Characterizing the growth dynamics of blue catfish in the Chesapeake Bay watershed

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1. Introduction

Terrestrial and aquatic ecosystems worldwide are experiencing invasions by non-indigenous species. Biotic invasions are not exclusively human-induced; however, the geographic scope, frequency, and number of species involved have grown considerably in recent years such that very few global habitats remain free of species introduced by humans (Mack et al. 2000). Freshwater systems worldwide have been the recipients of many invasive species (Garcia-Berthou et al. 2005), with high profiled examples including Nile perch (*Lates nilotica*) in Lake Victoria, East Africa and zebra mussels (*Dreissena polymorpha*) in the rivers and Great Lakes of North America. The effects of invasive species to a host ecosystem can vary from negligible to dramatic, and the scale of influence can be at the individual, population, community and ecosystem levels (Simon et al. 2003). For individual native organisms, invaders may alter habitat utilization and foraging behavior, while at the population level, invaders can change the abundance and distribution of native populations (Olden et al. 2006). Invaders can affect community dynamics by altering direct and indirect interactions among native species and impact ecosystem functioning through alterations of the pathways and magnitude of nutrient flux (Vitousek 1990, Elser et al. 2000). Regardless of the scale of the impact, virtually all non-indigenous species have been characterized as major threats to biodiversity and ecosystem integrity (Welcomme 1988, Mack et al. 2000).

The blue catfish (*Ictalurus furcatus*) is a large and relatively long-lived fish native to freshwater systems in the central and southern United States. Stocking programs and unauthorized introductions have established blue catfish populations in reservoirs and rivers of several regions outside of its native range, including tributaries of Chesapeake Bay. Since their initial introduction in the freshwater components of the James, York, and Rappahannock Rivers during the 1970s and 1980s, blue catfish populations have rapidly expanded into tidal riverine habitats (Schloesser et al. 2011). Currently, blue catfish are common in all Atlantic slope rivers of Virginia, occupy several rivers in Maryland including the Potomac, Patuxent, Elk, and Nanticoke Rivers, and are found in Chesapeake Bay as far up-estuary as the mouth of the Susquehanna River (Schloesser et al. 2011). The scale of influence that blue catfish have exerted on resident species and bay sub-ecosystems is not fully understood. Population growth and range expansions of blue catfish appear to have negatively influenced resident fish assemblages; in particular, declines in abundance of the native white catfish *I. catus*, were observed following the establishment of blue catfish populations in the mid-1990s (Schloesser et al. 2011). Trophic interaction data for blue catfish have shown their diets to be diverse with common prey types including various fishes, crustaceans, worms, clams, freshwater mussels, and crabs. Relatively recent stable isotope analyses of blue catfish tissues collected from several coastal rivers in Virginia indicated that this species occupies a novel trophic position that is significantly higher than that of native predatory fishes (MacAvoy et al. 2009, MacAvoy et al. 2000, Garman and Macko 1998). Collectively, these results suggest that blue catfish may be exerting influence on multiple scales. Their predatory demands have likely affected the foraging behavior of other resident individuals through resource competition, noted declines in the abundance of resident species is indicative of population level impacts, and fulfilling the role of a top predator is suggestive of altered community interactions and ecosystem level nutrient fluxes through the food web.

The study of invasive species can be broadly partitioned into two areas of focus. From a preventative perspective, effort has been directed at predicting which species are likely to be invasive or determining why potential invaders succeed or fail (Kolar and Lodge 2001). Secondarily but arguably equally important are questions regarding the impacts of invaders that have become successfully established. With respect to blue catfish in Chesapeake Bay, the latter area of focus is most germane presently, since there is little doubt that several viable blue catfish populations exist within bay tributaries. Therefore, a natural question to pose is, how should blue catfish be managed?

A basic but critical underlying requirement to science-based fisheries management is knowledge of a species' population dynamics. For an invasive species like blue catfish, population dynamics studies in Chesapeake Bay are crucial since similar information about blue catfish in its native home range may not be truly representative of the processes governing its abundance. At a minimum, an understanding of growth, recruitment, and mortality (both fishing and natural) is necessary to support the development of fisheries management strategies. Estimates of total abundance (biomass and number) are also extremely important underpinnings of management plans. In response to the most recent NOAA Chesapeake Bay Office RFP (NOAA-NMFS-NCBO-2011-2002881; Program Priority 1a, blue catfish), our research team submitted a series of companion proposals that outlined efforts designed to more formally address various aspects blue catfish population dynamics in Chesapeake Bay. The present progress report outlines work completed for one of those proposals, namely the project titled 'Characterizing the growth dynamics of blue catfish in the Chesapeake Bay watershed.'

2. Project objectives

The objectives of this study were to: 1) develop a 'master' database of existing and newly collected data on the growth of blue catfish in the James, York, Rappahannock, and Potomac River systems, and 2) analyze those existing and newly collected data to formally describe the growth patterns and dynamics of blue catfish in the aforementioned tributaries of Chesapeake Bay.

3. Summary

<u>Objective 1</u>: An electronic database was created to house available blue catfish growth information for populations in the primary tributaries of Chesapeake Bay. This database resides at the Virginia Institute of Marine Science (VIMS) and it contains 'historic' and 'current' length-at-age and weight-at-length information. The 'historic' data are from fish collected in the James, York, and Rappahannock Rivers during the years 1998-2000 (n=613 individual summed across rivers; Connelly 2001). The 'current' data are from fish collected in the same Virginia tributaries during 2010-2012 (n=560 summed across rivers) along with the Potomac River from 2008-2010.

A variety of sampling platforms were used to collect blue catfish growth data during both time periods. For the historic data, the majority of samples were obtained from the VIMS Juvenile Finfish and Blue Crab Trawl Survey (VIMS Trawl Survey), however, samples were also collected opportunistically from the VA Striped Bass Beach Seine Survey, anchor gillnets, and the VDGIF Electrofishing Survey (Table 1). For the current data, the VIMS Trawl Survey and the MDDNR Electrofishing Survey have supplied specimens (Table 1).

Objective 2: The overall scope of this project was to provide in-depth analyses of blue catfish growth dynamics as measured primarily by length-at-age and weight-at-length for the primary tributaries of Chesapeake Bay, and from as many time periods as possible.

Methods

Age determination: All blue catfish collected in the Potomac River were aged by scientists from the Maryland Department of Natural Resources (n = 97 of 330 specimens captured). For the 225 specimens processed for aging from the Virginia tributaries during 2010-2012, the following protocol was used. Otoliths were removed and stored in dry plastic vials. A thin (~ 0.5 mm) section was taken through the nucleus of the left lapillus, perpendicular to the longitudinal axis. The resulting section was mounted onto a glass slide using CrystalBond™ and wet sanded using 320 grit sandpaper until the clarity of annuli was satisfactory. Following sanding, the section was again covered with a thin layer of CrystalBond™. This sectioning technique was impractical for the smallest otoliths due to frequent breakage. In these cases, a single cut was made slightly off-center of the nucleus, and the piece of the otolith that contained the nucleus was mounted with the cut side facing the glass slide. The piece was then sanded to the nucleus, effectively producing a thin section, which was then covered with a thin layer of CrystalBond™.

The processed lapillus from each specimen was read independently by each of three readers at 50x magnification with transmitted light. The number of dark bands observed, including any found on the distal edge, was recorded. Once the dark bands were tabulated, ages were assigned depending on how the date of capture related to the period of mark formation for blue catfish. Peak frequency of this mark formation is June, so the assigned age for each specimen captured from July to December was taken to equal the number of dark bands observed. For those fish collected between January and June, the assigned age equaled the number of bands if the edge of the otolith was dark (i.e., annulus for that year was forming at the time of capture), or the age was given as the number of bands plus one if a dark band was absent from the edge (i.e., specimen captured prior to annulus formation for that year). The final age assigned to a given specimen was the mode of the assigned ages produced by the three readers for that fish.

Modeling: An analysis protocol was established to ensure consistency in the treatment of the observed length-at-age and weight-at-length data from each river system. For each data type from each river, preliminary models were fitted to generate diagnostic plots of residuals and QQ plots to aid in identifying the appropriate error structure. Once the error structure was defined, a suite of plausible growth model forms and parameterizations was fitted to the observed data. Multiple models were considered in an effort to identify the most parsimonious description of the available data. Model selection was achieved using Akaike's Information

Criterion (AIC, Burnham and Anderson 2002), which for growth model *m* can be written in terms of ordinary least squares output as follows (Kimura 2008):

$$\mathrm{AIC}_m = n(1+\log(2\pi \cdot RSS_m / n)) + 2p_m$$

where *n* is the number of data points, RSS_m is the minimized residual sum-of-squares for model *m*, and p_m is the number of estimated parameters for model *m*, including the error parameter. The most parsimonious model within the candidate set, which can be thought of as the model that best balances the tradeoff between fit and number of estimated parameters, has the lowest AIC value. Because AIC is on a relative scale, it is often important to calculate AIC differences, which are defined as $\Delta\mathrm{AIC}_m = \mathrm{AIC}_m - \mathrm{AIC}_{min}$, where AIC_{min} is the smallest AIC value within the set of models. Generally, $\Delta\mathrm{AIC}_m$ values between 0-2 are indicative of substantial empirical support for the fitted model, and values between 4-7 are associated with models that have less empirical support (Burnham and Anderson 2002). All statistical analyses were conducted using the software package R version 2.15.1 (R Core Development Team 2012, Vienna, Austria).

<u>Model suite 1, length-at-age:</u>

1) von Bertalanffy function: $L_a = L_\infty(1-e^{-k(a-t_0)})$
2) von Bertalanffy function parameterized with a categorical sex covariate (male vs. female, Kimura 2008): $L_a = (L_{\infty_0} + L_{\infty_1}x_{sex})(1-e^{-(k_0+k_1x_{sex})(a-(t_0+t_1x_{sex}))})$
3) von Bertalanffy function parameterized with a categorical time period covariate (current vs. historic, Kimura 2008): $L_a = (L_{\infty_0} + L_{\infty_1}x_{period})(1-e^{-(k_0+k_1x_{period})(a-(t_0+t_1x_{period}))})$
4) von Bertalanffy function parameterized with categorical sex and time period covariates (male vs. female; current vs. historic, Kimura 2008):
$L_a = (L_{\infty_0} + L_{\infty_1}x_{sex} + L_{\infty_2}x_{period})(1-e^{-(k_0+k_1x_{sex}+k_2x_{period})(a-(t_0+t_1x_{sex}+t_2x_{period}))})$
5) Linear function: $L_a = \beta_0 + \gamma_1 a$
6) Linear function parameterized with a categorical sex covariate (male vs. female, Kimura 2008): $L_a = (\beta_0 + \beta_1x_{sex})(\gamma_0 + \gamma_1x_{sex})a$
7) Linear function parameterized with a categorical time period covariate (current vs. historic, Kimura 2008): $L_a = (\beta_0 + \beta_1x_{period})(\gamma_0 + \gamma_1x_{period})a$
8) Linear function parameterized with categorical sex and time period covariates (male vs. female; current vs. historic, Kimura 2008):
$L_a = (\beta_0 + \beta_1x_{sex} + \beta_2x_{period})(\gamma_0 + \gamma_1x_{sex} + \gamma_2x_{period})a$

<u>Model suite 2, weight-at-length:</u>

1) Isometric function: $W = \alpha L^3$
2) Isometric function parameterized with a categorical time period covariate (current vs. historic, Kimura 2008): $W = (\alpha_0 + \alpha_1x_{period})L^3$

3) Allometric function: $W = \alpha L^{\beta}$
4) Isometric function parameterized with a categorical time period covariate (current vs. historic, Kimura 2008): $W = (\alpha_0 + \alpha_1 x_{period}) L^3$

Note that a sex covariate was not included in the weight-at-length model parameterizations. Since these date came from fisheries-independent sampling programs, very few animals are routinely sacrificed for increased biological information. Therefore, to maximize sample sizes for the analysis herein, we chose to ignore the sex covariate.

Results/Discussion
<u>James River:</u> For the James River blue catfish length-at-age data, ΔAIC statistics strongly supported a linear function parameterized with time period and sex covariates (Table 2). It is likely that growth is not linear as most fish exhibit growth trajectories that approach an asymptotic maximum size. Low sample sizes of older fish precluded fitting more complex and arguably realistic model formulations. Since blue catfish can live over 20 years (Graham 1999), the lack of older individuals in our data may be due to sampling inefficiency and/or an incompletely filled out age-structure within the James River population. Regardless, some caution should be exercised when interpreting these results.

Despite the aforementioned limitations, several important conclusions emerged from our analysis. Inclusion of time period covariate alone significantly improved model fit when compared to a model with only the sex covariate. Although both covariates are important, it is reasonable to infer that time period had a larger effect than sex. Directionally, blue catfish collected more recently showed a reduced accumulated length-at-age than those collected historically, and male fish achieved larger length-at-age than female fish (Figure 1). Sexual dimorphic growth with males growing faster and attaining larger sizes than females is consistent with results from blue catfish studies in Alabama lakes (Marshall et al. 2011). The coefficients of variation (CVs) associated with the estimated model parameters were generally low, which indicated good precision to the estimation (Table 3). It should be noted though that model diagnostics under additive error showed an acceptable plot of residuals but modest departure from the normality assumption.

In terms of weight-at-length, ΔAIC statistics strongly supported the allometric model parameterized with a time period covariate (Table 4). This result suggests that James River blue catfish more recently accumulated less weight per length increment than historically (Figure 5). CVs of the estimated parameters were good (Table 5) and model diagnostics under additive error showed good model fit. We believe that the these results are fairly robust, and given that the James River population abundance has increased substantially over the past decade (Schloesser et al. 2011), the decreased weight-at-length of fish collected more recently may be due to density-dependent effects.

<u>York River:</u> For the York River blue catfish length-at-age data, ΔAIC indicated the best fitting models were the von Bertalanffy function parameterized with time period followed by the von

Bertalanffy model with both time period and sex covariates (Table 2). Although nonlinear models were fitted successfully, the estimated asymptotic lengths were not precisely estimated as evidenced by several high CVs (Table 3). As with the James River data, sample sizes of older fish were generally low and may again be due to sampling inefficiency and/or an incompletely filled out age-structure. This latter point is potentially viable since the York River population was established in the 1980s and thus it is immature relative to the 1970s established James River population. Model diagnostic plots under additive error were acceptable and predicted length-at-age for contemporary fish was considerably higher than that of historic fish (Figure 2). With a filled out age-structure and more data from older animals, it is reasonable to speculate that sexual dimorphism could become more pronounced.

Weight-at-length results were again more robust, and ΔAIC indicated the best fitting model was the allometric function parameterized with a time period covariate (Table 4). Diagnostic plots of model fit were good under multiplicative error and, as with the James River blue catfish population, accumulated less weight per length increment for York River fish was less during recent years than historically (Figure 6). CVs of the estimated parameters were low (Table 5) and given that the York River population has also increased in abundance over the past decade (Schloesser et al. 2011), density-dependent effects on growth are likely also present in this population.

<u>Rappahannock River:</u> For the Rappahannock River blue catfish length-at-age data, ΔAIC statistics supported the linear function with a time period covariate as the best fitting model followed by the linear function with both the time period and sex covariates (Table 2). Model diagnostics under additive error were acceptable and CVs of the estimated parameters were all quite good (Table 3), despite the implausibility of linear growth. Although the base von Bertalanffy model was successfully fitted, efforts to apply parameterizations with covariates were unsuccessful due to low sample sizes of older fish. The interpretation of the York River length-at-age results applies here; the Rappahannock River population is relatively immature and low sample sizes of older fish may be due to sampling inefficiency and/or the age-structure is likely not completely filled out. Thus, a more robust characterization of length-at-age, including documentation of expected sexual dimorphism, will remain challenging until better sampling of older animals can be achieved from a representative age-structure.

Model selection using ΔAIC strongly indicated that the best fitting model to the Rappahannock River weight-at-length data was the allometric function parameterized with a time period covariate (Table 4). Again, model diagnostics under multiplicative error were good and accumulated less weight per length increment was less during recent years than historically (Figure 7), although it should be noted that the contemporary data set did not contain animals larger than 443mm FL. Model parameters were again well estimated as evidenced by low CVs (Table 5). Increase abundance of the Rappahannock River population over the past decade (Schloesser et al. 2011) supports the conclusion the inference of density-dependent effects on growth.

Potomac River: Historical length-at-age or weight-at-length data were not for the Potomac River, so modeling efforts were based on data collected during recent years. Model selection using ΔAIC indicated the best fitting length-at-age model was a simple linear function, although there was appreciable empirical support for the von Bertalanaffy model and the linear function parameterized with a sex covariate (Table 2, Figure 4). Model diagnostics under additive error showed good model fit and estimated CVs were low (Table 3), but the lack of older fish in the data set precluded fitting the arguably more realistic von Bertalanffy model with a sex covariate. Sampling inefficiency of older fish and/or relative immaturity of the population was again of concern.

The ΔAIC model selection statistics strongly indicated that the allometric model provided the best fit to the weight-at-length data (Table 4, Figure 8). Model diagnostics under multiplicative error were good and the estimated CVs were low (Table 3).

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Table 1. Gear type, time period, and river system sampled for blue catfish from historic and current time periods.

Survey	Gear type	Years	Months	Tributaries sampled
VIMS Trawl Survey	Otter Trawl	1975-present	Jan-Dec	James, Rappahannock, York
VA Striped Bass Seine	Beach Seine	1985-present	Jul-Sep	James, Rappahannock, York/Mattaponi, York/Pamunkey
Low-frequency (7.5 or 15 pps) Electrofishing	SR18 electrofishing boat	2001, 2007-present	Apr-Nov	Potomac
Low-frequency (15 pps) Electrofishing	Boat-mounted 9.0 GPP unit	Various years depending on tributary 1994-2008	Jul-Aug	James, Mattaponi, Pamunkey, Piankatank, Rappahannock

Table 2. Residual sum-of-squares (RSS), Akaike's information criterion (AIC), and ΔAIC for models fitted to the blue catfish (*Ictalurus furcatus*) length-at-age data set from the James, York, Rappahannock, and Potomac rivers. Models from suite 1 not listed were not able to be fitted successfully.

James River (n=272)

Model	No. pars.	RSS	AIC	ΔAIC
von Bertalanffy	4	1,843,495	3179.3	164.2
Linear	3	1,895,142	3184.8	169.7
Linear, sex covariate	5	1,563,184	3136.5	121.3
Linear, period covariate	5	1,173,986	3058.6	43.4
Linear, period & sex covariates	7	986,103	3015.1	0.0

York River (n=93)

Model	No. pars.	RSS	AIC	ΔAIC
von Bertalanffy	4	1,079,804	1142.4	35.3
von Bertalanffy, sex covariate	7	997,898	1141.0	34.0
von Bertalanffy, period covariate	7	692,493	1107.1	0.0
von Bertalanffy, sex & period covariates	10	661,229	1108.8	1.7
Linear	3	1,501,975	1171.1	64.0
Linear, sex covariate	5	1,388,212	1167.7	60.7
Linear, period covariate	5	785,371	1114.8	7.7
Linear, period & sex covariates	7	765,086	1116.3	9.3

*Rappahannock River (n=266)

Model	No. pars.	RSS	AIC	ΔAIC

von Bertalanffy	4	9.7	-117.0	98.7
Linear	3	9.8	-117.5	98.2
Linear, sex covariate	5	9.8	-113.6	102.1
Linear, period covariate	5	6.7	-215.7	0.0
Linear, period & sex covariates	7	6.6	-213.0	2.7

*multiplicative error assumed such that the observed data and fitted model were log transformed

Potomac River (n=92)

Model	**No. pars.**	**RSS**	**AIC**	**ΔAIC**
von Bertalanffy	4	587,659	1075.2	1.9
Linear	3	588,184	1073.3	0.0
Linear, sex covariate	5	581,027	1076.2	2.9

Table 3. Parameter estimates, standard errors (SE), and coefficients of variation (CV) from the best fitting model to the blue catfish (*Ictalurus furcatus*) length-at-age data set for each river system.

	Parameter	Estimate	SE	CV
James	β_0	67.7	10.6	0.16
	β_{sex}	38.4	12.5	0.33
	β_{period}	84.0	16.7	0.20
	γ_0	73.0	2.5	0.03
	γ_{sex}	-17.7	2.8	-0.16
	γ_{period}	-33.1	3.0	-0.09
York	L_{∞_0}	816.7	127.2	0.16
	$L_{\infty_{period}}$	134.1	619.5	4.62
	k_0	0.21	0.09	0.43
	k_{period}	-0.15	0.11	-0.73
	t_0	-0.50	0.62	-1.24
	t_{period}	-3.5	3.15	-0.90
Rappahannock	β_0	104.2	5.4	0.05
	β_{period}	116.3	18.4	0.16
	γ_0	49.7	1.4	0.03
	γ_{period}	-32.1	2.9	-0.09
Potomac	β_0	276.2	26.8	0.10
	γ_0	60.5	3.8	0.06

Table 4. Residual sum-of-squares (RSS), Akaike's information criterion (AIC), and ∆AIC for models fitted to the blue catfish (*Ictalurus furcatus*) weight-at-length data set from the James, York, Rappahannock, and Potomac rivers.

James River (n=582)

Model	No. pars.	RSS	AIC	∆AIC
Isometric	2	97.2	613.8	215.5
Isometric, period covariate	3	93.9	595.9	197.6
Allometric	3	69.8	423.2	25.9
Allometric, period covariate	5	66.4	398.3	0.0

*York River (n=206)

Model	No. pars.	RSS	AIC	∆AIC
Isometric	2	5.7	-151.7	178.4
Isometric, period covariate	3	3.2	-264.5	65.6
Allometric	3	2.9	-290.2	39.9
Allometric, period covariate	5	2.3	-330.1	0.0

* multiplicative error assumed such that the observed data and fitted model were log transformed

*Rappahannock River (n=383)

Model	No. pars.	RSS	AIC	∆AIC
Isometric	2	7.3	-425.4	260.0
Isometric, period covariate	3	6.6	-465.1	220.3
Allometric	3	4.0	-650.8	34.6

Allometric, period covariate	5	3.6	-685.4	0.0

* multiplicative error assumed such that the observed data and fitted model were log transformed

*Potomac River (n=326)

Model	No. pars.	RSS	AIC	ΔAIC
Isometric	2	12.2	-142.7	349.5
Allometric	3	4.1	-492.2	0.0

* multiplicative error assumed such that the observed data and fitted model were log transformed

Table 5. Parameter estimates, standard errors (SE), and coefficients of variation (CV) from the best fitting model to the blue catfish (*Ictalurus furcatus*) weight-at-length data set for each river system.

	Parameter	Estimate	SE	CV
James	α_0	1.67×10^{-9}	5.15×10^{-10}	0.31
	α_{period}	-1.50×10^{-9}	5.21×10^{-10}	-0.35
	β_0	3.38	0.046	0.01
	β_{period}	0.33	0.084	0.26
York	α_0	3.47×10^{-9}	7.32×10^{-10}	0.21
	α_{period}	5.76×10^{-9}	8.65×10^{-10}	0.15
	β_0	3.24	0.034	0.01
	β_{period}	-0.18	0.036	-0.20
Rappahannock	α_0	3.39×10^{-9}	2.86×10^{-10}	0.08
	α_{period}	5.08×10^{-9}	1.19×10^{-9}	0.23
	β_0	3.25	0.015	0.01
	β_{period}	-0.17	0.029	-0.17
Potomac	α	1.04×10^{-9}	2.87×10^{-10}	0.28
	β	3.39	0.043	0.01

Figure 1. Observed James River blue catfish length-at-age data and predicted growth curves derived from parameter estimates associated with linear model parameterized with time period and sex covariates. Panel designations are (a) male blue catfish from historic (black solid line) and current (gray solid line) time periods; (b) female blue catfish from historic (black solid line) and current (gray solid line) time periods; (c) historic male (black dotted line) and female (gray dotted line) blue catfish; and (d) current male (black dotted line) and female (gray dotted line) blue catfish.

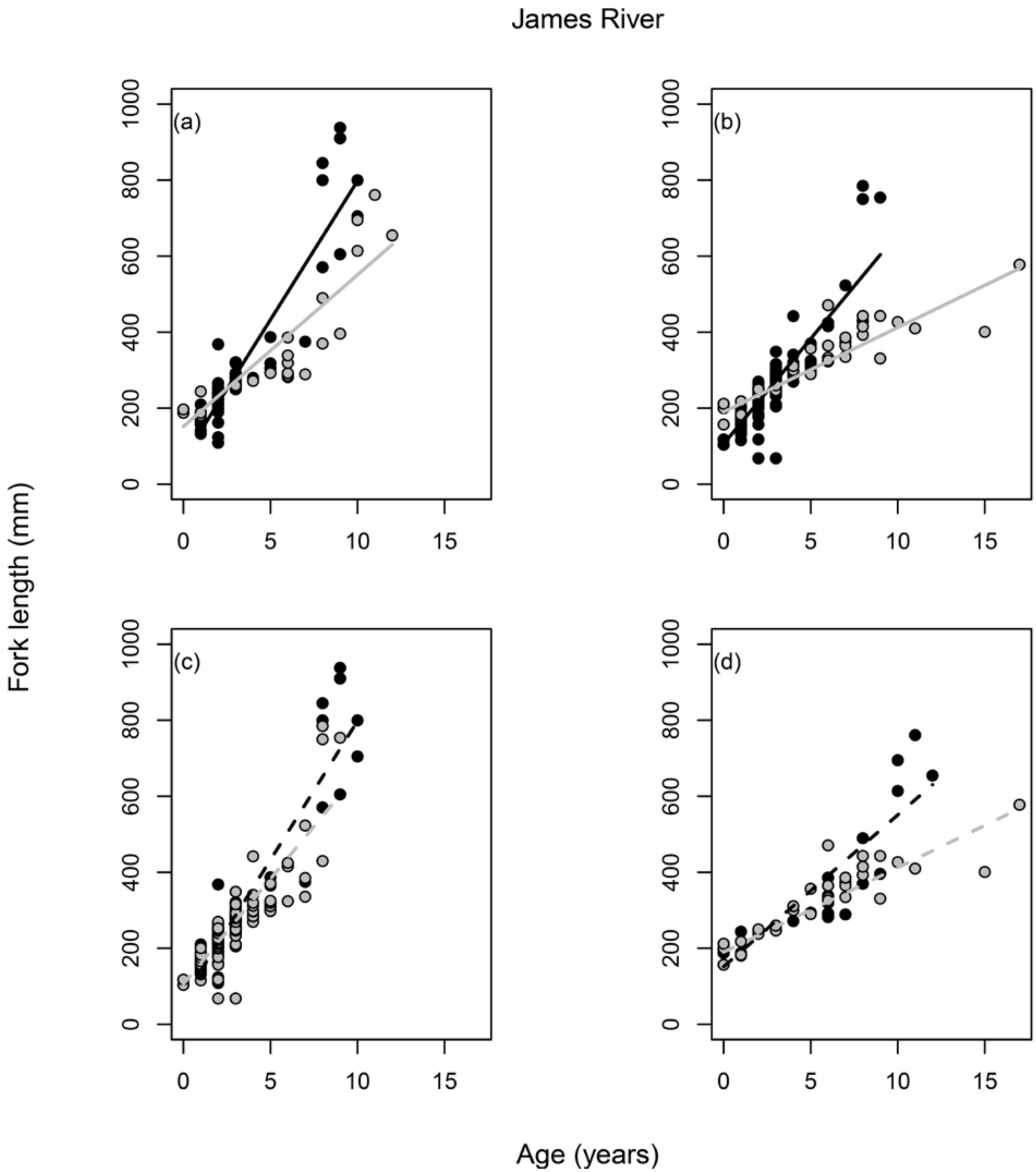

Figure 2. Observed York River blue catfish length-at-age data and predicted growth curves derived from parameter estimates associated with the von Bertalanffy model parameterized with a time period covariate (historic-black solid line; current-gray solid line).

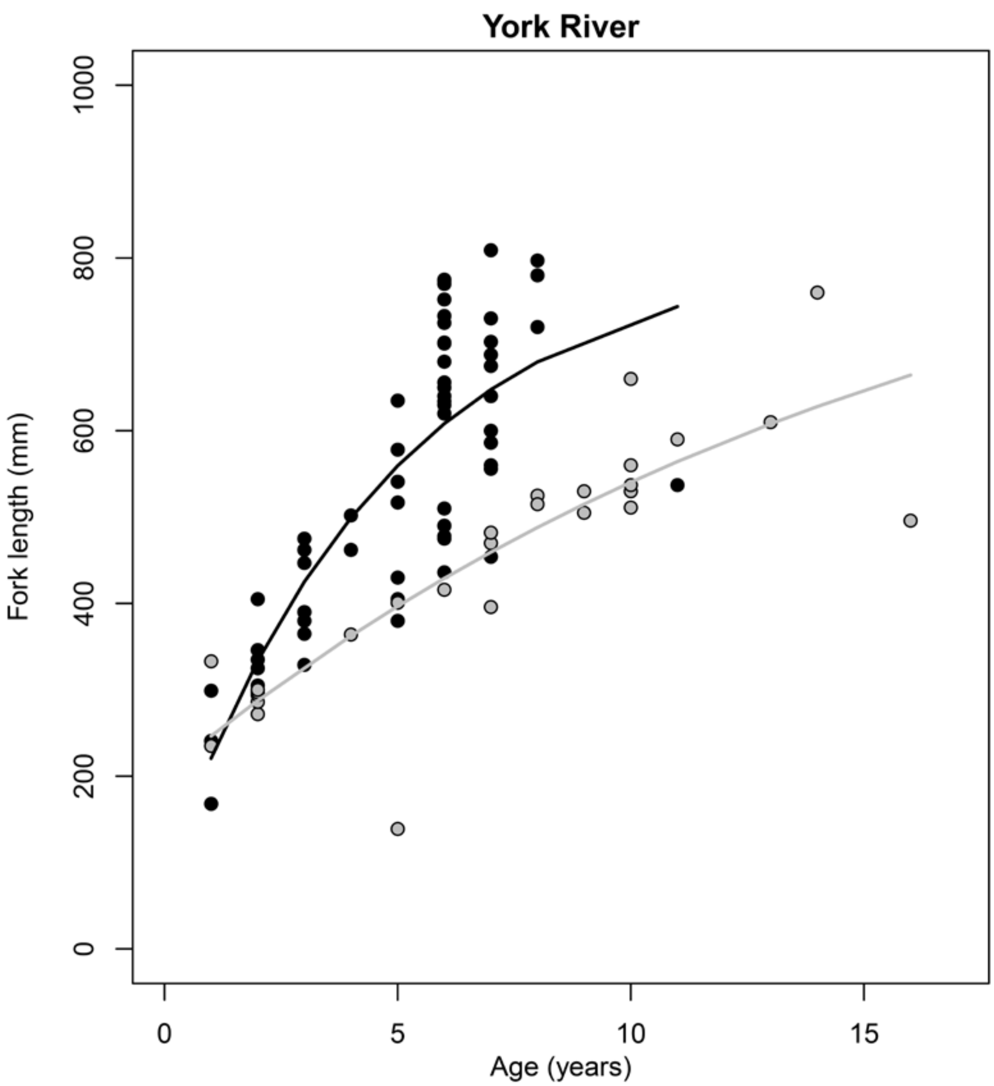

Figure 3. Observed Rappahannock River blue catfish length-at-age data and predicted growth curves derived from parameter estimates associated with the linear model parameterized with a time period covariate (historic-black solid line; current-gray solid line).

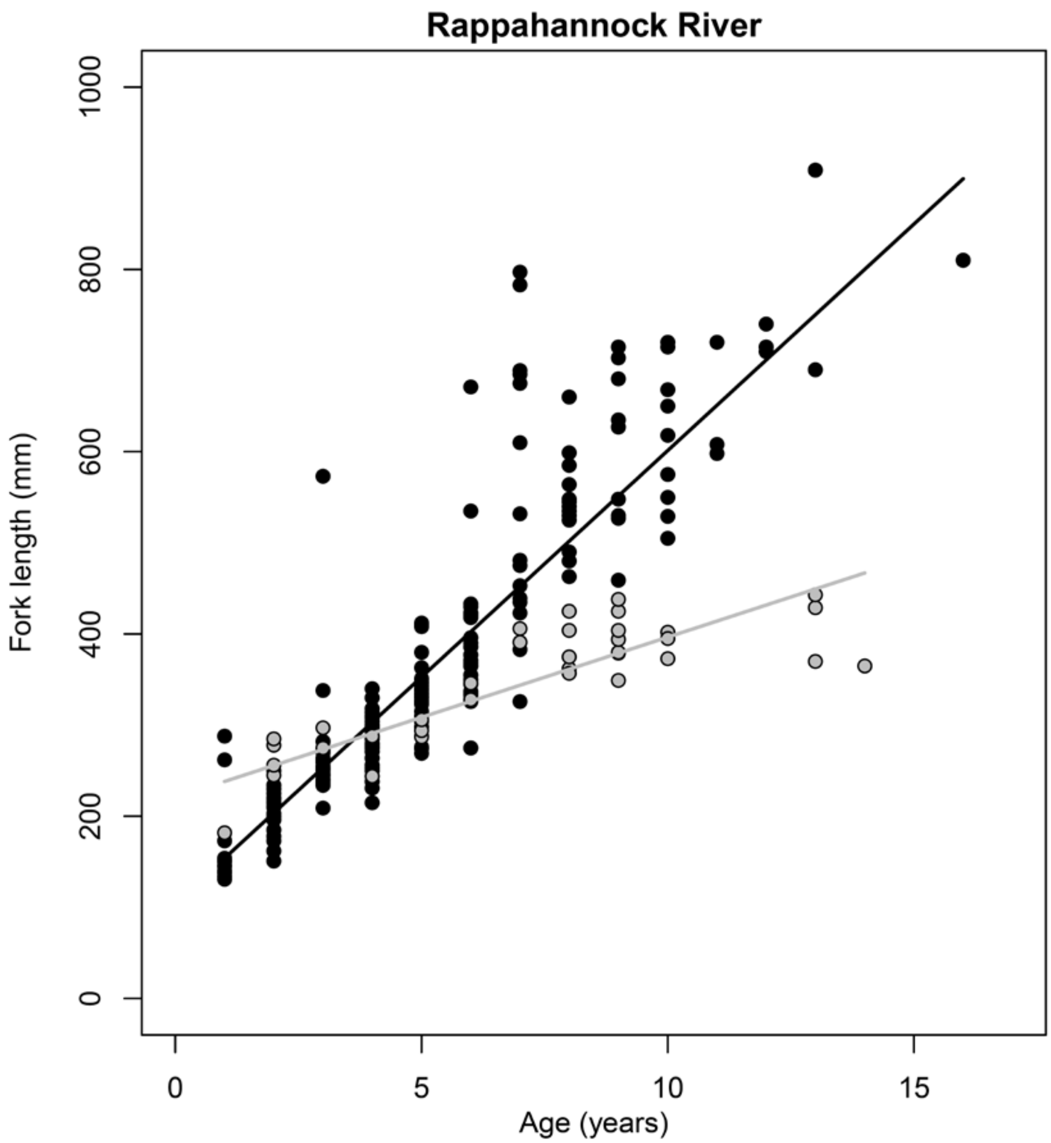

Figure 4. Observed Potomac River blue catfish length-at-age data and predicted growth curve derived from parameter estimates associated with the linear model.

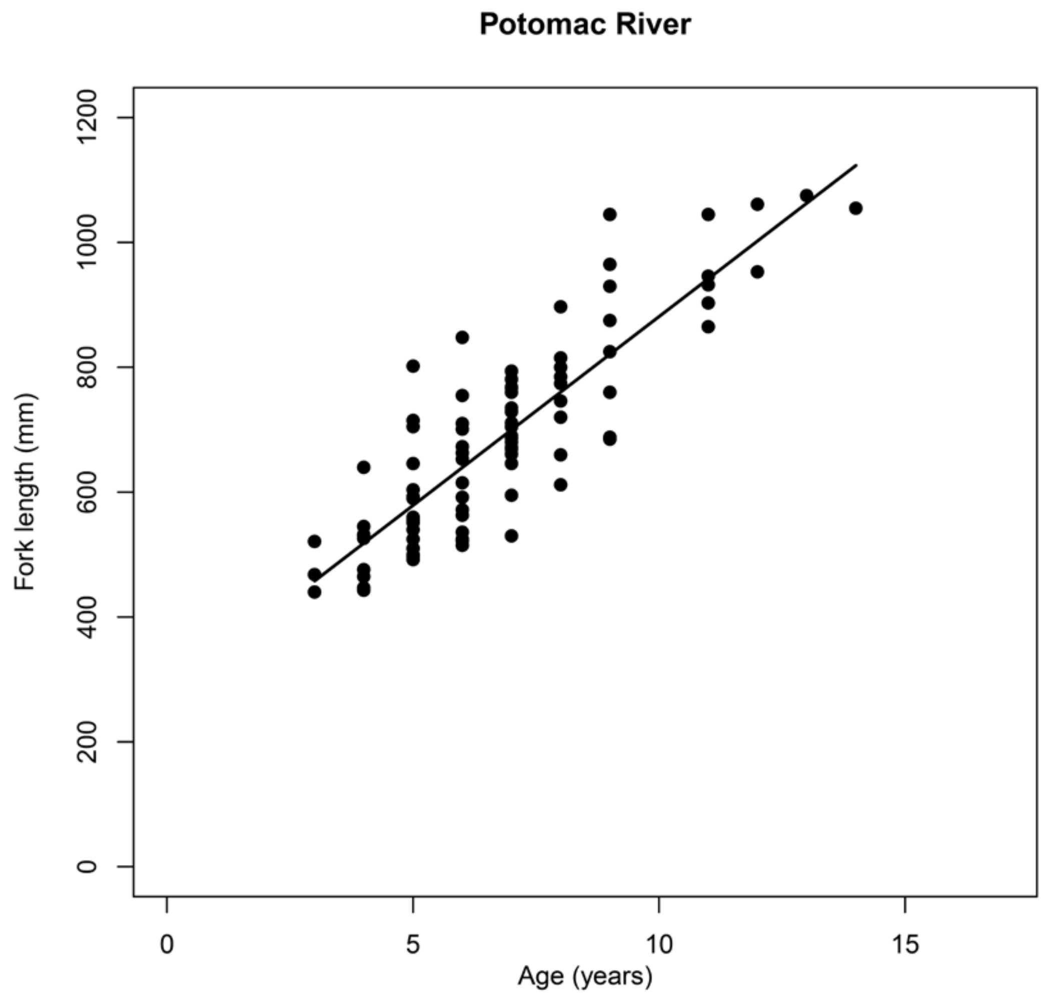

Figure 5. Observed James River blue catfish weight-at-length data and predicted growth curves derived from parameter estimates associated with the allometric model parameterized with a time period covariate (historic-black solid line; current-gray solid line).

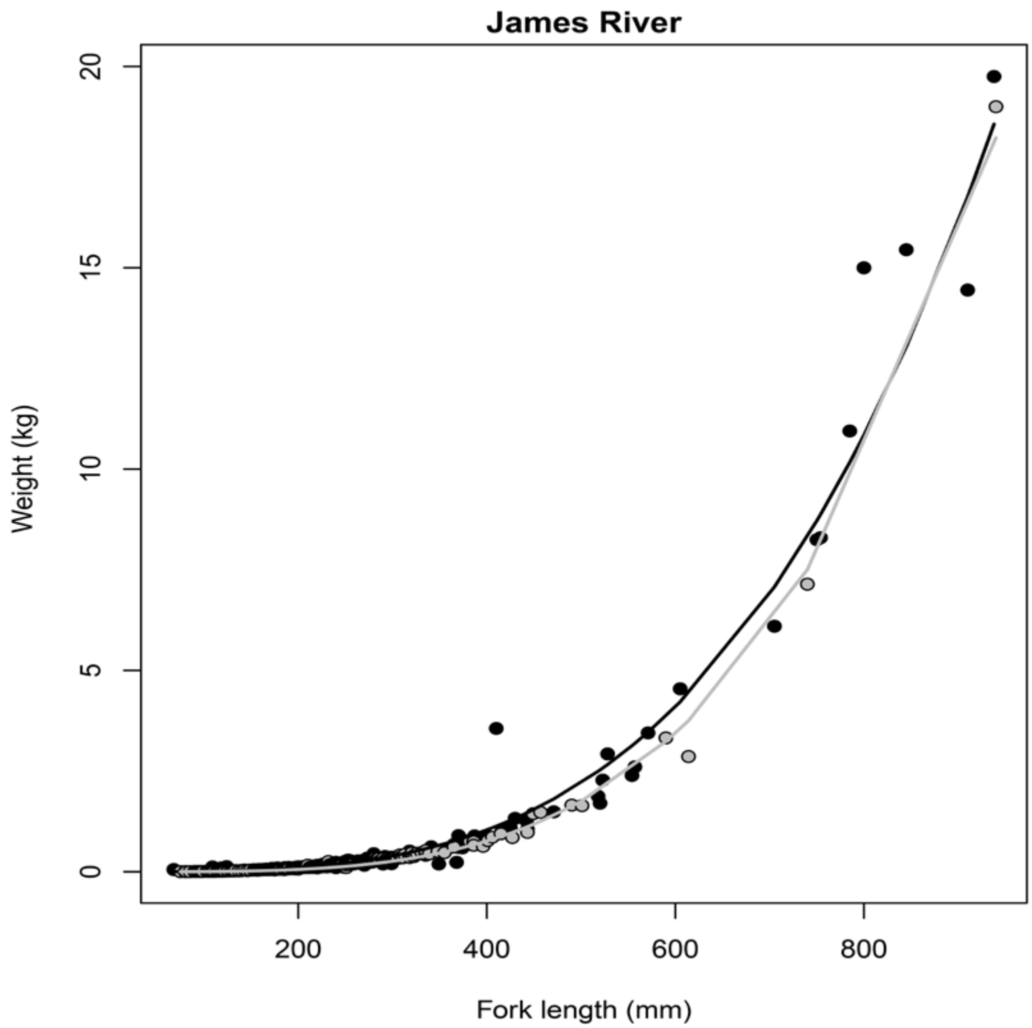

Figure 6. Observed York River blue catfish weight-at-length data and predicted growth curves derived from parameter estimates associated with the allometric model parameterized with a time period covariate (historic-black solid line; current-gray solid line).

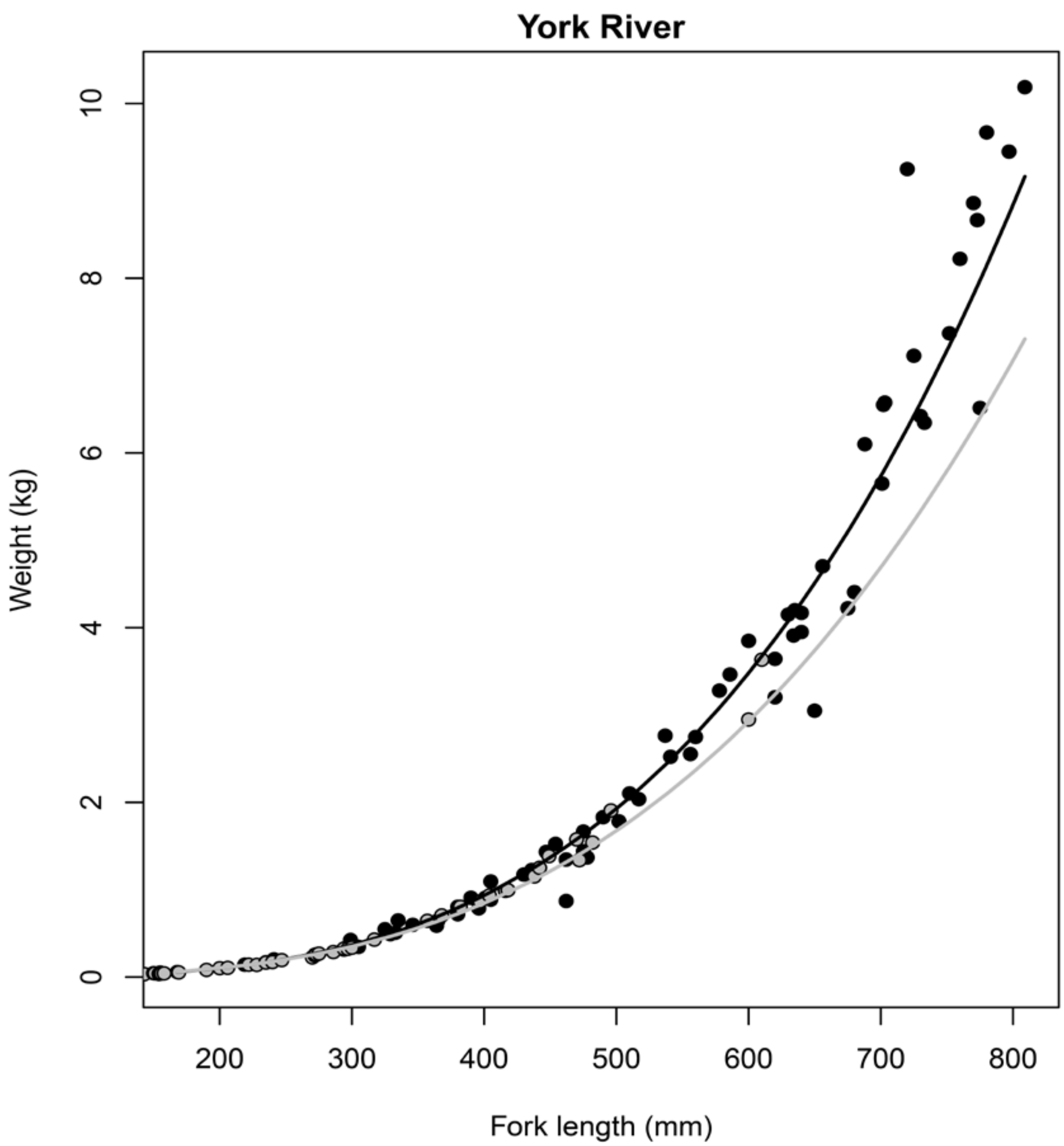

Figure 7. Observed Rappahannock River blue catfish weight-at-length data and predicted growth curves derived from parameter estimates associated with the allometric model parameterized with a time period covariate (historic-black solid line; current-gray solid line).

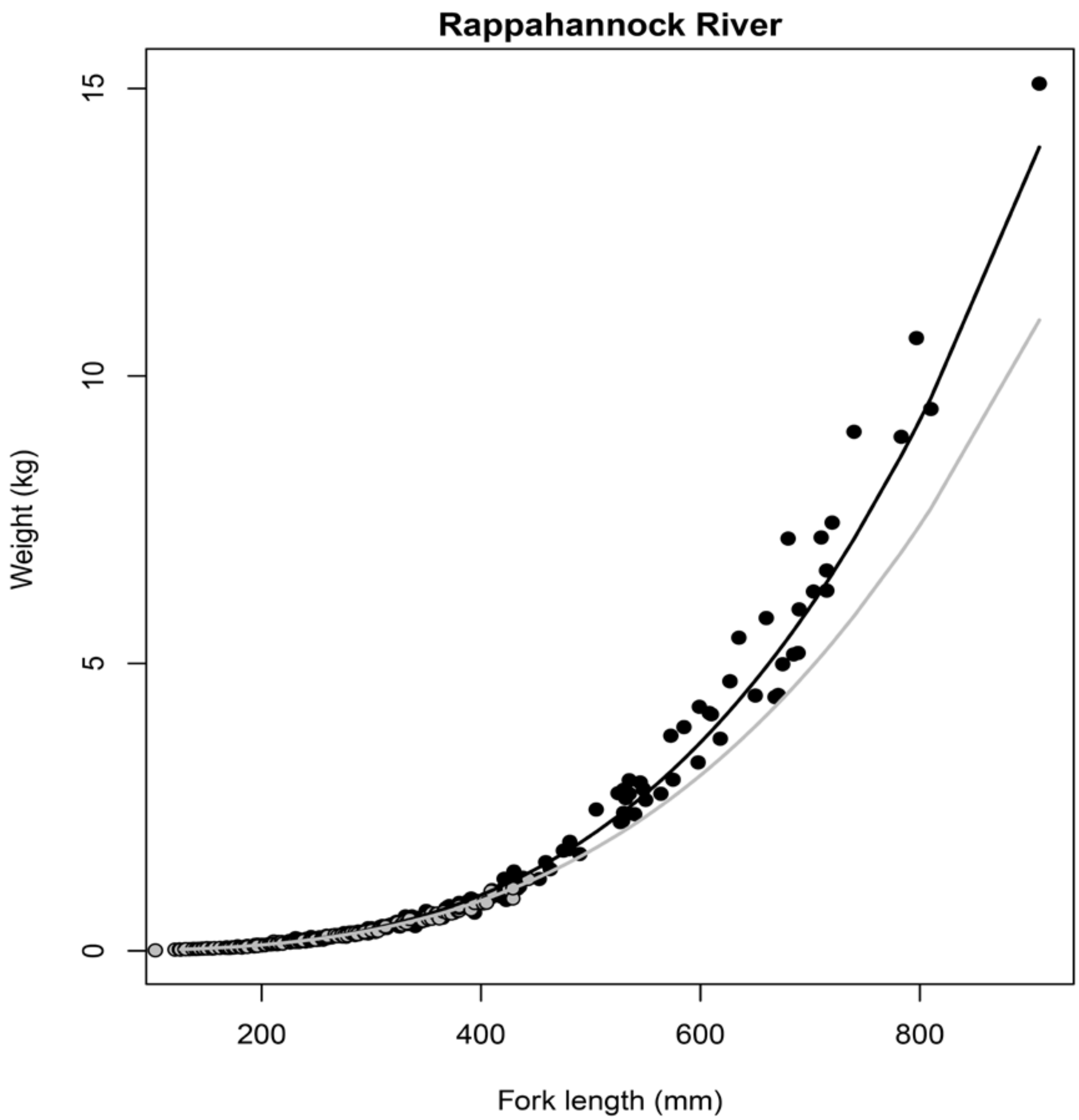

Figure 8. Observed Potomac River blue catfish weight-at-length data and predicted growth curves derived from parameter estimates associated with the allometric model.