

Title: Comparing relative abundance and population characteristics of Flathead Catfish across a range of establishment levels at the Susquehanna River
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2.0 Executive Summary

Flathead Catfish records in the Atlantic Slope drainage of Pennsylvania date back to the early 1990s; however, large-scale range expansion and population increases were not observed until the late 1990s in the Delaware River drainage and the early 2000s in the Susquehanna River drainage (Brown et al. 2005). Flathead Catfish were first detected in the Susquehanna River during 2002 by recreational anglers downstream of Safe Harbor Dam, Lancaster County, Pennsylvania (Brown et al. 2005). There have been no systematic surveys for this species in the Susquehanna River since its detection in 2002.

As such, we set out to estimate the relative abundance (catch per effort [CPE]) of invasive Flathead Catfish in three reaches of the mainstem Susquehanna River with different presumed degrees of population establishment. By examining abundance in river reaches with different degrees of population establishment, data collected during this study will serve to help understand current distribution patterns to inform changes that may occur in reaches where they are not yet present. Additionally, we attempted to evaluate age and growth characteristics in three reaches of the mainstem Susquehanna River with different presumed degrees of population establishment. Resulting models can be used to help inform management of Flathead Catfish and native species throughout the Susquehanna River Basin

We focused on a 173-km reach of the Susquehanna River between Sunbury, Pennsylvania and the Maryland border. This reach was parsed into three sections using presumed levels of establishment based on the first records of Flathead Catfish being in those respective sections: from the York Haven Dam to Maryland border (A), from the Juniata River to York Haven Dam (B), and from the inflatable dam at Sunbury to the Juniata River (C). Three segments were randomly selected within each of the three reaches for sampling. Four baited tandem hoop nets (three nets per series, each 4.9 m long with 38.1 mm mesh and seven 1.2 m hoops that taper toward the cod end) were set at each segment and fished parallel to shore with mouths facing downstream in water depths greater than 1 m and left undisturbed for approximately 72 hours. Several environmental and spatial variables (velocity, river kilometer, depth, distance downstream of a dam, and distance upstream of a dam) were included in a Bayesian hierarchical Poisson regression model to evaluate if these factors influenced the relative abundance of Flathead Catfish at sampled locations. Total length (mm) and weight (g) of Flathead Catfish were measured and lapilli otolith extracted for age determination from all Flathead Catfish. Bayesian hierarchical Poisson models with a log-link function were used to compare CPE per reach as well as evaluate variables that contributing to differences in CPE. We used total length (mm) and age (years) from individuals in a non-linear least squares (nl) von Bertalanffy growth model to evaluate growth parameters in the different reaches of the Susquehanna River.

Flathead Catfish were sampled at nine sites. Of these, three sites were pooled into Reach A, three sites in Reach B, and four sites in Reach C. We found CPE was highest in Reach A (μ_{α_r} , 90% credible interval; A=0.09, (0.02-0.19); B=0.02, (0.00-0.04); and C=0.05, (0.01-0.113)). However, the 90% credible interval of the differences in reach mean CPE overlapped zero, indicating that CPE was not found to differ between reaches (difference between A and B (0.00-3.1), difference between B and C (-2.60, 0.51), and difference between A and C (-0.90-1.9). Covariates of velocity, river kilometer, and distance between

net set location and the nearest upstream dam were added to investigate potential influences of CPE. All covariates demonstrated a negative relationship with CPE. In particular, the 90% credible interval for the slope of CPE-flow relationship did not overlap zero (95% probability of a negative effect), indicating that fewer Flathead Catfish were caught at locations with higher flows. River kilometer demonstrated a negative effect on CPE. On average, as we sampled up river, CPE of Flathead Catfish declined. However, the river kilometer-CPE relationship was not found to be significant due to the overlapping credible interval with zero; also there was a relatively low probability (60%) of a negative effect. Distance of net set location downstream of the nearest dam was estimated to have a 94% probability of a negative effect on catch rates. Flathead Catfish catch rates tended to increase closer to an upstream dam.

The age composition of Flathead Catfish varied among reaches ($\bar{x} \pm SD$; A = 7.65±1.53; B=4.58±1.41; C=3.87±1.22 years). Age and length data were included for all Flathead Catfish caught (n=135) and grouped into downstream (A; n=83) and upstream (Z; n=52) populations for von Bertalanffy growth model analysis. The estimated growth parameters for reach C were $L_{\infty} = 1025.26$ (SE=108.70; $t = 9.432$; $\Pr(>|t|) = 1.24 e^{-14}$), $K = 0.17592$ (SE=0.07821; $t=2.249$; $\Pr(>|t|) = 0.0272$), and $t_0 = -0.42241$ (SE=1.50642; $t = -0.280$; $\Pr(>|t|) = 0.7799$). The nls model failed to converge for the combined upstream population Z. Small sample size, limited number of year classes and highly variable growth within those age classes were likely contributors.

Not surprisingly, CPE of Flathead Catfish was highest in the reach of the Susquehanna River between York Haven and Conowingo dams where they were first documented in 2002. However; the similarity with CPE in upstream reaches was unexpected, as the CPE among reaches did not statistically differ. It was anticipated that a gradient of abundance would exist moving upstream from more established reaches. This expectation assumed that there would be a density-dependent scenario relative to habitat availability that dispersing fish would occupy available habitat until a density threshold (i.e., carry capacity) was met and then individuals would disperse looking for suitable habitat further from the establishment point. This suggests that some other ecological or behavior factors are contributing to dispersal and abundance than simply density. Results of a Bayesian hierarchical Poisson model suggested that the only observed covariate to significantly influence CPE of Flathead Catfish was river velocity; however, distance downstream of nearest dam had a high probability of having a negative effect. While the passability of Flathead Catfish may not be restricted directly by dams, the passability of potential prey species may be so delays in passing may be opportunistic. Although not significant, we found a 60% probability of a negative correlation between Flathead Catfish CPE and river kilometer. Based on initial detection, population establishment, and subsequent range expansion this association is logical. As more data is collected over a broader range of habitats the relationships with these covariates should become more pronounced.

Unfortunately, we were unable to compare growth parameters among reaches for the Susquehanna River as anticipated. While we were able to fit a von Bertalanffy growth model to downstream reach (reach A), models for combined upstream reaches B and C failed to converge. Other studies have been able to fit models with fewer individuals (Lumber River, n=36, Kwak et al. 2006; seven population, Massie et al. 2018), suggesting that population characteristics in the upstream reaches of the Susquehanna River were too variable. This phenomena of nonconvergence is common with nonlinear

models (Midway et al. 2015). In addition, Massie et al. (2018) used length-at-age data collected from this study (pooled all data into one Susquehanna River population) to quantify the spatial variability of Flathead Catfish population growth parameters across a large portion of their contemporary range using a Bayesian nonlinear hierarchical modeling framework (see appendix for full article). The Susquehanna Flathead Catfish population growth parameters estimated by the model suggested they reached a greater maximum size than other introduced populations at lower latitudes (Neuse River, NC; Little Pee Dee River, SC, and Apalachicola River, FL).

Overall, we found that Flathead Catfish growth at the Susquehanna River to be rapid and similar to other invasive Flathead Catfish populations in the Atlantic Slope. Relative abundance of Flathead Catfish in all three reaches were not significantly different; suggesting that the species was more established in upstream reaches than first thought. Environmental factors such as flow velocity, dams, and river kilometer appear to affect relative abundance of Flathead Catfish at the Susquehanna River. Additional age and growth analysis of upstream reaches of the Susquehanna River will help to develop growth parameters for that reach as sample size was small. Future research should continue to focus on upstream reaches where small sample sizes, limited number of cohorts, and variable growth prevented accurate estimation of growth parameters. Continued collection of specimens within this reach should strengthen future analysis. Additional focus on areas such as the West Branch Susquehanna River and Juniata River where establishment is not known or where there is little documentation is needed. Similar base-line relative abundance and growth parameter estimates should be developed for other invasive populations in the mid-Atlantic regions like the Schuylkill and Delaware rivers to aid future population management. On-going monitoring of populations should continue in the future to understand changing population dynamics as they continue to become more established. Other topics of interest related to Flathead Catfish include diet, population genetics, and fish movement.

3.0 Introduction

Flathead Catfish records in the Atlantic Slope drainage of Pennsylvania date back to the early 1990s; however, large-scale range expansion and population increases were not observed until the late 1990s in the Delaware River drainage and the early 2000s in the Susquehanna River drainage (Brown et al. 2005). Flathead Catfish were first detected in the Susquehanna River during 2002 by recreational anglers downstream of Safe Harbor Dam, Lancaster County, Pennsylvania (Brown et al. 2005). There have been no systematic surveys for this species in the Susquehanna River since its detection in 2002.

The impacts of introduced Flathead Catfish on migratory and resident fishes are well documented (Guier et al. 1984, Ashley and Buff 1988, Thomas 1995, Brown et al. 2005, Pine et al. 2005, Sakaris et al. 2006, Pine et al. 2007, Bonvechio et al. 2009); however, few studies have focused on populations located in northern latitudes. Models suggest that Flathead Catfish suppress native fish biomass 5 – 50% through predation and competitive interactions (Pine et al. 2007). In other areas of the Atlantic Slope where Flathead Catfish occur, they often became established prior to pre-establishment data

being collected, so the full extent of the implications of their introduction could not fully be assessed (Pine et al. 2005, Pine et al. 2007). Some areas within the Susquehanna River Basin still have not seen establishment of Flathead Catfish populations, so this represents a unique opportunity to gather baseline data and improve our understanding of the effects this species has on native communities.

Rapid growth of populations (abundance and biomass) and individuals have been cited as major concerns of introduced Flathead Catfish populations in other portions of the Atlantic Slope drainage. Kwak et al. (2006) found that introduced riverine populations in North Carolina had higher growth rates than native populations and lower annual mortality. Similarly, growth rates in riverine populations of introduced Flathead Catfish in Georgia were higher when compared with those from native riverine populations in Alabama (Sakaris et al. 2006). This study found Flathead Catfish biomass to be higher in introduced populations, largely a result of rapid growth rates. Therefore, Flathead Catfish biomass increases can substantially affect biomass of resident prey species and can extend for long periods of time (i.e., >20 years; Sakaris et al. 2006). Within the Susquehanna River, resident fishes that may be adversely affected by Flathead Catfish populations include native and resident species of economic and ecologic importance as well as migratory species (i.e., American Shad *Alosa sapidissima*) – where considerable efforts are on-going in an attempt to re-establish populations. A recent study in the James River in Virginia suggests that Flathead Catfish selectively prey on migrating American Shad, and to a lesser degree, river herring in high-gradient, non-tidal freshwater areas (Schmitt et. al 2017), like those occurring in the Susquehanna River. Understanding growth variation of Flathead Catfish is especially important given their popularity as a sport fish, widespread introduction outside their native range, and the negative effects on native fish populations. The goal of this study was to compare the relative abundance and population dynamics of Flathead Catfish across a range of presumed establishment levels in the Susquehanna River.

Resource management organizations such as the Atlantic States Marine Fisheries Commission (ASMFC) and the Chesapeake Bay Program, have recently expressed their concerns over the status of invasive catfishes in the Chesapeake Bay drainage. Further, the National Oceanographic and Atmospheric Administration (NOAA), Sustainable Fisheries Goal Implementation Team (GIT) had adopted an invasive catfish policy ([http://www.chesapeakebay.net/channel_files/17972/final_catfish_policy_git_1-24-12_\(with_signatures\).pdf](http://www.chesapeakebay.net/channel_files/17972/final_catfish_policy_git_1-24-12_(with_signatures).pdf)) and developed an Invasive Catfish Taskforce to research the ecological impacts of these species, provide guidance on management efforts moving forward, and provide public education and outreach. The Taskforce includes resource agencies (including the Pennsylvania Fish and Boat Commission [PFBC]), university researchers, and local watermen that report to NOAA and the ASMFC.

Project objectives

1. Estimate the relative abundance (catch per effort [CPE]) of invasive Flathead Catfish in three reaches of the mainstem Susquehanna River with different presumed degrees of population establishment. By examining abundance in river reaches with different degrees of population establishment, data collected during this study will serve to help understand current distribution patterns to inform changes that may occur in reaches where they are not yet present.

2. Evaluate age and growth characteristics in three reaches of the mainstem Susquehanna River with different presumed degrees of population establishment. These models can be used to help inform management of Flathead Catfish and native species throughout the Susquehanna River Basin.

4.0 Methods

Data Collection

Site Description

The Susquehanna River is a broad and shallow river, originating at Otsego Lake, Cooperstown, New York; and flowing through Pennsylvania before entering the Chesapeake Bay at Havre de Grace, Maryland. This study focused on a 173-km reach of the Susquehanna River between Sunbury, Pennsylvania and the Maryland border. This reach was parsed into three sections using presumed levels of establishment based on the first records of Flathead Catfish being in those respective sections. The downstream most section (A; Figure 1) extended downstream from York Haven Dam (rkm 90.5) to the Maryland border (rkm 24.6) and was the initial location where Flathead Catfish were documented in the Susquehanna River in 2002 (Brown et al., 2005). The middle section (B, Figure 1) extended from the confluence of the Juniata River (rkm 136.2) downstream to the York Haven Dam where Flathead Catfish were first documented in 2009 (PFBC, unpublished data). The upstream most section (C; Figure 1) extended downstream from an inflatable, seasonal dam at Sunbury, Pennsylvania (rkm 197.1) downstream to the confluence of the Juniata River where Flathead Catfish were first documented in 2013 (PFBC, unpublished data).

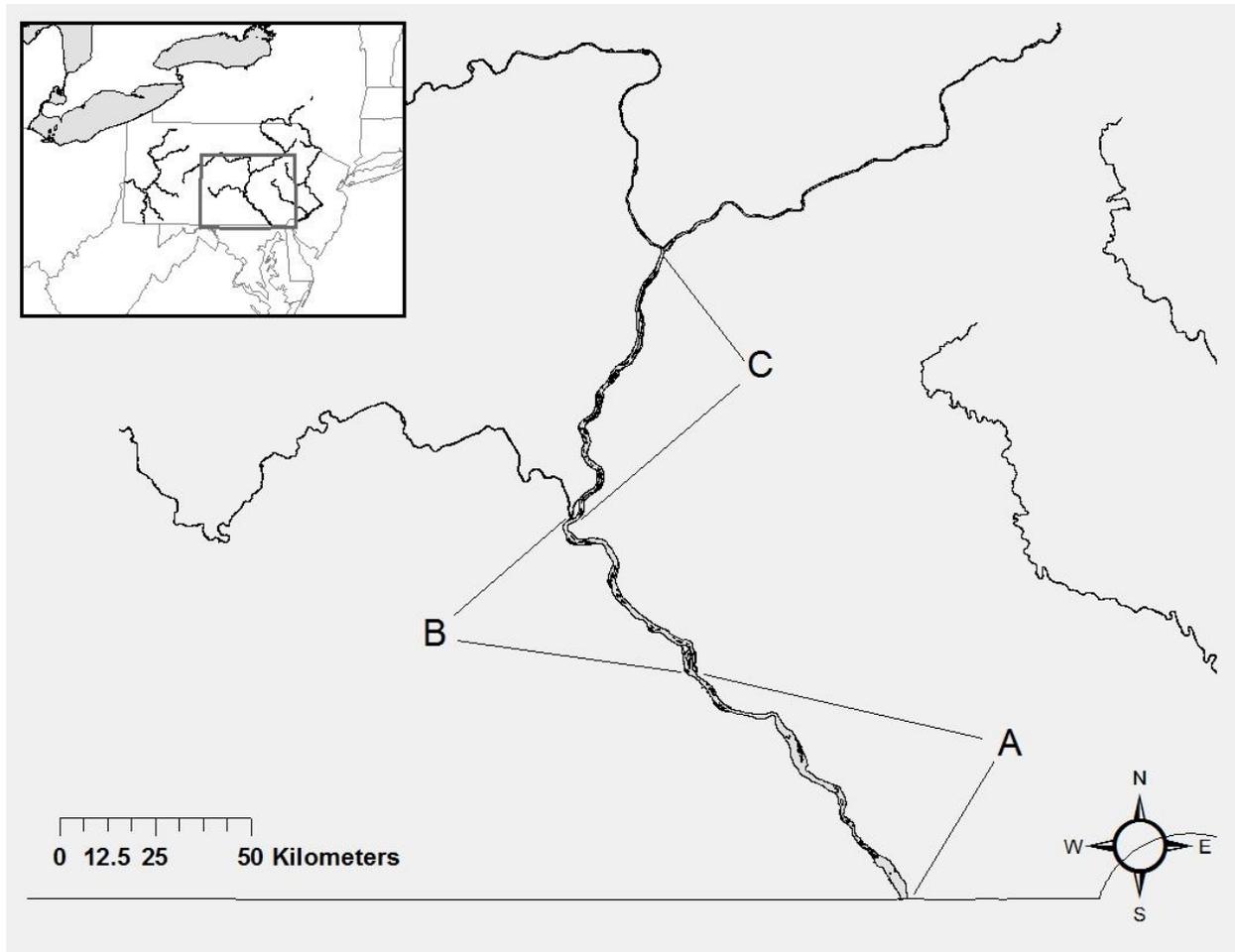


Figure 1: Map depicting study reach of the Susquehanna River with focal reaches A (York Haven Dam to Maryland border), B (Juniata River to York Haven Dam), and C (inflatable dam at Sunbury to Juniata River).

Site Selection

Due to the unique geomorphology of the Susquehanna River, access is limited through portions of the study reach. Fifty discrete segments were identified using ArcGIS version 10.4 (ESRI, Redlands, California) where johnboat access was possible to deploy gear. Three segments were randomly selected within each of the three reaches for sampling. Ten random sampling locations were created within each of the three segments using data management tools in ArcGIS version 10.4. Random points were evaluated sequentially for placement of hoop net series based on water depth (≥ 1 m) and eliminating competition with other net series.

Hoop Nets

Hoop nets were used to sample the Flathead Catfish population between July and September 2016 to estimate relative abundance (catch per effort, CPE; fish per series) and collect specimens for age and growth analysis. Hoop nets have been shown to be an effective means of catfish sampling within large

impoundments (>200ha; Stewart and Long 2012) and minimize size bias due to gear selectivity (Buckmeier and Schlechte 2009). Four tandem hoop nets (three nets per series, each 4.9 m long with 38.1 mm mesh and seven 1.2 m hoops that taper toward the cod end [Miller Net Company, Inc., Memphis, Tennessee]) were set at three sites per reach based on recommendation of Walker et al. (1996); Michaletz and Sullivan (2002); Buckmeier and Schlechte (2009); Stewart and Long (2012); and Stewart and Long (2016). The cod end of each hoop net was baited with 1 kg of cheese log (Boatcycle, Henderson, Texas), and restricted with zip ties to prevent fish from escaping (Porath et al. 2011). All four tandem sets at a site were deployed on the same day in each of the randomly selected segment. Nets were fished parallel to shore with mouths facing downstream in water depths greater than 1 m and left undisturbed for approximately 72 hours (Michaletz and Sullivan 2002, Stewart and Long 2016).

Several environmental and spatial variables (velocity, river kilometer, depth, distance downstream of a dam, and distance upstream of a dam) were included in a Bayesian hierarchical Poisson regression model to evaluate if these factors influenced the relative abundance of Flathead Catfish at sampled locations. Velocity (m/S) was measured at the mouth of the downstream most net in each series at 0.6m from the substrate using a Marsh-McBirney, Inc. Flo-mate Model 2000 portable flowmeter. This distance from the substrate represents the midpoint of the mouth of the net (1.2m hoop) and best represented the velocity in the area where the net was set. Depth (m) measurements were taken at the midpoint of each series using a Garmin GPSmap 531s depth finder with a transom mounted transducer. River kilometer and distance measurements were calculated using the measurement function in ArcMap 10.4 and measured parallel to river midpoint in NHD Flowline (U.S. Geological Survey, National Hydrology Dataset).

Enumeration and age estimation

Total length (mm) and weight (g) of Flathead Catfish were measured in the field and tagged with a unique tag prior to fish being preserved in an ice bath until otoliths could be extracted. Total length and weight data for each fish was recorded relative to the unique tag number to prevent changes in length and weight that may occur during storage of fish in an ice bath, which could subsequently affect the quality of the age and growth data. Additional Flathead Catfish were also captured to increase sample size for age and growth analysis using boat mounted VVP 15-B electrofishers [Smith-Root, Inc. Vancouver, Washington] using pulse direct current (PDC; 60 Hz, 25% duty cycle) as well as targeted hoop net deployments during August 2017. These additional sampling efforts were made to capture individuals from size groups that were underrepresented in the hoop net samples. These collections were not included in CPE estimates. The total length (mm) of all other species were measured and then released on site. Age determination of all Flathead Catfish was done using otoliths (lapilli; Long and Stewart 2010) which were removed and processed similar to Buckmeier et al. (2002). To make annuli more apparent, otoliths were heated on a hot plate until turning an opaque color. Otoliths were mounted perpendicular to the glass microscope slide using a small amount of mounting adhesive (Crystalbond™; Ladd Research Industries, Williston, Vermont). Otoliths were sanded until exposing the nucleus using 400-grit sandpaper, and then polished with 600-grit sandpaper. We found annuli to be more visible when using fiber optic filaments to project light at different angles around the otolith

similar to suggestions of Buckmeier et al. (2002). Two readers independently read otolith ages with dissecting microscopes. All age discrepancies were reanalyzed during a concert read.

Data analysis and model application

Relative abundance estimation

In order to determine if there was a difference in the relative abundance (CPE) per reach, we developed a Bayesian hierarchical Poisson model with a log-link function as follows:

$$C_{ijr} \sim \text{Pois}(\lambda_{ijr})$$

$$\log(\lambda_{ijr}) = \eta_i + \alpha_j + \mu_{\alpha_r}$$

$$\alpha_j \sim N(0, \sigma_\alpha^2)$$

where C_{ijr} is the catch per net set i from site j within reach r and is assumed to come from a Poisson distribution with some mean (λ_{ijr}). $\log(\lambda_{ijr})$ is then modeled as a function of covariates. The offset term η_i accounts for the unbalanced effort (hours) among net sets and is equal to the \log_e duration of time net set i was deployed. The random site effects, α_j , are assumed to be normally distributed with a mean 0 and among-site variance σ_α^2 . The random site effects are used to accommodate unequal net sets per site and the lack of statistical independence between net sets within a site. μ_{α_r} are the mean CPE values per reach.

Factors influencing relative abundance

To estimate how Flathead Catfish abundance varies across a presumed establishment gradient of the Susquehanna River, we developed a Bayesian hierarchical Poisson model with a log-link function as follows:

$$C_{ij} \sim \text{Pois}(\lambda_{ij})$$

$$\log(\lambda_{ij}) = \eta_i + \alpha_j + \beta_1 \times \text{covariate}_{1_i} \dots \dots \beta_n \times \text{covariate}_{n_i}$$

$$\alpha_j \sim N(\bar{\alpha}, \sigma_\alpha^2)$$

where C_{ij} is the catch per net set i from site j is assumed to come from a Poisson distribution with some mean (λ_{ij}). $\log(\lambda_{ij})$ is then modeled as a function of covariates. The offset term η_i accounts for the unbalanced effort (hours) among net sets and is equal to the \log_e duration of time net set i was deployed. The random site effects, α_j , are assumed to be normally distributed with a mean $\bar{\alpha}$ and among-site variance σ_α^2 . The random site effects are used to accommodate unequal net sets per site and the lack of statistical independence of individual net sets within a site. The effects (i.e., slopes) of the catch-covariate relationships are represented with β_x . All covariates were standardized prior to analysis.

Only initial hoop net deployment data were included in the analysis since removal of fish prior to second deployment could negatively affect catch at a given location. Models were fitted using JAGS version 3.30

software (Plummer 2003) called from the programming environment R (R Development Core Team 2017) via the “r2jags” package (Su and Yajima 2012). Three Markov chains were run, beginning at different starting values. The chains ran for 20,000 iterations, of which, 5,000 were discarded as burn in values. Diffuse normal priors were used for the intercept ($\bar{\alpha}$) and slope parameters (β). A diffuse uniform distribution was used for σ_{α} . Models were visually assessed for convergence and confirmed using the Brooks-Gelman-Rubin statistic (\hat{R}), with values less than 1.1 indicating convergence. We defined a significant difference in CPE between reaches as when the 90% credible interval for the difference in means did not overlap zero. Predictor variable significance was determined by examining whether the 90% credible interval of the covariate-CPE relationship overlapped with zero. Additionally, probabilities that the slope relationships were in the same direction as the posterior mean were calculated (Filstrup et al. 2004) to fully capture the uncertainty in the posterior distributions of parameter estimates.

Evaluating growth parameters

Age data was log transformed and mean and standard deviation were calculated by reach to describe composition within each reach. We used total length (mm) and age (years) from individuals in a non-linear least squares (nls) von Bertalanffy growth model to evaluate growth parameters in the different reaches of the Susquehanna River.

$$L_t = L_{\infty}(1 - e^{k(t-t_0)})$$

where L_{∞} , K , and t_0 are the three von Bertalanffy model parameters representing the asymptotic length (theoretical maximum average length), the Brody growth coefficient (the rate of approaching L_{∞} , and the hypothetical age at which size equals 0, respectively. Reach Z was created in an effort to increase sample sizes because reaches B (n=20) and C (n=32) each had small sample sizes.

Von Bertalanffy growth models were fit using the “stats” package (version 3.3.2) in the R programming environment (R Development Core Team, 2016). Starting values for the von Bertalanffy models used were from an introduced Flathead Catfish population from the Northeast Cape Fear River published in Kwak et al. (2006).

5.0 Results and Discussion

Results

Relative abundance

Flathead Catfish were sampled at nine sites. Of these, three sites were pooled into Reach A, three sites in Reach B, and four sites in Reach C. We found CPE was highest in Reach A (μ_{α_r} , 90% credible interval; A=0.09, (0.02-0.19); B=0.02, (0.00-0.04); and C=0.05, (0.01-0.113)). However, the 90% credible interval of the differences in reach mean CPE overlapped zero, indicating that CPE was not found to differ between reaches (difference between A and B (0.00-3.1), difference between B and C (-2.60, 0.51), and difference between A and C (-0.90-1.9). Since assigning sites to reaches is a somewhat arbitrary cut off, we also estimated how CPE varied across river km (see model: Factors influencing relative abundance)..

Factors affecting relative abundance

Flathead Catfish catch rates from 34 net set observations at nine sites were used in analysis. The number of fish caught per net set ranged from 0 to 16 ($\bar{x} \pm SD$; 3.2 ± 3.6) and sampling effort ranged from 24 to 71 hours per net set ($\bar{x} \pm SD$; 64.4 ± 14.8). Variability in sampling effort was driven by one site (four series) being pulled after only 24 hours because of flash flooding. Covariates of velocity, river kilometer, and distance between net set location and the nearest upstream dam were added to investigate potential influences of CPE. River depth and distance between net set and the nearest downstream dam were excluded from analysis due to strong correlation with river kilometer ($r = 0.72$ and 0.60 , respectively).

All covariates demonstrated a negative relationship with CPE (Table1). In particular, the 90% credible interval for the slope of CPE-flow relationship did not overlap zero (95% probability of a negative effect), indicating that fewer Flathead Catfish were caught at locations with higher flows (Figure 1). River kilometer demonstrated a negative effect on CPE (Figure2). On average, as we sampled up river, CPE of Flathead Catfish declined. However, the river kilometer-CPE relationship was not found to be significant due to the overlapping credible interval with zero; also there was a relatively low probability (60%) of a negative effect. Distance of net set location downstream of the nearest dam was estimated to have a 94% probability of a negative effect on catch rates (Figure 3). Therefore, Flathead Catfish catch rates tended to increase closer to an upstream dam.

Table 1. Outputs of the Bayesian hierarchical Poisson model for modeling catch per effort (CPE) of Flathead Catfish as a function of velocity (m/s), river kilometer, and distance downstream of dam (km). The row β reports the posterior mean for the relationship between CPUE and the given covariates, and the 90% credible intervals are shown in parentheses. The probability that the covariate relationship with CPE is negative is also provided.

Outputs	Velocity	River km	Distance DS of dam
β	-0.24 (-0.51, 0.00)	-0.09 (-0.74, 0.51)	-0.60 (-1.28, 0.04)
Prob. of negative effect	0.95	0.60	0.94

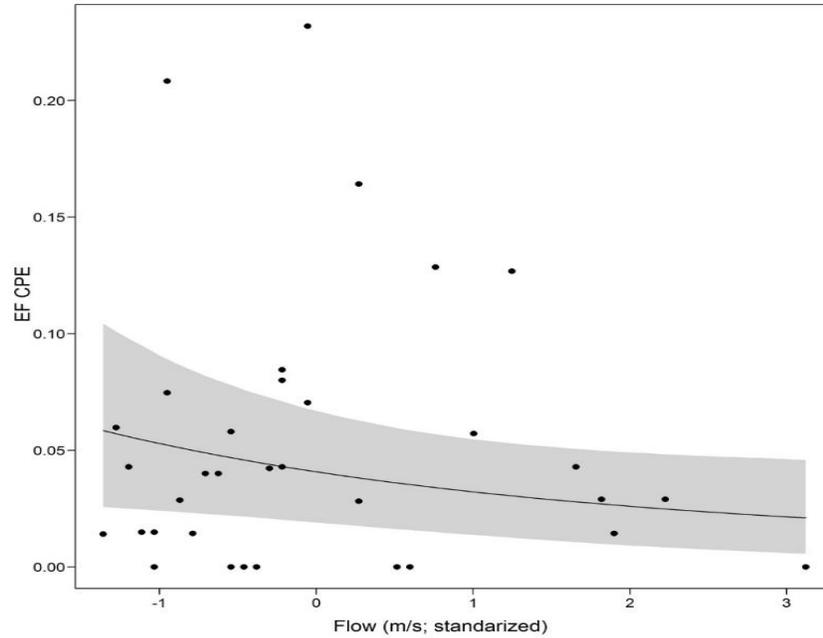


Figure 4. Relationship between velocity (m/s) and CPE of Flathead Catfish. The black dots represent observed CPE and standardized flow rate per net set. The solid line shows the posterior mean regression fit and the shaded area represents the 90% credible region.

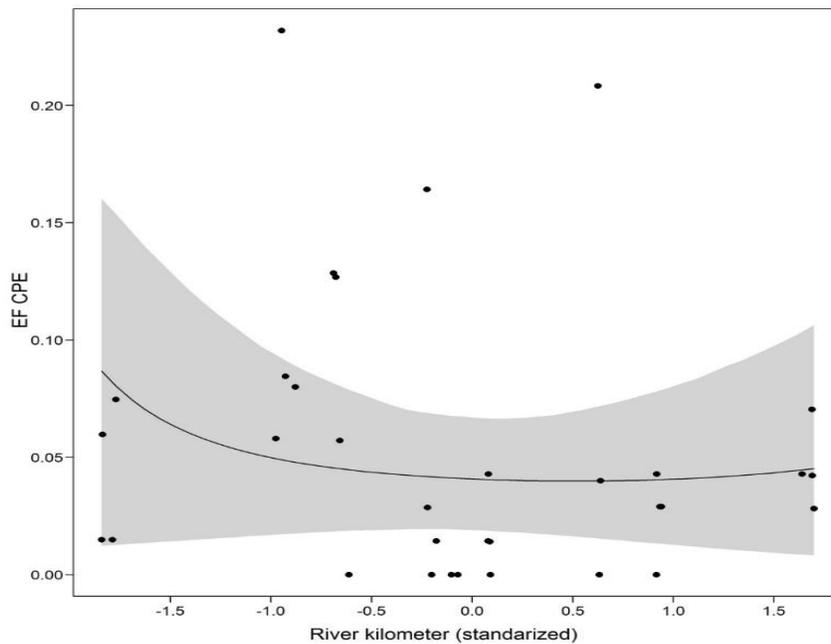


Figure 4. Relationship between the river kilometer and CPE of Flathead Catfish. The black dots represent observed CPE and the standardized river kilometer. The solid line shows the posterior mean regression fit and the shaded area represents the 90% credible region.

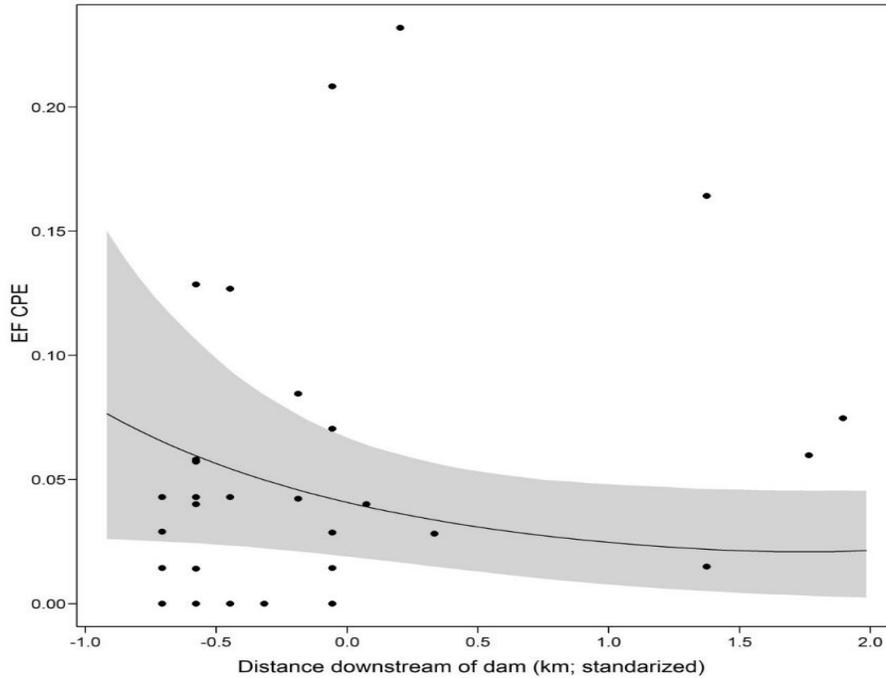


Figure 5. Relationship between the distance between net sets to nearest downstream dam and CPE of Flathead Catfish. The black dots represent observed CPE and the standardized distance between the net set and nearest downstream dam. The solid line shows the posterior mean regression fit and the shaded area represents the 90% credible region.

Evaluation of growth parameters

The age composition of Flathead Catfish varied among reaches ($\bar{x} \pm SD$; A = 7.65 ± 1.53 ; B = 4.58 ± 1.41 ; C = 3.87 ± 1.22 years; Figure 6). Age and length data were included for all Flathead Catfish caught (n=135) and grouped into downstream (A; n=83) and upstream (Z; n=52) populations for von Bertalanffy growth model analysis. The estimated growth parameters for reach C were $L_{\infty} = 1025.26$ (SE=108.70; $t = 9.432$; $\Pr(>|t|) = 1.24 \times 10^{-14}$), $K = 0.17592$ (SE=0.07821; $t = 2.249$; $\Pr(>|t|) = 0.0272$), and $t_0 = -0.42241$ (SE=1.50642; $t = -0.280$; $\Pr(>|t|) = 0.7799$) (Figure 7). The nls model failed to converge for the combined upstream population Z. Small sample size, limited number of year classes and highly variable growth within those age classes were likely contributors.

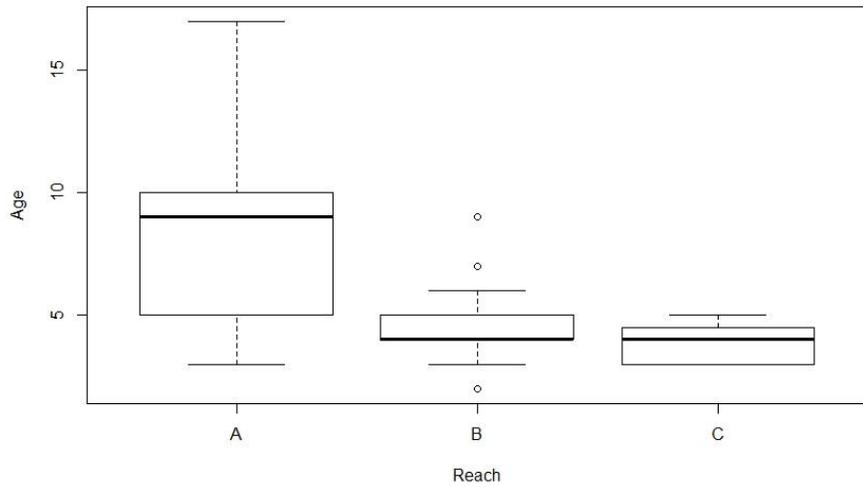


Figure 6: Boxplot comparing ages of Flathead Catfish caught at each of the three sampled reaches at the Susquehanna River. Bold lines indicate reach wide median age, boxes indicate interquartile range of ages within the reach, and open circles represent outlier values.

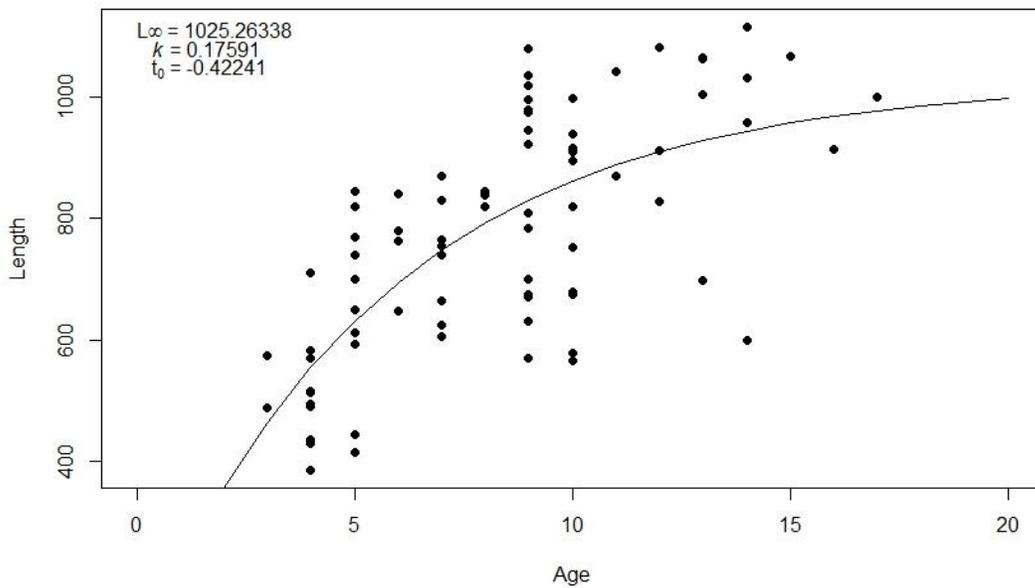


Figure 7: Scatter plot of ages of Flathead Catfish caught at downstream reach A at the Susquehanna River. The black line represents the fitted von Bertalanffy growth curve based on non-linear least squares model.

Discussion

Not surprisingly, CPE of Flathead Catfish was highest in the reach of the Susquehanna River between York Haven and Conowingo dams where they were first documented in 2002. However; the similarity with CPE in upstream reaches was unexpected, as the CPE among reaches did not statistically differ. It was anticipated that a gradient of abundance would exist moving upstream from more established reaches. This expectation assumed that there would be a density-dependent scenario relative to habitat availability that dispersing fish would occupy available habitat until a density threshold (i.e., carry capacity) was met and then individuals would disperse looking for suitable habitat further from the establishment point. This suggests that some other ecological or behavior factors are contributing to dispersal and abundance than simply density.

Results of a Bayesian hierarchical Poisson model suggested that the only observed covariate to significantly influence CPE of Flathead Catfish was river velocity; however, distance downstream of nearest dam had a high probability of having a negative effect. Daugherty and Sutton (2005) found that flow rates (i.e., velocity) associated with habitats occupied by Flathead Catfish were significantly different than random; suggesting different flow rates were preferred. Flathead Catfish occupied higher velocity areas in a greater proportion than they existed during spring and summer periods and only used high velocity areas (> 1.0 m/s) during those periods (Daugherty and Sutton 2005). While our collections were limited to the summer period, the Poisson model suggests that habitat usage by Flathead Catfish in our study reaches was negatively correlated with river velocity. Within our study, the variability of velocity among sites was limited (0.01 – 0.56 m/s) and only overlapped the lower range of flow rates observed by Daugherty and Sutton (2005). A number of factors may have influenced this observation in our study. Due to the unique geomorphology of this system, there are relatively few areas where high velocity and adequate depth (i.e., 1.0 m to cover nets) are coincident which may have limited range of velocities in our study. Also, baited hoop nets were used to collect fish in this study and because fish were attracted to baits, conditions at the net may not necessarily be indicative of preferred habitat.

Although not significant, we found a 60% probability of a negative correlation between Flathead Catfish CPE and river kilometer. Based on initial detection, population establishment, and subsequent range expansion this association is logical. Initial documentation of Flathead Catfish at the Susquehanna River occurred at Safe Harbor Dam (rkm 51.3) in the lower portion of the Susquehanna River and expanded outward, but primarily upstream (i.e., increasing rkm). Similarly, the initial documentation of Flathead Catfish generally progressed upstream; with observations upstream of Safe Harbor Dam in 2005, York Haven Dam in 2008, upstream of Harrisburg in 2010 and upstream of the confluence of the Juniata River in 2013 (PFBC, unpublished data). Kaesar et al. (2011) analyzed abundance and biomass data from several invasive Flathead Catfish populations and suggested that peak biomass and abundance occurred 10 to 15 years after establishment. Based on this suggestion, the observation of decreased CPE as we moved upstream, or into areas with shorter time since establishment, is supported by observations of other invasive Flathead Catfish populations. Interestingly, the lower reaches included in this study were approaching that 15-year timeframe suggested as the peak during our 2016 collections. It will be interesting to track CPE in those areas moving forward to see how the Susquehanna population dynamics compared to the other invasive populations.

Despite differences in passability of dams within the study area, the presence of dams as a barrier to dispersal appears to influence CPE of Flathead Catfish. Within the study reach, there are three hydropower dams (York Haven, Safe Harbor, and Holtwood) that are unpassable except for fishways. The fishways at Safe Harbor and Holtwood are seasonal and operate mechanically (elevators) with design and operation focused on moving American Shad. York Haven Dam currently has a vertical slot fishway that allows for volitional movement during April through December; making it readily passable for resident species including Flathead Catfish. Upstream of York Haven, there are three low-head dams; all of which are at least seasonally passable. One has a large notch at the east end of dam that allows passage, another has a very low head height so under higher flows is readily passable, and the third is seasonal to allow for a recreational pool but is deflated for approximately six months a year and allows adequate passage during those times. Raabe and Hightower (2014) found that notched dams or partial removals are less passable than full removals. This could account for aggregation downstream of Dock Street Dam in Harrisburg which has a large notch in the eastern portion of the dam. Also, Raabe and Hightower (2014) found dams may be less passable under low-flow conditions which could further interrupt or delay movement and lead to aggregation. This may have influenced that relationship in our data as the primary collection year (2016) had a prolonged low-flow period during the survey period. However, Flathead Catfish were observed passing under all conditions which suggests that aggregation downstream of dams may be volitional (e.g. foraging) rather than forced (Raabe and Hightower 2014). While the passability of Flathead Catfish may not be restricted directly, the passability of potential prey species may be so delays in passing may be opportunistic.

Unfortunately, we were unable to compare growth parameters among reaches for the Susquehanna River as anticipated. While we were able to fit a von Bertalanffy growth model to downstream reach (reach A), models for combined upstream reaches B and C failed to converge. Other studies have been able to fit models with fewer individuals (Lumber River, $n=36$, Kwak et al. 2006; seven population, Massie et al. 2018), suggesting that population characteristics in the upstream reaches of the Susquehanna River were too variable. This phenomena of nonconvergence is common with nonlinear models (Midway et al. 2015). Only six year classes (i.e., 2-6, 8 years) were represented in the upstream reaches; therefore, little information was provided about the younger and older members of the population. Of those six cohorts, three only contained one individual and one contained two individuals. Further, the well represented cohorts (i.e., 3, 4, and 5 years old) had broad total length at age ranges (i.e., 334 mm, 224 mm, and 450 mm, respectively). The combination of these two factors likely contributed to the failure of the von Bertalanffy model to converge using the combined data for the upper reaches. Future data collection to increase sample size in all reaches are needed but is of more importance in upstream reaches (i.e., B and C) where abundance is still relatively low and growth rates appear highly variable.

Massie et al. (2018) used length-at-age data collected from this study (pooled all data into one Susquehanna River population) to quantify the spatial variability of Flathead Catfish population growth parameters across a large portion of their contemporary range using a Bayesian nonlinear hierarchical modeling framework (see appendix for full article). The Susquehanna Flathead Catfish population growth parameters were estimated to be: $L_{\infty}=989$, $K=0.19$, and $t_0=0.29$. Flathead Catfish in the

Susquehanna River reached a greater maximum size than other introduced populations at lower latitudes (Neuse River, NC; Little Pee Dee River, SC, and Apalachicola River, FL). However, for all introduced populations in the study, Massie et al. (2018) did not find L_{∞} to be significantly different across latitudes and thus are expected to be more influenced by local scale processes (e.g.; prey availability, exploitation rates). Growth coefficients were negatively correlated with latitude for introduced populations. The Susquehanna River population growth coefficient was an exception to this negative trend with latitude, as other more southern populations had lower growth coefficients (i.e., Altamaha River, GA; Lake Marion, SC; Lumber River, NC; NECFR, NC). This effect may be due to the Susquehanna River population is younger than other southern introduced populations, and thus are expected grow faster (Bonvechio et al. 2011). However, Massie et al. (2018) did not find the time since introduction to be a significant predictor of introduced population growth parameters.

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6.0 Conclusions

We found that Flathead Catfish growth at the Susquehanna River to be rapid and similar to other invasive Flathead Catfish populations in the Atlantic Slope. Relative abundance of Flathead Catfish in all three reaches were not significantly different; suggesting that the species was more established in upstream reaches than first thought. Environmental factors such as flow velocity, dams, and river kilometer appear to affect relative abundance of Flathead Catfish at the Susquehanna River. Additional age and growth analysis of upstream reaches of the Susquehanna River will help to develop growth parameters for that reach as sample size was small.

7.0 Future Research

Future research should continue to focus on upstream reaches where small sample sizes, limited number of cohorts, and variable growth prevented accurate estimation of growth parameters. Continued collection of specimens within this reach should strengthen future analysis. Additional focus on areas such as the West Branch Susquehanna River and Juniata River where establishment is not known or where there is little documentation is needed. Similar base-line relative abundance and growth parameter estimates should be developed for other invasive populations in the mid-Atlantic regions like the Schuylkill and Delaware rivers to aid future population management. On-going monitoring of populations should continue in the future to understand changing population dynamics as

they continue to become more established. Other topics of interest related to Flathead Catfish include diet, population genetics, and fish movement.

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9.0 Appendix A: Metrics

- Undergraduate and graduate student support: None
- Faculty and staff support: None
- Publications:
 - Massie, D.L., G.D. Smith, T.F. Bonvechio, A.J. Bunch, D.O. Lucchesi, and T. Wagner. Spatial variability and macro-scale drivers of growth for native and introduced Flathead Catfish populations. Transactions of the American Fisheries Society. 147:554-565. (Attached)
 - Massie, D.L., G.D. Smith, T.F. Bonvechio, A.J. Bunch, D.O. Lucchesi, and T. Wagner. Spatial variability & macro-scale drivers of growth for native and introduced Flathead Catfish populations (poster). 148th Meeting of the American Fisheries Society. August, 19-23, 2018, Atlantic City, New Jersey. (Attached)
- Volunteer hours: none
- Public and professional presentations:
 - Smith, G.D. Pennsylvania SeaGrant Flathead Catfish Project, Susquehanna River, Pennsylvania. Invasive Catfish Symposium. NOAA Sustainable Fisheries Goal Implementation Team, Invasive Species Taskforce. November 6, 2017. Charles City, Virginia.
 - Smith, G.D., D. Massie, T. Wagner. Comparing relative abundance and population characteristics of Flathead Catfish across a range of establishment levels at the Susquehanna River. 12th Annual Susquehanna River Symposium. November 11, 2017, Lewisburg, Pennsylvania.
- Project collaborators:
 - Brett Coakley, Maryland Department of Natural Resources, Fishing and Boating Services, Freshwater Fisheries Program

10.0 Appendix B: Impact and/ Accomplishment Statement(s)

- **Impact Statement**
- **Title:** Comparing relative abundance and population characteristics of Flathead Catfish at different reaches of the Susquehanna River
Cooperators: Geoffrey Smith, Pennsylvania Fish and Boat Commission and Tyler Wager and Danielle Massie, Cooperative Fish and Wildlife Research Unit, Pennsylvania State University
Recap: We established initial relative abundance and estimated growth parameters of invasive Flathead Catfish population in the middle and lower reaches of the Susquehanna River and compared these parameters among reaches assuming varying degrees of establishment.
Relevance: Invasive Flathead Catfish were first documented in 2002 at the Susquehanna River and establishment and range expansion have potential local and regional (i.e., mid-Atlantic or Chesapeake drainage) impacts on existing fisheries including current interagency efforts to re-establish migratory species such as American Shad.

Response: Data indicates that Flathead Catfish are more established across the surveyed reaches than first thought. Relative abundance was not significantly different among reaches as was presumed. Growth parameters suggest rapid growth similar to other invasive populations in the Atlantic Slope.

Results: Relative abundance and growth information will inform management of existing populations and serve as a warning for areas where the species is not yet established but the threat of introduction exists. By understanding similarities observed in Susquehanna population to other areas Flathead Catfish have invaded previously we can infer potential fisheries impacts and threats.

- **Accomplishment Statement**

- **Title:** Comparing relative abundance and population characteristics of Flathead Catfish at different reaches of the Susquehanna River

Cooperators: Geoffrey Smith, Pennsylvania Fish and Boat Commission and Tyler Wager and Danielle Massie, Cooperative Fish and Wildlife Research Unit, Pennsylvania State University

Recap: We established initial relative abundance and estimated growth parameters of invasive Flathead Catfish population in the middle and lower reaches of the Susquehanna River.

Relevance: This was the first systematic documentation of Flathead Catfish abundance and population characteristics in the Susquehanna River since detection of population in the 2002. Developing current abundance and growth parameters will help to understand change as the population becomes more established as well as help anticipate what will happen as they invade other waterbodies or reaches to inform proper management on both a local and regional scale.

Response: Data indicates that Flathead Catfish are more established across the surveyed reaches than first thought. Analysis of covariate data suggested that variables such as river velocity, dam location, and river kilometer affect abundance. Growth parameters for Flathead Catfish at the Susquehanna River suggest rapid growth similar to other invasive populations in the Atlantic Slope. Growth in the upper reach was too variable to accurately model at this point and future collections should strengthen this data set.

- **Results:** We were able to determine preliminary relative abundance and growth parameters for the middle and lower Susquehanna River. This information will be used to guide management and inform future data collection in other waterbodies and reaches. Comparison of growth parameters with other native and invasive populations puts development in the Susquehanna in a broader context as well as informs managers of potential for invasion in other areas.