = 0.014$) rivers, but not the James ($\rho = -0.46$, $P = 0.302$) and Rappahannock rivers ($\rho = -0.31$, $P = 0.462$; Figure 3). There were no significant trends in PSD over time for any of the four rivers (Figure 3). Of stock length fish (>30 cm), more than 90% were <60 cm in the Rappahannock River in all sampling years. The James River and York populations had proportionately more trophy-sized (≥114 cm) fish than the Rappah-

annock River. No trophy-sized fish were collected in the Rappahannock River from 2002–2016 using low-frequency electrofishing, whereas trophy fish made up as much as 0.3% of fish >30 cm in some years in the other three rivers.

Maximum reported length and weight from VARP data increased over time in three of the four rivers considered (Figure 4). With respect to maximum reported length, there were significant increases over time in the James ($\rho = 0.565$, $P = 0.003$), Mattaponi ($\rho = 0.804$, $P < 0.001$), and Pamunkey rivers ($\rho = 0.599$, $P = 0.011$). Maximum reported weight increased significantly in the James ($\rho = 0.879$, $P < 0.001$), Mattaponi ($\rho = 0.832$, $P < 0.001$) and Pamunkey rivers ($\rho = 0.869$, $P < 0.001$). Trends in VARP data were insignificant for the Rappahannock River for length ($\rho = -0.265$, $P = 0.191$) and weight ($\rho = 0.012$, $P = 0.954$). However, increases in maximum weight, though significant in three rivers, appeared to be leveling off in later years (Figure 4). From 1990 to 2015, maximum reported weight increased 208% and 220%, in the James and Mattaponi rivers, respectively. The Pamunkey River maximum reported weight increased 196% from 1999 to 2015. Maximum reported length increased 208%, 230% and 196% over the same periods for the James, Mattaponi and Pamunkey rivers, respectively.
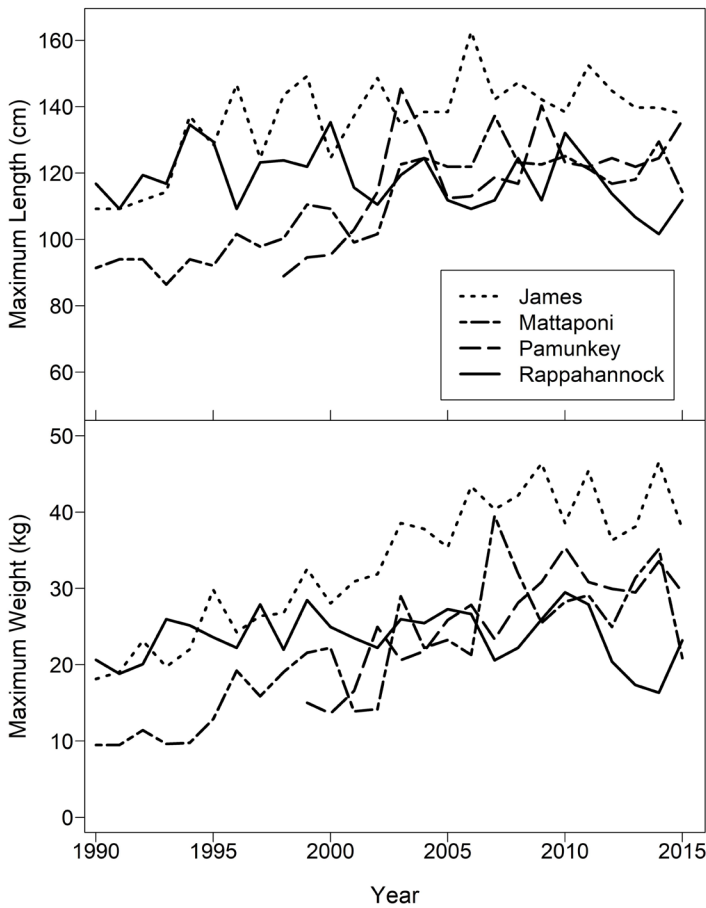
Figure 4. Trends in maximum reported blue catfish length and weight from Virginia Angler Recognition Program trophy angling award database from 1990–2015 from four Virginia tidal rivers.

Discussion

Theoretical work on fish life history has identified linkages in certain life history traits related to tradeoffs among growth, reproduction, and survival (Roff 1984, Jensen 1996). Consequently, understanding some life history processes can provide insight on others. Published information on introduced blue catfish M was lacking from Virginia tidal rivers. However, existing information on other life history traits provided estimates of M that helped fill this knowledge gap. Empirical estimates of M provide useful comparisons with future estimates generated by stock assessment models and can provide inputs for simulation studies evaluating management strategies for this introduced species.

The low estimates of M indicate these blue catfish populations are likely sensitive to overfishing (Adams 1980). Two overlapping studies on Wilson Reservoir, Alabama, reported mean M from multiple estimators as 0.15 and 0.16 (Maceina 2007, Holley et al. 2009). Our M estimates were similar to both Maceina (2007) and Holley et al. (2009), with lower estimates for the James and Rap-

pahannock rivers. Natural mortality estimates were higher for the York tributaries, which received blue catfish a decade later than the James and Rappahannock. The blue catfish populations in the York tributaries are likely still stabilizing, possibly leading to biased estimates of M. Estimating M using empirical estimators does not allow for estimation of uncertainty and is subject to quality of inputs (Maceina and Sammons 2016). High variability in growth among individuals may have caused unreliable estimates of von Bertalanffy growth parameters; however, M estimates derived from von Bertalanffy growth parameters were similar to those calculated using other estimators, with the exception of estimates from the Jensen (1996) estimator for the James and Rappahannock rivers. Use of other methods to estimate M (e.g. tag-recapture) could provide more reliable estimates, but associated costs may be prohibitive.

Greenlee and Lim (2011) estimated total mortality from these same rivers using catch-curve regressions with multi-year pooled catch-at-age data. Resulting total instantaneous mortality (Z) estimates were 0.308, 0.233, 0.390, and 0.212 for the James, Mattaponi, Pamunkey and Rappahannock rivers, respectively. Pairing these estimates with our estimates of M suggest that exploitation of blue catfish in these rivers was low during the period of blue catfish expansion. However, no published work has explored the exploitation of these blue catfish populations. In 2016, commercial blue catfish harvests in Virginia exceeded 1000 metric tons (Virginia Marine Resources Commission, unpublished data), including experimental removals via low-frequency electrofishing (Trice and Balazik 2015). Quantitative evaluation of alternative management strategies would benefit from robust estimates of fishing mortality and total mortality.

Size-structure indices revealed declines in the proportion of preferred- and memorable-sized blue catfish over time in the York tributaries. Given that these populations originated later than those of the James and Rappahannock rivers, size structure appears to be continuing to stabilize. Further, maximum size from reported angler data increased during the study, but appeared to stabilize in recent years for most rivers. Differences in size structure among rivers can also be a reflection of nutrient influences regulating productivity (Randall et al. 1995). The reductions in large blue catfish over time appear to be related to reductions in growth (Greenlee and Lim 2011) and possibly to increases in fishing mortality rates. Commercial harvest shows no discernable trend in the James River, while there were increases in the Rappahannock and York rivers (Virginia Marine Resources Commission, unpublished data). Because harvest data lack fish size information, the possibility that size-selective harvest will reduce large blue catfish abundance remains unexplored. However, Maceina (2007) reported blue catfish >68 cm had lower mortality rates than fish <68 cm and harvest

of large fish was uncommon. Further, reductions in size structure indices could be related to increasing numbers of juvenile blue catfish as spawning stock size increased, reducing the proportion of larger fish over time. However, length-frequency distributions showed apparent fluctuations in recruitment over time. While our results show linear trends in size-related metrics for blue catfish, more sophisticated analytical methodologies may provide better insight into size structure trends.

Understanding size structure of blue catfish populations is critically important for balancing the interests of multiple stakeholders and managing impacts to native species. The James River provides a popular trophy blue catfish fishery, providing recreational and economic benefits to the region (Orth et al. 2017) via guide services and independent anglers. In addition, commercial catfish harvest in Virginia in 2016 was valued at US$990,842 (Virginia Marine Resources Commission, unpublished data). Stakeholders have preferences related to fish size for commercial markets and recreational angling. Further, Schmitt et al. (2017) reported variability in blue catfish diet related to size, with fish becoming the major component of the diet by weight once blue catfish reach about 50 cm in the James River. Natural shifts in size-structure as blue catfish stabilize in these systems have likely altered proportions of piscivorous fish within populations. Further manipulating blue catfish size-structure by allowing harvest of large individuals could further reduce predation on species of concern (e.g., *Alosa* spp., American eel). However, recent research on contaminant loads revealed high levels of polychlorinated biphenyl and mercury in blue catfish, with increased loads in larger fish (Hale et al 2016). Future work in these systems should integrate these sources of information and engage stakeholders to identify strategies to manipulate size structure to maximize satisfaction, ecosystem integrity, and human health and safety.

This study provides insight on population characteristics for an established introduced species in four Virginia tributaries of the Chesapeake Bay. We provided the first estimates of natural mortality for blue catfish in Virginia. Further, we explored trends in size structure over time from fishery-independent surveys and maximum size from trophy angling. These data will provide the basis for model simulations to assess population trends and compare with estimates from more complex population dynamics models. The trends in size structure explored here will provide resource managers with critical information on the prevalence of trophy fish and improve inferences in examining predatory impacts due to size-based dietary variability. This study also provides additional information on invasion dynamics through examination of population characteristics across systems and time. Robust stock assessments based on population dynamics models parameter-

ized with data from continued monitoring efforts and food habits work will provide estimates of consumption for important species. These data coupled with stakeholder input and cooperation among agencies are necessary to generate a unified management approach for blue catfish in the Chesapeake Bay tributaries.

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