2020

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Recommended Citation

Fabrizio, Mary C.; Nepal, Vaskar; and Tuckey, Troy D., Invasive Blue Catfish in the Chesapeake Bay Region: A Case Study of Competing Management Objectives (2020). *North American Journal Of Fisheries Management*.
DOI: 10.1002/nafm.10552

North American Journal of Fisheries Management
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ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1002/nafm.10552

SPECIAL ISSUE: CATFISH 2020—THE 3RD INTERNATIONAL CATFISH SYMPOSIUM

Invasive Blue Catfish in the Chesapeake Bay Region: A Case Study of Competing Management Objectives

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Abstract
Freshwater fishes have been introduced outside their native range to establish recreational fisheries, but management conflicts arise when such introductions also result in potentially harmful effects on native species. In this case study, we focus on Blue Catfish *Ictalurus furcatus*, which were introduced in the Chesapeake Bay region and are now considered invasive. In many tidal tributaries, Blue Catfish have increased dramatically in abundance, expanded into high-salinity habitats (up to 21.8 psu), and negatively affected native species, prompting calls for the development of an effective management plan. However, management of this conflict species is complicated by multiple competing objectives, including control of population size, maintenance of trophy fisheries, and expansion of commercial fisheries for Blue Catfish. Seven management recommendations were advanced by the Invasive Catfishes Work Group to control the spread and limit the ecological impacts of Blue Catfish on native species. We highlight opportunities for addressing these complex management issues and guide our suggestions using results from research on invasive Blue Catfish ecology and population dynamics, as well as management of invasive species in general. A formal approach, such as structured decision analysis, is required to resolve conflicts among user groups and to address the wicked problem of Blue Catfish in the Chesapeake Bay region.

Freshwater fishes have been introduced widely around the world, primarily to create recreational fishing opportunities (Jackson 2002; Crawford and Muir 2008; Carpio et al. 2019), with introductions typically reflecting angler preferences for black basses, salmonids, and catfishes. Many of these fishes were subsequently recognized as invasive species in receiving ecosystems (Dextrase and Mandrak 2006), challenging the management of fisheries that are simultaneously desired by anglers and potentially harmful to native aquatic communities (Hickley and Chare 2004; Shollenberger et al. 2019). Additional challenges arise when nonnative species support trophy (Churchill et al. 2002; Ng et al. 2016) or commercial (Macnaughton et al. 2015) fisheries. Such species may be considered “conflict species,” and management thereof may become a “wicked problem” as the perspectives and competing agendas of multiple stakeholders appear unreconcilable (Woodford et al. 2016).

Recreational fisheries for at least three large catfish species were established throughout U.S. Atlantic Slope drainages after the introduction of nonnative Blue Catfish *Ictalurus furcatus*, Flathead Catfish *Pylodictis olivaris*, and Channel Catfish *I. punctatus*. Subsequently, Blue Catfish and Flathead Catfish populations have become invasive in the Chesapeake Bay region (ASMFC 2011), and concerns have been raised elsewhere about the potential negative impacts of these catfishes on native species (Bringolf et al. 2005; Brown et al. 2005). Here, we focus on the

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Received February 3, 2020; accepted November 13, 2020

highly abundant and invasive Blue Catfish in Chesapeake Bay; however, the management challenges and opportunities we discuss are applicable to many invasive sport fishes.

Blue Catfish were introduced into tidal rivers of the Chesapeake Bay region in the 1970s and 1980s (Schloesser et al. 2011); they currently occupy all of the major tidal rivers in Virginia and Maryland (Figure 1) and are present in Delaware (Delaware DNREC 2019). Occurrences of Blue Catfish in nonstocked waters resulted from their dispersion to and colonization of adjacent rivers and from translocations by anglers (Higgins 2006). Primarily a freshwater species, Blue Catfish occur in salinities up to 11.4 psu in their native range (Perry 1968). In the Chesapeake Bay region, they have been captured in salinities as high as 21.8 psu (Fabrizio et al. 2018), although most are found in brackish habitats <10 psu (Nepal and Fabrizio 2019). Although the salinity tolerance of Flathead Catfish is similar to that of Blue Catfish (Bringolf et al. 2005), Flathead Catfish prefer low-salinity areas (Schmitt et al. 2017) and are generally absent from the higher-salinity waters where Blue Catfish are commonly observed. Similarly, introduced Channel Catfish also remain confined to freshwater and low-salinity reaches in the Chesapeake Bay region (Aguilar et al. 2016).

In addition to the observed expansion into brackish and estuarine waters, the Blue Catfish is the only one of the three nonnative catfish species to increase dramatically in abundance in Virginia's tidal waters (Tuckey and Fabrizio 2019). Up to 2,379 Blue Catfish were observed in a single, 5-min bottom-trawl tow in tidal tributaries of Virginia, where the greatest annual mean catch rate is 137 fish/tow (T.D.T and M.C.F., unpublished data). Comparably high catch rates for Blue Catfish were observed in low-frequency electrofishing surveys in Virginia, where mean catch rates ranged between 223 and 6,106 fish/h (Greenlee and Lim 2011). Note that the upper range of these electrofishing catch rates is an order of magnitude higher than the upper range of catch rates typically reported for Blue Catfish in the USA (75th percentile for low-frequency electrofishing = 373.0 fish/h; Bodine et al. 2013).

After the establishment of Blue Catfish populations in the James, York, Rappahannock, and Potomac rivers, the average size of harvested fish increased (Hilling et al. 2018) and two nationally recognized trophy fisheries developed in the region. These trophy fisheries generated economic opportunities for fishing guides and other local businesses. However, the high abundance of Blue Catfish in the region also had unintended consequences, both positive and negative; together with the challenges of managing an interjurisdictional resource, these consequences led to competing management objectives.

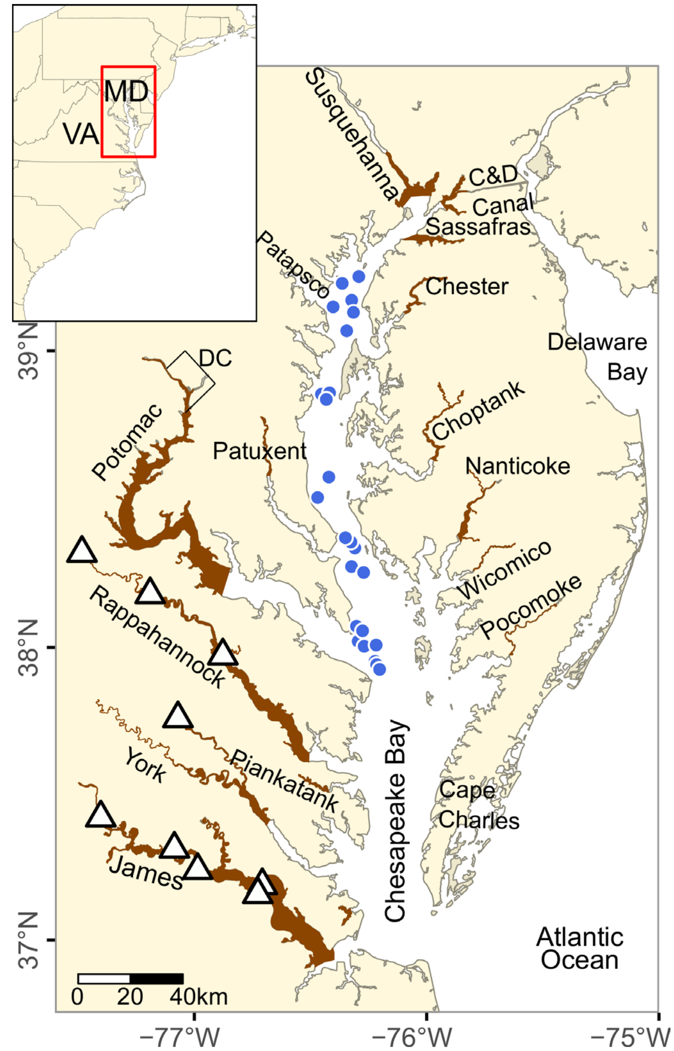

FIGURE 1. Current distribution (dark brown areas) and original stocking locations (white triangles) of invasive Blue Catfish in the Chesapeake Bay region (C&D = Chesapeake and Delaware). The blue dots indicate locations where 63 Blue Catfish were captured in the main stem of Chesapeake Bay in 2018 and 2019. Occurrences depicted in this figure are based on information from fishery-independent surveys (trawl, electrofishing, and seine) from the Virginia Institute of Marine Science, Virginia Commonwealth University, Virginia Department of Wildlife Resources, and Maryland Department of Natural Resources. Blue Catfish have also been captured from the lower bay near the village of Cape Charles. The location of Chesapeake Bay along the U.S. Atlantic coast is shown in the inset. (Figure adapted from Nepal and Fabrizio 2019.)

UNINTENDED CONSEQUENCES

An unintended but economically positive consequence was the development of small-scale commercial fisheries for Blue Catfish in Virginia and Maryland. Prior to the late 1990s, catfish landings from tidal tributaries were likely comprised primarily of the native White Catfish *Ameiurus catus* and introduced Channel Catfish. As Blue Catfish abundance increased, Blue Catfish became the predominant species in the catch. In addition to directed fisheries, Blue Catfish occur as unwanted bycatch in gill-net and pound-net fisheries for Striped Bass *Morone saxatilis*, Atlantic Croaker *Micropogonias undulatus*, and other native species. As such, Blue Catfish bycatch may reduce the efficiency of traditional fisheries by damaging nets and increasing handling time (M. Gary, Potomac River Fisheries Commission, personal communication).

The establishment and growth of Blue Catfish populations in tidal tributaries of Chesapeake Bay produced unintended ecological effects in the region, including negative effects on native species, particularly those of economic or conservation concern. These negative effects include predation, competition for resources, or both. Blue Catfish occupy freshwater and brackish habitats that are similar to those used by native White Catfish (Murdy et al. 1997), and following the introduction of Blue Catfish, White Catfish populations declined in abundance, likely due to predation or competition (Schloesser et al. 2011).

Another negative ecological effect arises from Blue Catfish predation on native freshwater and estuarine species. Blue Catfish are opportunistic generalist feeders that consume a variety of species from invertebrates to fishes as well as vegetation (Schloesser et al. 2011; Schmitt et al. 2019b). Alosines, including American Shad *Alosa sapidissima* and river herring (Blueback Herring *Alosa aestivalis* and Alewife *Alosa pseudoharengus*), are consumed by Blue Catfish primarily in spring (Schmitt et al. 2017, 2019a), when alosines migrate upriver to spawn. These alosines are species of conservation concern due to their greatly reduced abundances along the Atlantic coast (Limburg and Waldman 2009). Although alosines occur in the diets of a small percentage (4.5%) of Blue Catfish (Schmitt et al. 2017), the predatory impact on alosines may be significant due to the high number of Blue Catfish in these systems; however, the true impact is unknown due to a lack of population size estimates for alosine species. The Blue Catfish population in a 12-km stretch of the James River is estimated to comprise 1.6 million fish between 21.4 and 46.6 cm FL (95% CI = 0.9–2.9 million fish; Fabrizio et al. 2018). This is equivalent to 544 Blue Catfish/ha (Fabrizio et al. 2018), which exceeds density estimates reported for many fishes in their nonnative ranges (Table 1). Furthermore, larger Blue Catfish are more likely to prey on alosines and other fishes (Schmitt et al. 2019b). Blue Catfish also consume blue crabs *Callinectes sapidus*, which support one of the most valuable fisheries in Chesapeake Bay (NOAA Fisheries 2020); blue crabs are present in up to 32% of stomachs from Blue Catfish sampled at salinities between 5 and 11 psu in the James River (Schmitt et al. 2019a, 2019b).

Because of the potential negative effects of Blue Catfish on alosines, blue crabs, and other managed species, the Blue Catfish was declared an invasive species in the region (ASMFC 2011). Managers were directed to make “all practicable efforts” to reduce the range expansion and

TABLE 1. Comparison of estimated densities (fish/ha) for nonnative fishes, including invasive Blue Catfish in the Chesapeake Bay region. All density estimates were based on mark–recapture estimates of population size except those for Round Goby, which were based on diver surveys. We provide uncertainty estimates for the estimated fish densities as 95% CIs or SDs when those values were reported.

Species	Location	Estimated density (fish/ha)	Reference
Northern Snakehead *Channa argus*	Potomac River (tidal tributaries)	2.77	Love et al. (2015)
Flathead Catfish *Pylodictis olivaris*	Flint and Altamaha rivers, Georgia	3.1 (CI = 1.3–4.9) to 14.7 (CI = 10.6–18.8)	Kaeser et al. (2011)
Flathead Catfish	Diamond Valley Lake, California	3.6–3.8	Granfors (2014)
Lake Trout *Salvelinus namaycush*	Priest Lake, Idaho	4.6 (CI = 3.3–6.3)	Ng et al. (2016)
Common Carp *Cyprinus carpio*	Lake Herman, South Dakota	35.1–83.0	Weber et al. (2016)
Common Carp	Lake Madison, South Dakota	62.6–255.3	Weber et al. (2016)
Common Carp	Brant Lake, South Dakota	108.6–210.7	Weber et al. (2016)
Blue Catfish *Ictalurus furcatus*	Powell Creek, Virginia	239 (CI = 223–258); 708 (CI = 674–747)	Bunch et al. (2018)
Blue Catfish	James River, Virginia	544 (CI = 307–967)	Fabrizio et al. (2018)
Round Goby *Neogobius melanostomus*	Lake Ontario	22,000 (SD = 11,800)	Pennuto et al. (2012)
Round Goby	Lake Erie	65,000 (SD = 19,000); 140,000 (SD = 10,000)	Barton et al. (2005)

population abundance of this species (ASMFC 2011). In 2012, under the directives of the Chesapeake Bay Program, the Invasive Catfishes Work Group (ICWG) was created to synthesize research and address management issues in the region concerning invasive Blue Catfish. The ICWG comprises a wide array of stakeholders—namely, agency scientists, academic researchers, industry representatives, and fisheries managers from Virginia, Maryland, the Potomac River, Delaware, Pennsylvania, and the District of Columbia.

A CONFLICT SPECIES WITH COMPETING MANAGEMENT OBJECTIVES

Shortly after the ICWG was convened, two competing management objectives emerged: one objective centered on continuation of the trophy fishery for Blue Catfish, whereas the other focused on limiting the ecological impacts of Blue Catfish on native fish and invertebrate communities. The desire to maintain the trophy fisheries in the James and Potomac rivers was fueled by outspoken anglers and river guides who viewed the potential loss or diminution of the trophy fisheries as an unwelcomed hardship. Other stakeholders sought to reduce Blue Catfish population abundance and control the further spread of populations, particularly in Maryland, where some tidal rivers remained free of Blue Catfish. Managers were also keen on preventing the illegal movement and stocking of fish by anglers.

Underlying the tension between competing objectives was the challenge arising from the apparent lack of coordinated directives from management agencies in the region and between management agencies in Virginia. Specifically, the Virginia Marine Resources Commission regulates and manages commercial fisheries, including those for Blue Catfish, and the Virginia Department of Wildlife Resources (formerly the Virginia Department of Game and Inland Fisheries) regulates and manages the recreational and trophy fisheries for Blue Catfish. As such, management of Blue Catfish in the region was characterized by several types of conflicts commonly observed in freshwater fisheries (Arlinghaus 2005): conflicts between jurisdictions, between anglers and managers, and among users.

Mindful of the conflicts and the directives from the Atlantic States Marine Fisheries Commission, the ICWG developed seven recommendations for controlling range expansion and population growth of Blue Catfish in the region (Invasive Catfishes Task Force 2014):

1. Educate anglers and the general public in a clear, consistent, and accessible manner across jurisdictions to reduce the risk of unauthorized introductions.
2. Streamline current fishing policies and regulations pertaining to Blue Catfish and provide consistency across jurisdictions.
3. Continue to monitor the distribution and status of Blue Catfish in the region using fishery-independent surveys in tidal tributaries and Chesapeake Bay.
4 Evaluate the risk of opening upriver habitat to invasive Blue Catfish when considering the removal of dams in the Chesapeake Bay watershed.
5. Focus removal efforts in areas of significant ecological interest, such as riverine habitats used as spawning and nursery habitats by anadromous fishes.
6. Provide incentives for small-scale commercial fishers to increase harvests.
7. Develop a large-scale commercial fishery by removing barriers to market expansion and simplifying seafood inspections.

CHALLENGES AND OPPORTUNITIES IN MANAGING A CONFLICT SPECIES

In this section, we examine the challenges and opportunities associated with the ICWG recommendations in light of research on Blue Catfish in the region and invasive species in general. Recommendations 6 and 7 address similar outcomes and are considered jointly.

Recommendation 1: Angler and Public Education about Blue Catfish

The ICWG suggested that anglers and the general public be informed that the Blue Catfish is an invasive species in the Chesapeake Bay region and that Blue Catfish should be retained or killed rather than released into the water from which they were captured. Currently, the only capture-and-kill regulations in the region are in Maryland and Delaware; Virginia regulations are not clear on how anglers should handle a Blue Catfish that they do not wish to harvest. A poster about these regulations was distributed at boat launch ramps and bait shops throughout Maryland, but education and outreach efforts have not yet materialized elsewhere.

Recommendation 2: Consistency of Regulations

Regulations concerning creel and size limits and the transport of live fish are fairly consistent among jurisdictions, but the consequences of failure to comply with regulations vary among states. For example, the recreational Blue Catfish fishery is open year-round and is not subject to a daily creel or size limit in Delaware, Maryland, or Virginia, although Virginia allows the retention of only one fish greater than 81.3 cm due to consumption advisories. Delaware prohibits the purchase, sale, and possession of live Blue Catfish. The transport of live Blue Catfish is prohibited in Maryland, Virginia, and Delaware; stocking of Blue Catfish into inland waters is illegal in Virginia and Maryland, but violators are fined in Maryland only.

An important regulation that varies regionally concerns consumption advisories due to mercury and polychlorinated biphenyl concentrations in Blue Catfish. These advisories acknowledge tributary-specific variability in contaminant concentrations but fail to account for the recently documented long-distance movements of Blue Catfish in these systems. For example, the average minimum distance moved by Blue Catfish in the Potomac River was 24.1 km and was not related to fish size (30.0–116.5 cm TL; Tuckey et al. 2017). Furthermore, the entire Potomac River is used by Blue Catfish (Tuckey et al. 2017), yet consumption advisories vary depending on capture location within this river. Advisories based on fish size also warrant reconsideration. In particular, the Virginia harvest regulation that allows harvest of a single fish greater than 81.3 cm may not adequately protect human health because polychlorinated biphenyl concentrations in some fish smaller than 81.3 cm may exceed the U.S. Environmental Protection Agency's "do not eat" limit (Luellen et al. 2018). Consumption advisories for Blue Catfish throughout the region merit reevaluation, particularly in light of the desire to expand commercial fisheries.

Recommendation 3: Continued Monitoring of Populations

In the Chesapeake Bay region, bottom trawls and low- or high-frequency electrofishing are the primary survey gears used to evaluate Blue Catfish population attributes. However, many surveys either lack a probabilistic sampling design or are spatially and temporally fragmented, hampering statistical inferences. In addition, some surveys were designed primarily for assessment of other freshwater or estuarine fishes. Consistent, standardized methods and survey designs are needed in the region to improve the comparability and spatial scope of information across tidal tributaries (Bonar et al. 2009; Pergl et al. 2020). We suggest that a regional survey will likely employ multiple gears because electrofishing is less effective across the salinity gradient that is currently occupied by invasive Blue Catfish. Furthermore, because fishery extractions appear to be the primary means by which Blue Catfish populations may be controlled in the region, adequate and comprehensive monitoring is required to determine the efficacy of harvest-based removals (Pergl et al. 2020). A concerted and focused effort to standardize sampling across jurisdictions can increase our understanding of how populations adapt to estuarine conditions, disperse into novel habitats, and respond to the growing fisheries in the region.

Although traditional catch-based surveys provide quantitative abundance estimates of Blue Catfish, alternative approaches to detect the presence of Blue Catfish in tidal tributaries may be useful. In particular, environmental DNA may be used for early detection of aquatic invasive species (Díaz-Ferguson et al. 2014; Zaiko et al. 2018) and to comprehensively sample habitats used by Blue Catfish (Díaz-Ferguson et al. 2014). Early detection is important for newly introduced populations that are spatially constrained because this is when control efforts are most likely to be successful (Britton et al. 2011). Following refinement of molecular sample preparation methods, development of appropriate molecular probes, and standardization of analysis methods (Plough et al. 2018; Zaiko et al. 2018), field validation of the relationship between environmental DNA abundance and observed Blue Catfish abundance will be necessary to ensure the reliability of this method as an early detection tool (Moyer et al. 2014).

Recommendation 4: Risk Evaluation for Dam Removal

Many dams in the Chesapeake Bay watershed are slated for removal, and some of these dams are in systems that are currently occupied by invasive fishes, including Blue Catfish (e.g., James and Potomac rivers). Dam and obstruction removals in the region primarily benefit diadromous fishes, such as river herring, American Shad, and American Eel *Anguilla rostrata*. These migratory species occupy habitats that overlap with those of Blue Catfish; as such, dam removals facilitate upstream habitat use by native species as well as opportunities for upstream colonization by invasive fishes. Where feasible, we suggest consideration of selective fish passage methods to prevent or reduce the upstream movement of Blue Catfish and other invasive fishes but allow passage of native fishes. A recently developed framework for achieving selective fish passage based on physical capabilities, body morphology, sensory capabilities, behavior, and movement phenology of fishes may be useful to consider (Rahel and McLaughlin 2018). Research is needed, however, to understand which of these traits, if any, may be exploited for selective exclusion of Blue Catfish from upriver passage.

Recommendation 5: Targeted Removals in Areas of Ecological Interest

Although high salinities were believed to constrain long-term occupancy of estuarine habitats by Blue Catfish (Greenlee and Lim 2011), the species has moved into and colonized increasingly saline habitats. Blue Catfish from the Chesapeake Bay region survive acute salinity exposures of up to 15.7 psu for 72 h, and larger and more robust individuals (i.e., higher body condition) tolerate higher salinities than smaller and less-robust fish do (Nepal and Fabrizio 2019). During wet conditions or wet years in the region, areas from the mouth of the Potomac River and north are habitable by Blue Catfish; in addition, Blue Catfish may gain access to Delaware Bay through the Chesapeake and Delaware Canal (Nepal and Fabrizio 2019). The implications for the region are sobering: access to the main stem of Chesapeake Bay and the Chesapeake and

Delaware Canal will allow Blue Catfish to spread into systems that are currently free of this species.

Because of the high expense and low likelihood of success, eradication is infeasible in systems where Blue Catfish have become established (e.g., Britton et al. 2011). However, eradication of Blue Catfish may be a viable control method in newly invaded systems. Limited funding for eradication prompted the ICWG to recommend implementation of a triage strategy that allocates effort to systems that serve as spawning and nursery areas for species of conservation concern. For example, Blue Catfish have not yet been reported from the Patapsco River, Maryland, which is targeted for restoration of river herring. If Blue Catfish colonize this system, then early detection and rapid eradication may yield proportionally high removal rates of Blue Catfish. Unfortunately, the lack of monitoring in systems that are potentially vulnerable to colonization by invasive Blue Catfish and the perceived costs and uncertainty of success have impeded development of eradication plans in the Chesapeake Bay region. Pilot studies are also needed to evaluate the efficacy and cost-effectiveness of eradication methods.

Recommendations 6 and 7: Increased Commercial Harvest and Development of New Commercial Fisheries for Blue Catfish

Recommendations 6 and 7 were developed in recognition that commercial exploitation rates were probably light or negligible and that additional extractions could be warranted. However, two formidable hurdles impede the growth of commercial fisheries for Blue Catfish in the Chesapeake Bay region: (1) new regulations concerning the inspection of catfish, and (2) suppression of exvessel prices due to low market demand.

In 2016, a federal regulation assigned responsibility for the inspection of catfishes (order Siluriformes) to the Food Safety and Inspection Service of the U.S. Department of Agriculture. This change was intended to benefit catfish farmers in the USA by reducing competition from imported farmed-raised catfish. Unfortunately, the new regulation placed an increased burden on seafood processors handling wild-captured Blue Catfish because it required compliance with the U.S. Department of Agriculture's stringent regulations (e.g., screening for *Salmonella*) and because of increased inspection costs for catfish processed during overtime hours.

Attempts to increase market demand for Blue Catfish in the Chesapeake Bay region were modest at first, but concerted efforts in recent years began to yield noticeable results. For example, in 2015 a Seafood Watch report from the Monterey Bay Aquarium identified Blue Catfish from Chesapeake Bay as a "best choice" seafood item (Simon 2015). Commercial fishers in the Potomac River began to shift their effort toward Blue Catfish and away from traditional species, such as Striped Bass and White Perch *Morone americana*. In Virginia, a cooperative study examined the feasibility of using low-frequency electrofishing gear to expand small-scale commercial fisheries. Bycatch and gear interference studies followed, and a limited commercial electrofishing fishery was established in the James, Pamunkey (a tributary of the York River), and Rappahannock rivers in 2020. Recently, seafood processors in Maryland significantly increased the number of Blue Catfish processed by providing fillets to correctional facilities, higher education, hospitals, and public schools in the state. Processors also increased their efforts to sell locally harvested Blue Catfish to restaurants and large supermarkets in the region. A catfish burger made with Chesapeake Bay Blue Catfish was introduced by a farm-to-table restaurant chain (Barnes 2019). Invasivorism—the idea that increased human consumption may control the abundance or curtail the spread of invasive species (Nuñez et al. 2012)—is alive and well in the Chesapeake Bay region, but not all consumers embrace the idea of catfish for dinner. Nevertheless, as regional market demand grew, landings increased in Maryland and Virginia, so much so that harvests by weight of Blue Catfish from the Chesapeake Bay region have exceeded those of Striped Bass since 2015 (NMFS 2019).

ADDRESSING THE WICKED PROBLEM: CAN COMPETING OBJECTIVES BE RECONCILED?

Currently, the principal strategy to curtail the spread and growth of Blue Catfish populations in the Chesapeake Bay region is increased harvesting; however, the likelihood of success of this strategy is unknown. Some managers favor the continuation of trophy fisheries in the region because of the presumed economic value of these fisheries and because some managers and stakeholders perceive that commercial harvesting is not likely to effectively control Blue Catfish populations. Trophy fisheries in the James and Potomac rivers rely on viable populations of Blue Catfish, which may not be well contained. Through reproduction, trophy-size fish may supply recruits to downestuary habitats; long-range movements of individual fish may also contribute to downestuary dispersals (Tuckey et al. 2017). A trophy fishery in the Potomac River could thus counteract efforts to eradicate or control nearby populations, especially because the salinity bridge that forms during wet conditions aids in the dispersal and colonization of Blue Catfish throughout the northern portion of Chesapeake Bay (Nepal and Fabrizio 2019). Seasonally connected habitats can be invaded by even a small contingent of migratory individuals (Bajer et al. 2015). Thus, trophy fisheries in the region risk the costs of invasion or reinvasion of Blue Catfish from occupied areas.

With two competing objectives, some stakeholders asked, “Is it possible to manage some systems for trophy fisheries and the remainder for control or prevention of colonization?” This approach has been proposed for management of conflict species in the southwestern USA (Clarkson et al. 2005), but even if such a plan is ecologically possible for the Chesapeake Bay region, it may not be understood by the public. The justification for a seemingly disparate approach to management of invasive Blue Catfish will be challenging to communicate; in addition, the approach could backfire by desensitizing the public to the need for the control of invasive species in general.

Fishery removals may minimize the ecological impacts of Blue Catfish on native species when exploitation rates are sufficiently high to reduce overall abundance, but the magnitude of removals necessary to achieve this outcome must be determined (Nuñez et al. 2012; Pennock et al. 2018). Typically, for managed fisheries, a stock assessment is used to estimate such removal rates; however, a stock assessment for Blue Catfish is not yet available. Because Blue Catfish in the major tributaries of Chesapeake Bay comprise genetically distinct populations (Higgins 2006) marked by differences in invasion history, population growth, and individual fish growth (Tuckey and Fabrizio 2019; Nepal and Fabrizio 2020), each population warrants its own assessment. This is a formidable challenge because of limited information on species-specific harvests of catfishes from these tributaries and a lack of information on the size or age composition of commercially harvested Blue Catfish.

In the absence of a stock assessment, population models that incorporate demographic structure, vital rates, and density-dependent processes may be used to investigate responses to removals (Zipkin et al. 2009; Ng et al. 2016; Pennock et al. 2018). For some invasive species, such models indicate that as population abundance declines, population growth is stimulated through compensatory changes in survival and recruitment (Nuñez et al. 2012; Weber et al. 2016; Lyu et al. 2019). Even when annual survival rates are low, invasive species with high maximum per-capita fecundity tend to increase in abundance in response to harvest (Zipkin et al. 2009). Furthermore, recruitment is the primary density-dependent process responsible for increased abundance in species with distinct breeding periods (Zipkin et al. 2009). Indeed, compensatory increases in recruitment were observed after intensive electrofishing removals of nonnative Flathead Catfish in Georgia (Bonvechio et al. 2011).

We suggest that Blue Catfish populations in the Chesapeake Bay region are likely to exhibit compensatory responses to increased harvest rates through changes in growth (Nepal and Fabrizio 2020; Nepal et al. 2020), maturation rates (Nepal 2020), or both. Compensatory changes in the directed, dispersive movements of Blue Catfish may also be observed after removals, but research on the relationship between population density and dispersive movements is lacking. Harvesting strategies aimed at controlling the population size of invasive species thus require careful consideration that includes model-based explorations of control strategies. Such approaches are useful for understanding the potential for failed responses to removal efforts. In particular, compensatory responses are more likely when harvests are directed at larger individuals. This has been shown for nonnative Channel Catfish populations from the San Juan River, New Mexico–Utah (Pennock et al. 2018), and with simulation models for Bighead Carp *Hypophthalmichthys nobilis* and Silver Carp *H. molitrix* in the Illinois River, Illinois (Tsehaye et al. 2013). In general, when adult survival rates are low, harvesting of juvenile and adult stages is more effective than strategies that target the harvest of adult fish only (Zipkin et al. 2009). In some cases, young-of-the-year fish must also be removed to effectively reduce the abundance of invasive fishes (Loppnow and Venturelli 2014).

The harvest of invasive species may contribute to local economies (Nuñez et al. 2012), but economic gains may give rise to perverse incentives to ensure the sustainability of fisheries for invasive species (Pasko and Goldberg 2014). For example, if Blue Catfish populations dwindle in size, agencies may be pressured to manage the fishery for sustainability rather than allowing the removals to deplete the resource. Here, the benefits of continued harvests overshadow the original goal of limiting the ecological effects of Blue Catfish on native species. Another perverse incentive is the unauthorized introduction of Blue Catfish throughout the region as individuals seek to profit from the fishery (Nuñez et al. 2012). In the presence of perverse incentives, Pasko and Goldberg (2014) recommended development of an “exit strategy” to provide opportunities for displaced fishers to harvest native species. In the Chesapeake Bay region, such an exit strategy may involve fisheries for Striped Bass, blue crab, and oysters.

Unfortunately, in only a limited number of cases has the successful control of invasive species through harvesting been documented: specifically, red deer *Cervus elaphus* in New Zealand and nutria *Myocastor coypus* in Great Britain (Pasko and Goldberg 2014). When the invasive species is highly abundant, the control of populations by promoting their consumption is less likely to be successful (Nuñez et al. 2012). To evaluate the efficacy of harvest-based removals for population control, we recommend re-estimation of population size in the James River after 5–10 years of elevated fishing pressure. Although fishery-independent surveys may reveal declines in relative abundance, the detectability of individual fish may change with declining fish density. In this scenario, survey-based estimates of relative abundance may not be reliable because the assumption of constant catchability may be violated. We therefore recommend estimation of detectability using mark–recapture approaches to assess population responses following increased removal efforts.

Even if population size is not controlled, the removal of large Blue Catfish (>30 cm) may be ecologically beneficial because large fish are more likely than smaller conspecifics to consume native fishes (Schmitt et al. 2019b). Large fish are also more likely to disperse and contribute to range expansion (Nepal and Fabrizio 2019); as such, removal of large Blue Catfish may also reduce the likelihood of range expansion. Removal of very large catfish (>96 cm), however, is opposed by trophy fishery stakeholders. A population model for nonnative Lake Trout in Priest Lake, Idaho, suggested that a strategy targeting the removal of intermediate-size fish can allow for retention of the trophy fishery while effectively reducing overall abundance (Ng et al. 2016). In the short term, removals of intermediate-size Blue Catfish (between 30 and 96 cm) may permit continuation of the trophy fishery as population abundance is reduced. In the long term, however, this strategy is unlikely to be viable for Blue Catfish: eventually, a sufficient proportion of the non-trophy fish will need to grow to trophy size. These types of responses to removals highlight the need for adaptive management strategies that are based on current understanding of population structure and vital rates.

In addition to harvests, other approaches to controlling the spread and growth of Blue Catfish populations may be considered; learning from managers of invasive species elsewhere may avoid costly mistakes and implementation of ineffective methods. For instance, bounties have been used to cull populations of invasive species (Pasko and Goldberg 2014), but such programs are best implemented during early colonization; bounties are not legal in Maryland, where many systems remain vulnerable to colonization. Other methods include introducing viruses (McColl et al. 2014) and disrupting reproduction. The latter method takes the form of the release of sterile males (Sea Lamprey *Petromyzon marinus*; Twohey et al. 2003) and the application of the Trojan Y chromosome (TYC) approach (Teem et al. 2014). The TYC approach involves a reassortment of sex chromosomes so that only male offspring are produced; over time, the proportion of females decreases and the population collapses to extinction (Lyu et al. 2019). The TYC approach works well in complex systems and is particularly applicable to species that, like Blue Catfish, can be cultured (Schill et al. 2017). A hybrid method using the TYC approach combined with harvesting appears to work best (Lyu et al. 2019). Because a single method is not likely to control an invasive species (McColl et al. 2014), an integrated pest management approach may be considered; this comprehensive, multiprong approach may be useful for managing populations of invasive species like Blue Catfish in the Chesapeake Bay region.

OUTLOOK

Competing management objectives for Blue Catfish in the Chesapeake Bay region are unresolved, primarily because of competing stakeholder agendas and the lack of a coordinated approach to define goals and build consensus for managing this conflict species. Solutions to such disagreements require the application of scientific models and explicit consideration of social values. The efficacy of possible management actions can be informed by science, and social values and preferences can help to better understand trade-offs and priorities (Maguire 2004). For example, population models, stock assessments, and ecosystem models are tools that can be used to explore the necessary magnitude of removals and the size-classes to target for removals. Such models should also consider potential metapopulation dynamics because movements of invasive species among interconnected systems could jeopardize control efforts (Bajer et al. 2015; Zelasko et al. 2016). Similarly, socioeconomic studies of Blue Catfish fisheries are needed to provide quantitative estimates of the acceptability and value of invasive species fisheries in the region. Economic benefits are important to quantify, but human dimensions—particularly regarding equity, access, and future opportunities—must also be considered (Arlinghaus 2005; Gozlan 2008).

Although the creation of the ICWG facilitated dialogue among managers, scientists, industry representatives, anglers, fishing guides, and commercial fishers, future public and community engagement is needed to expand the base of participating stakeholders and the consideration of broader perspectives about invasive Blue Catfish (Crowley et al. 2017). Parallel efforts to address the competing management objectives for Blue Catfish in the region should also be pursued and include decision analysis methods, such as structured decision making (SDM) and similar approaches (Maguire 2004; Irwin et al. 2011; Woodford et al. 2016). Structured decision making is an inclusive, participatory approach that uses a formal framework to help managers make informed choices using results from quantitative models that reflect key population processes and uncertainties (Irwin et al. 2011). As such, SDM holds promise for resolving complex problems in natural resource management by explicitly evaluating trade-offs in management options. The SDM approach has recently been applied in the Chesapeake Bay region to recommend actions that support oyster restoration and improve management (OysterFutures Stakeholder Workgroup 2018).

Above all, management of Blue Catfish in the region should be characterized by flexible, consistent policies and well-considered approaches that have quantifiable likelihoods of success. Attempts to reconcile conflicting objectives by finding a middle ground that is not supported by science or fully endorsed by all stakeholders could backfire and promote a lack of acceptance, erosion of trust in management institutions, and recurring conflicts (Ellender et al. 2014). Open dialogue and shared knowledge facilitated through a decision analysis framework appear to constitute a viable approach to solving the wicked problem of invasive Blue Catfish in the Chesapeake Bay region.

ACKNOWLEDGMENTS

We thank the ICWG members for insightful discussions, particularly Bruce Vogt (National Oceanic and Atmospheric Administration, Chesapeake Bay Office), Martin Gary (Potomac River Fisheries Commission), and Mary Groves (Maryland Department of Natural Resources). Three anonymous reviewers provided thoughtful suggestions that improved the presentation of this case study. Funding for the research conducted by the Fabrizio Lab at the Virginia Institute of Marine Science was provided by the National Oceanic and Atmospheric Administration's Chesapeake Bay Office, U.S. Fish and Wildlife Service, Virginia Marine Resources Commission, and Virginia Sea Grant through a graduate research fellowship to V.N. The views expressed in this paper represent those of the authors and do not necessarily reflect the views of our funding agencies or partners. There is no conflict of interest declared in this article.

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