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INVITED PAPER

Harvest of Northern Snakehead with Bowfishing in Maryland

Joseph W. Love[*,1], Joshua J. Newhard[†], Shannon J. Amato[†], Meghan Walker[†] and Jason Hanlon[†]

[*]Maryland Department of Natural Resources, Fishing and Boating Services, 580 Taylor Avenue, B-2, Annapolis, MD 21401, USA; [†]U.S. Fish and Wildlife Service, Maryland Fish and Wildlife Conservation Office, 177 Admiral Cochrane Drive, Annapolis, MD 21401, USA

[1]E-mail: joseph.love@maryland.gov

Synopsis Illegal introductions in North America have helped establish populations of Northern Snakehead (*Channa argus*), an invasive freshwater fish from Asia. Once targeted for eradication, widespread establishment of populations in the Chesapeake Bay watershed has now led management to prioritize mitigation. One method of mitigation has been harvesting via bowfishing. We measured the influence of bowfishing in the snakehead fishery between 2022 and 2024. Ten charter boat captains who operated bowfishing trips across 17 rivers in 2024 provided 556 trip reports for snakehead trips (March to November) that represented an average of four bowfishing clients (range = 1 client to 12 clients) who fished an average of 4.8 hours (standard error = 0.05) per evening trip (high ebb to slightly beyond low tide). Harvest ranged between 0 fish and 32 fish per river-trip, with an average median of 10 fish (standard error = 2.7). Harvest was greatest in spring and fall (3.5°C < air temperature < 17°C) and full or new moons. Bowfishing and gigging accounted for the majority of annual fishing mortality, which was 19.1% in 2023 and 20.0% in 2024. This was lower than the target of 25% to achieve population declines. Our results highlight both the value of bowfishing and the need to encourage bowfishing as means of harvesting snakeheads in ecosystems.

Introduction

Northern Snakehead (*Channa argus*) is an invasive, freshwater species that has been introduced into North America from Asia (Courtenay and Williams 2004). Northern Snakehead consumes numerous types of prey (Saylor *et al.* 2012) and could cause declines in species diversity (Newhard *et al.* 2024) depending in part on the population's biomass (Love and Newhard 2021). Following their discovery in the Potomac River in 2004 (Odenkirk and Owens 2007), the species is found in every major river drainage of the Chesapeake Bay (Love and Newhard 2018). The species occurs in freshwater and oligohaline habitats that include wetlands and swamps, tidal freshwater rivers, lakes, and high-order streams. To help lower biomass in these ecosystems, outreach and incentives have been used to increase informed participation in the harvest fishery in Maryland (Love and Genovese 2018). Agency-led harvest may not be sufficient for reducing biomass of invasive fish (Zelasko *et al.* 2016). Recreational and commercial harvest has been increasingly encouraged to lessen biomass and consequently, mitigate impacts from invasive fishes (Pasko and Goldberg 2014; Newhard *et al.* 2019). Harvest has periodically reduced the abundance of Northern Snakehead in streams of the Potomac River (Odenkirk and Isel 2016; Newhard *et al.* 2019). Even so, harvest levels within a fishery may be difficult to maintain over time when fish become harder to capture and effort wanes. Monetary incentive programs have been used to encourage the public to remove select invasive species. Incentives supporting fishing derbies and contracts for commercial harvest of invasive fishes have helped control biomass of Red Lionfish *Pterois volitans* in the southwest Atlantic Ocean (Hoag 2014; Smith *et al.* 2023), Silver Carp *Hypophthalmichthys molitrix* and Bighead Carp *H. nobilis* in the Midwest (Altenritter *et al.* 2022), and Northern Pikeminnow *Ptychocheilus oregonensis* in the western United States (Friesen and Ward 1999). Here, we used incentive-based projects to lower biomass of Northern Snakehead and to obtain fishery-dependent data.

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Beginning in spring 2022, the Maryland Fish and Wildlife Conservation Office (MDFWCO) and the Maryland Department of Natural Resources (MDNR) began new initiatives to incentivize harvest of Northern Snakehead in the Chesapeake Bay watershed. A commercial market currently incentivizes harvest, but anecdotal data indicated that un-incentivized recreational bowfishing eclipsed those harvest efforts. Beginning in 2010 bowfishing tournaments began to focus effort on harvesting snakehead and since then, bowfishing for snakeheads has become more widespread in Maryland. Bowfishing has been popular worldwide for centuries and is growing in popularity in the United States (Scarnecchia and Schooley 2020). Commonly targeted fishes during bowfishing include ones of management and conservation interest, such as Alligator Gar *Atractosteus spatula* (Bennett *et al*. 2015), other gar species (*Lepisosteus* spp.), and suckers (F. Catostomidae), specifically buffalo *Ictiobus* spp. and redhorse *Moxostoma* spp. (Quinn 2010). As Northern Snakehead spread and became abundant in tidally influenced freshwater rivers of Maryland's Chesapeake Bay, bowfishers targeted the species because of its large size (up to 9.5 kg; unpublished data, MDNR), its vulnerability in occupied shallow shorelines and vegetation (Lapointe *et al*. 2010; Love *et al*. 2015), its distinctive coloration, and its unlimited take by size or creel in the watershed. While annual fishing mortality can be attributed to agency, commercial, and recreational biomass reduction efforts, the relative impact owed to bowfishing had not been measured owed to poor monitoring of that aspect of the fishery. Because of the small fraction of bowfishers relative to hook-and-line anglers, documenting the relative contributions of each aspect in the fishery to harvest can be important for future mitigation strategies.

Our work supported actions to incentivize and document harvest identified in national (SPDC 2014), regional (CBNSWG 2023), and state management plans (MDNR 2016). We achieved two primary objectives: 1) to measure and document environmental and effort conditions during bowfishing harvest of Northern Snakehead; and 2) to measure the relative contribution of bowfishing to the annual harvest of Northern Snakehead. We examined environmental and effort conditions during bowfishing to determine if they should be considered covariates to harvest in mitigation strategies and to identify optimal conditions for harvesting Northern Snakehead. Our ancillary objectives included examination of the efficacy of a diary survey and generating tag reporting rates for bowfishing and hook-and-line fishing in the upper Chesapeake Bay. Achieving these objectives was critically important for the upper Chesapeake Bay where outreach and incentives have been less focused because of its more recent discovery in 2015. The upper Chesapeake Bay also serves as a gateway to other states via the Susquehanna River and the Chesapeake-Delaware Canal. Therefore, the importance of the work extended to prevention efforts in Delaware, Pennsylvania, New Jersey, and New York. Additionally, Northern Snakehead has also been introduced into Mississippi River basin, where bowfishing may help control biomass, but is understudied relative to angling in North America.

Methods

Charter boat diary–procedure

We chartered two charter boat captains between April and July (2023) to conduct 29 bowfishing trips ($1,300/trip) that targeted Northern Snakehead on Potomac River ($n = 14$), Gunpowder River ($n = 11$), and Susquehanna River ($n = 4$). In 2024, we chartered captains for an additional seven boat trips on Susquehanna River ($n = 4$) and Nanticoke River ($n = 3$). The price for these chartered trips was similar to market price for a client-chartered bowfishing trip. During each chartered trip, we recorded the number and size of Northern Snakehead harvested with bowfishing. Captains brought expert shooters but also trained the participating staff in bowfishing. We collected additional details regarding weather, tidal stage, start and end time, water visibility, and the number of shooters. These data were collected to compare with trip reports by captains as part of an unstaffed diary project.

We paid 10 captains ($1,800/book) to record data in diary logbooks during unstaffed chartered bowfishing trips that targeted various freshwater fishes in multiple tidal freshwater rivers of the Chesapeake Bay watershed (Fig. 1). From these logbooks, we received a total of 599 reports between March and November (2024) to characterize the bowfishing fishery for Northern Snakehead. However, all species of harvested fish were tallied and reported. Reports were obtained from 17 tidal freshwater rivers within Chesapeake Bay watershed: Bohemia River ($n = 13$), Bush River ($n = 23$), Chester River ($n = 1$), Choptank River ($n = 5$), Elk River ($n = 7$), Gunpowder River ($n = 8$), Middle River ($n = 4$), Nanticoke River ($n = 31$), Patuxent River ($n = 8$), Potomac River ($n = 354$), Rappahannock River ($n = 45$), Sassafras River ($n = 1$), Smith Creek ($n = 1$), South River ($n = 1$), Susquehanna River ($n = 49$), Wicomico River ($n = 1$), and Wye Mills River ($n = 6$). We excluded 40 trips conducted in mesohaline habitats (i.e., Eastern Bay) because those purposely targeted Cownose Ray *Rhinoptera bonasus*. We also excluded one trip from an unspecified waterbody. Two additional trips in Potomac River and Nanticoke River were excluded because they were scouting trips. Therefore, we analyzed 556 trip

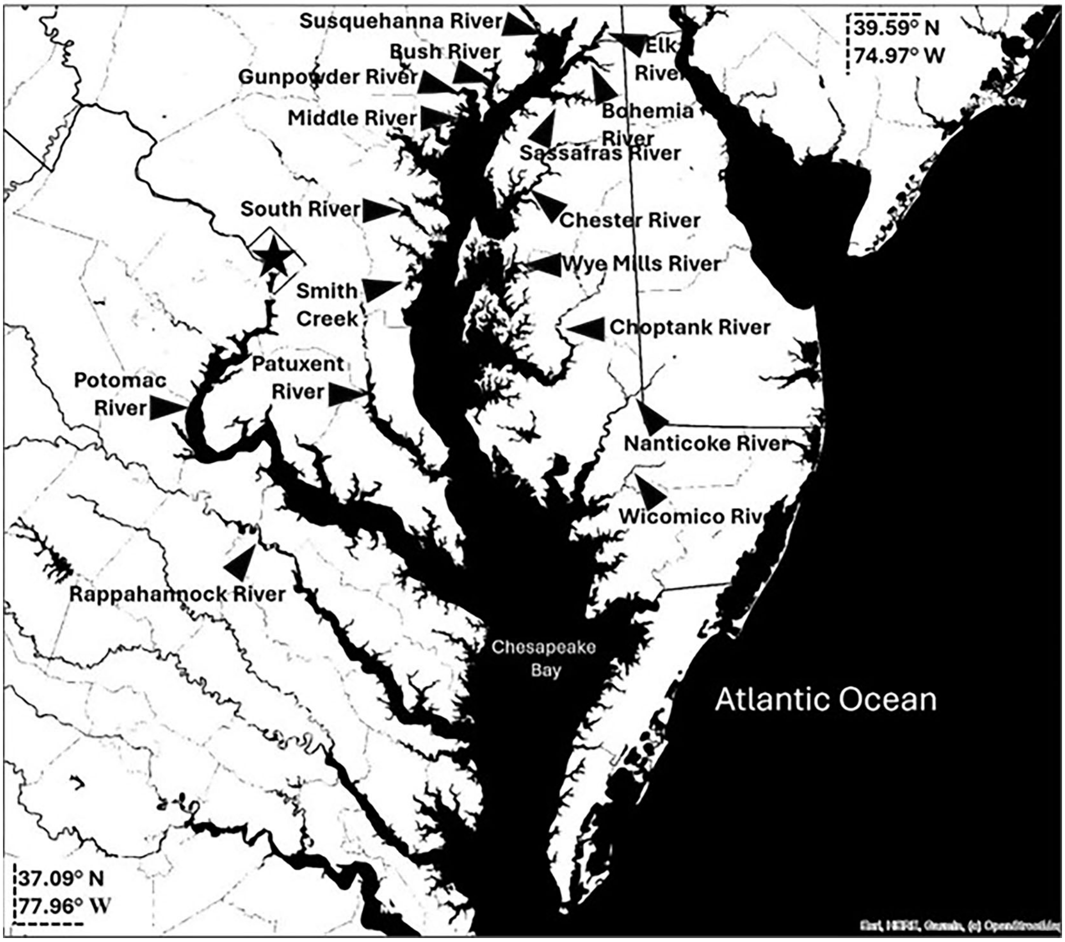

Fig. 1 Map of Chesapeake Bay watershed and river drainages where bowfishing had been reported by charter boat captains in 2024.

reports. Charter captains reported the number of each fish species harvested during each night, along with the number of shooters, the start and end times of the trip, and helpful notes regarding the fishing trip (e.g., "all trophy cats," "4 NSH seen. . .horrible choppy river," or "poor shooters."). On occasion, captains reported climatic conditions (wind speed and direction, air temperature) and time of low tide.

Charter boat diary–analysis

For staffed and unstaffed charter trips, we determined the total number of harvested fish per trip. We did not estimate harvest per shooter-hour because hunting is cooperative during a trip, the number harvested per shooter was not known, and shooters could not be treated analytically as independent observations. We calculated the median harvest per trip across trips for all staffed and unstaffed charter trips taken on each of the Potomac River, Gunpowder River, Nanticoke River, and Susquehanna River. These reasonably isolated fisheries represented both the western and eastern shores of the Chesapeake Bay, and the upper Chesapeake Bay (Fig. 1). In addition to the medians, we computed 25th and 75th percentiles for the unstaffed chartered trips per river system. When we observed that the median for the staffed charter trip fell outside of the percentiles for the unstaffed charter trips, then we concluded harvest meaningfully differed between staffed and unstaffed trips. We determined if such differences occurred because of under-reporting owed to fear that regulatory agencies might impose harvest restrictions.

We also examined the relationship between bowfishing harvest and fishing conditions to identify conditions associated with high and poor harvest. The predictor variables describing fishing conditions in our analysis included available data: 1) the number of shooters; 2) the time spent bowfishing; 3) average wind velocity (m/s); 4) total precipitation (mm); 5) lunar phase (%); and 6) air temperature (average). For consistency in reporting, we utilized only data reported during the diary program for unstaffed bowfishing trips. The time spent bowfishing and the number of shooters were reported by captains participating in the charter boat diary survey. Though captains occasionally reported measurements for climatic variables, to produce a robust dataset of climatic observations, we exclusively used data downloaded from RAWS USA Climate Archive (Western Regional Climate Center, Desert Research Institute; Reno, Nevada) for Patuxent River (Chesapeake Bay watershed). The data included: daily wind velocity, total precipitation, and air temperature. Data for lunar phase for each bowfishing day was downloaded from the Scientific Visualization Studio of NASA (https://svs.gsfc.nasa.gov/). Most climatic variables likely differed across specific fishing sites and during fishing, potentially causing problems with accurate, fine-scale predictions; and therefore, we limited our interpretation to general patterns rather than precise numerical thresholds.

Bowfishing harvest per trip (dependent variable) was related to predictor variables using rpart and rpart.plot in R (Breiman *et al.* 1984; Therneau and Atkinson 1997).We subjected data to classification and regression tree methods that compartmentalized variance in the dependent variable by subdividing data into two groups at a decision node, and so on until forming terminal nodes (or leaves). Subdivision reached a maximum threshold of complexity that minimized model error or mean square error (MSE). Because the dependent and predictor variables were continuous variables, we used a regression tree that subdivided data at nodes, which were defined by a quantitative predictor condition. The predictor condition defined the split at the node as either greater or less than the value of the predictor. We divided predictors into either primary if defining the first node of the branching tree, or secondary if further subdividing the data. A variable's importance (or G) in subdividing the dataset was determined as the sum of the goodness of the split in the primary node and the goodness for all subsequent splits in which it was surrogate (Therneau and Atkinson 1997). Values for G were scaled as a percentage and the greatest percentage reflected the greatest importance. The resulting tree was assessed for overcomplexity and consistency.

We assessed overcomplexity of branching in the regression tree by comparing its structure with a pruned tree that had less complexity. The size and complexity of the tree was controlled by a complexity parameter (cp) with an aim to split the tree just enough to minimize the reduction in MSE. We split the tree until the cp was minimized to 0.008, which allowed for a complex tree that had multiple splits. However, cp was allowed to vary in model development so that the best cp could be evaluated in order to prune the tree. For the best cp, the MSE of the pruned true was compared with the original tree and the tree with the lowest MSE was chosen to represent the relationships in the dataset.

We assessed the ability of the dataset to produce consistent splits by subsampling the data and creating training and testing datasets. Because missing values in the dataset, as well as anomalous observations, can affect the structure and complexity of the tree, we tested the repeatability of the tree by randomly subsampling 70% of the observations ($n = 390$) and designating them as the training dataset. We also randomly subsampled 100 observations from the remaining 30% of the dataset to create a training dataset. Twenty training datasets were created using this procedure to generate a forest. We compared the structure of the tree derived from the training dataset against trees in the forest. For each tree in the forest, we tallied the predictor type of the primary node and secondary nodes. We determined the greatest proportions of predictor types for primary and secondary nodes and hypothesized no difference between those identified when using testing datasets from those derived using the training dataset.

Survey and tagging-procedures

We used an incentivized mark-recapture project to assess the relative contributions of harvest by bowfishing and other sources of fishing mortality for Northern Snakehead. These other sources of fishing mortality could include harvest by agencies, hook-and-line, gigs, and commercial harvesters. Because gigs or prongs are often used to impale fish similar to bows in bowfishing, we combined harvest with gigs with the harvest from bowfishers. To tag fish we collected Northern Snakehead using directed boat electrofishing (Smith-Root, Inc. GPP 9.0 or Apex Generator; 30–60 pps; 100–640 Volts) between May and November in 2022 (April–October) and 2023 (February–December) in tidal freshwater of Gunpowder River, Middle River, Bush River, lower Susquehanna River, Swan Creek and Furnace Bay, Northeast River, Elk River and Sassafras River (Fig. 1). Fish were removed from the water and immersed in a live well where they recovered from electrotaxis before being measured, tagged, and released. We tagged all snakeheads greater than 250 mm. Tagging needles directed Floy tags (Floy FD-94 Anchor Tags, 16 mm, mono extra-long T) into the dorsum and below the dorsal fin to set the tag between the pterygiophores of the fin. Of all 925 tagged fish between 2022 and 2023, 30% of them had high reward tags (i.e., "$200 reward") and the rest with standard or low reward ("$10.00 reward"). All tag reporters were required to submit a photo of the harvested fish and the tag as verification before a check was issued. All reporters also received outreach to support the harvest of Northern Snakehead, including a hat and certificate with information about their fish.

Survey and tagging-analysis

We computed the standard tag reporting rate (λ) as:

$$\lambda = \frac{R_s N_r}{R_r N_s}, \quad (1)$$

where R_s is the number of standard tags returned, N_s is the number of standard tags released, R_r is the number of high reward tags released, and N_r is the number of high reward tags released (Pollock *et al.* 2001). We assumed that $200 was sufficient incentive for harvesting Northern Snakehead and achieving 100% reporting because studies indicate such a high level of reward effectively works (Taylor *et al.* 2006; Meyer *et al.* 2012). If high-reward reporting does not equal 100%, then estimates of fishing mortality may be negatively biased. We also assumed no tag loss during this time period because previous work had demonstrated high tag retention (Amilhat and Lorenzen 2005) and consequently, has not been included when estimating population sizes of Northern Snakehead using tag reporting (Odenkirk and Isel 2016; Newhard *et al.* 2019). Most fish were reported and verifiably harvested. We excluded four tagged and reported snakeheads from our analysis because they were released alive.

Depending on the number of harvested tags and λ, we computed the proportion of harvested fish, or annual fishing mortality (μ) for specific years of interest (i). Annual fishing mortality was a proportion of the number of harvested tags (t) in year (i) to the number of available tags in the population (T) corrected for reporting rate:

$$\mu_i = \frac{t_i}{(T \times \lambda)}, \quad (2)$$

Annual fishing mortality was calculated for reporting years of 2023 (μ_{2023}) or 2024 (μ_{2024}). Because both tagging and harvest occurred throughout the tagging years of 2022 and 2023, we needed to reduce the number of tagged fish by the number of harvested fish during the tagging years, resulting in the number of available tagged fish for the start of the reporting year. We used the pool of 2022-tagged fish that were available (i.e., unharvested) at the beginning of the reporting year, 2023. For the reporting year of 2024, we obtained three estimates of μ depending on how we structured the tagging year sample pool: (1) tagging year of 2022 and available fish for the beginning of 2024; (2) tagging year of 2023 and available fish for the beginning of 2024; and (3) tagging years of 2022 and 2023 and available fish for the beginning of 2024. We computed μ for 2024 from three tagging pools because estimates of μ could be influenced if assumptions noted above (e.g., tag loss, tag reporting) were violated. Given our rationale above regarding tag loss and tag reporting bias, we predicted that variation in μ among these three calculations would not be biologically meaningful. We were unable to calculate μ within a year because tagging occurred throughout the year and the length of time tagged fish were available for harvest within a year differed; instead, we decided to examine the data between tagging years and reporting years, assuming that all available tagged fish at the beginning of a reporting year would be available to harvest for a full year.

We computed μ for each mode of harvest (h), which included bowfishing, gigs, and hook-and-line fishing, depending on the number of harvested tags by mode (t_h) in year (i) and a reporting rate calculated for the mode of harvest (λ_h). Therefore, to calculate μ we modified equations [1] and [2] to calculate μ for a specific year of interest and mode of harvest as:

$$\mu_{ih} = \frac{t_{ih}}{(T \times \lambda_h)}, \quad (3)$$

We summed μ_{ih} across modes of harvest to report μ_i for a year of interest (i.e., 2023 or 2024). The percentage of μ_i ascribed to h was calculated by dividing μ_{ih} by μ_i and multiplying by 100.

Results

Charter boat diary

Ten charter boat captains who operated unstaffed bowfishing trips in 2024 from 17 major tidal freshwater rivers in Chesapeake Bay watershed (Fig. 1) provided 556 trip reports (March to November) that represented an average of four bowfishing clients (range = 1 client to 12 clients) who fished an average of 4.8 hours (standard error = 0.05) per evening trip (high ebb to slightly beyond low tide). People reportedly harvested 4,056 snakeheads and an average median across major river systems of 10 snakeheads per trip (standard error = 2.7) (Table 1). Harvest did not vary with the number of people but was greater for trips longer than 5 hours (Fig. 2).

Staffed charter boat trips resulted in harvesting 425 adults that differed in size among rivers (total length, $F_{3,419} = 10.04$, $P < 0.0001$; mass, $F_{3,419} = 13.73$, $P < 0.0001$). Average sizes of snakeheads from Gunpowder River (total length = 599 mm, standard error = 8; mass = 2.2 kg, standard error = 0.1) and Potomac River (total length = 601 mm, standard error = 14; mass = 2.1, standard error = 0.1) were less than for Nanticoke River (total length = 660 mm, SE = 27; mass = 2.8 kg, standard error = 0.3) or upper Chesapeake Bay (total length = 667 mm, SE 10; mass = 3.2 kg, standard error = 0.1). Averaging across rivers, snakeheads globally averaged a total length of 632 mm and a mass of 2.6 kg.

The average median number of snakeheads harvested during staffed charter boat trips ranged between 2

Table 1 Staffed and unstaffed bowfishing trips harvesting Northern Snakehead *C. argus* from rivers of the Chesapeake Bay watershed (United States) in 2023 and 2024.

Trip	River	Nu. of trips	Total harvest	Median harvest
Staffed	Potomac	14	60	2
Staffed	Gunpowder	11	204	17
Staffed	Susquehanna	8	145	16
Staffed	Nanticoke	3	16	5
Average		**9**	**106**	**10**
Unstaffed	Potomac	354	1664	1
Unstaffed	Gunpowder	8	132	17
Unstaffed	Susquehanna	49	340	3
Unstaffed	Nanticoke	31	328	8
Unstaffed	Bohemia	13	168	11
Unstaffed	Bush	23	320	11
Unstaffed	Chester	1	0	0
Unstaffed	Choptank	5	0	0
Unstaffed	Elk	7	208	19
Unstaffed	Middle	4	117	32
Unstaffed	Patuxent	8	34	1
Unstaffed	Rappahannock	45	582	9
Unstaffed	Sassafras	1	13	13
Unstaffed	Smith Creek	1	0	0
Unstaffed	South	1	42	42
Unstaffed	Wicomico	1	5	5
Unstaffed	Wye Mills	6	65	12
Unstaffed	Unspecified	1	4	4
Average		**31**	**223**	**10**

snakeheads per trip (Potomac River) to 17 snakeheads per trip (Gunpowder River) (Table 1). Average medians did not differ from those reported during the unstaffed charter trips for the same rivers, Potomac River (median = 1; percentiles: 0, 7), Gunpowder River (median = 17; percentiles 7, 22), or Nanticoke River (median = 8; percentiles: 5, 11) (Table 1). The average median harvest per staffed charter trip for Susquehanna River (median = 16); however, was greater than that for unstaffed charter trips (median = 3; percentiles: 0, 10). Therefore, for most river fisheries, the average median harvest per unstaffed charter trip was similar to the average median harvest per staffed charter trip.

Average harvest was predicted by six environmental variables during chartered trips (Fig. 3). The full dataset yielded 15 splits based on these environmental variables (MSE = 83.8; cp = 0.008). Time spent bowfishing defined the primary node. When the time spent bowfishing was above 5.4 hours, average harvest was greater (Fig. 3), particularly when the number of shooters exceeded five; but these conditions did not frequently occur among trips (see Fig. 2); neither time nor the number of shooters caused many splits within the regression tree (G = 18% and 8%, respectively). Secondary splits for daily air temperature (G = 20%) and total precipitation (G = 16%) tended to importantly direct trends in bowfishing harvest. Bowfishing harvest was at least double (on average) when air temperatures were lower than 17°C (i.e., spring and fall) and during days with low precipitation less than 11.1 cm. During these days of low precipitation, average harvest was moderately less during nights with light winds (wind velocity < 2.2 kph) and summer (wind velocity < 1.3 kph) (Fig. 3). Similar to precipitation, wind velocity accounted for a moderate level of splitting in the regression tree (G = 15%). When air temperature was lower than 17°C, average harvest doubled around full moons (lunar phase > 0.97) and new moons (lunar phase < 0.05), which are periods of spring tides. This pattern was not as well-identified during summer when air temperature exceeded 17°C, but average harvest during trips with precipitation less than 1 cm tended to have the greatest average harvest around new moons (1.5%<lunar phase < 8.5%).

While assessing the complexity of the regression tree, we observed that the best pruned tree yielded two splits and two variables, which were time spent bowfishing

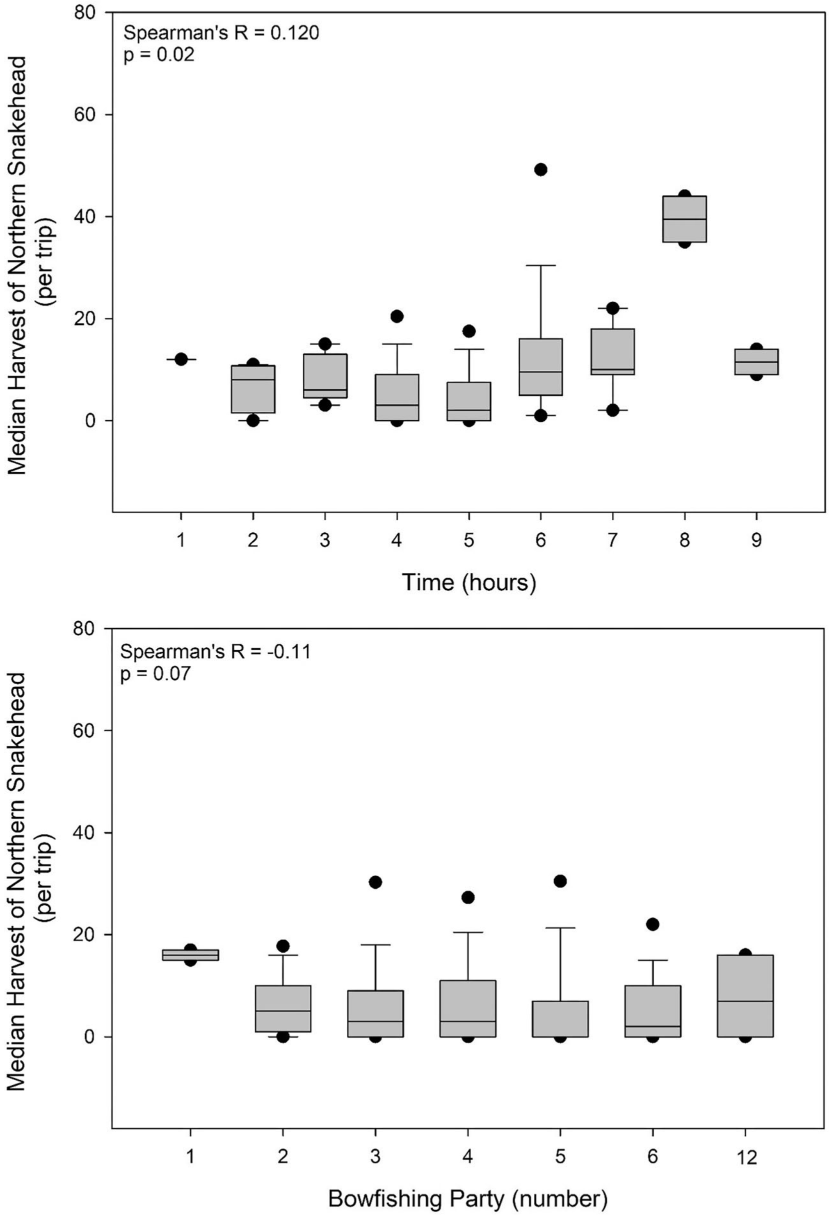

Fig. 2 Box plot with median harvest (line in box) of Northern Snakehead *C. argus* reported by captains in 2024 during bowfishing trips that differed in time of fishing (upper figure) and number of shooters in the bowfishing party (lower figure). Whiskers of box represent 25th and 75th percentiles and black dots represent range of values. Spearman's correlation relates either time or number of shooters to median harvest (upper left corner of the graph).

(primary node) and air temperature (secondary node). However, based on its lesser ability to resolve patterns in the data (MSE = 101.5; cp = 0.023), the pruned tree was not considered a better tree. We also assessed the ability of our dataset to produce consistent results. The training model tree with 12 splits (MSE = 125.6; cp = 0.008) had three variables with the greatest influence: air temperature (G = 31%), wind velocity (G = 24%), and lunar phase (G = 15%). Additional variance in harvest was owed to the number of shooters (G = 12%), time (G = 11%), and precipitation (G = 6%). Across the 20 forest trees, air temperature (10 trees) and lunar phase (9 trees) commonly resolved as primary and secondary nodes, respectively. Time was also identified in the forest as an important secondary node, but for just one tree. Because primary and secondary nodes in the forest matched those of the training model, we concluded that our dataset was robust to observational error and that the unpruned tree reflected a robust representation of the dataset.

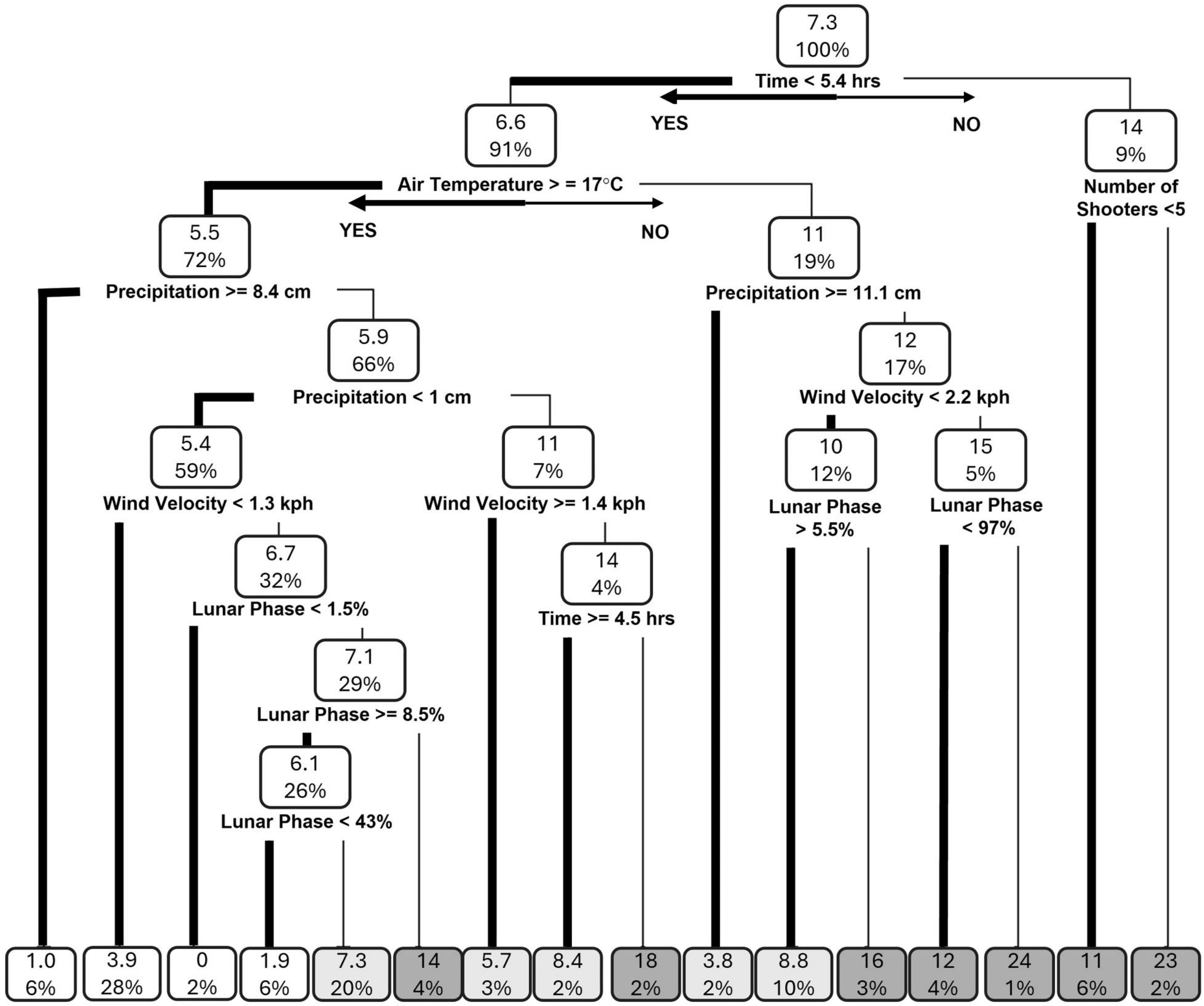

Fig. 3 Regression tree analysis of the number of harvested Northern Snakehead *C. argus* as reported by charter boat captains in 2024 during bowfishing trips that differed in the shooter number, time of fishing, and environmental conditions (air temperature, wind velocity, lunar phase, and precipitation). Harvest was divided into subsets of observations using a series of decisions from bowfishing conditions noted at each split. Average harvest for each subset is given in the box along with its percentage of observations within the subdivided dataset. Greater averages are depicted with darker shading of terminal nodes or boxes.

Survey and tagging

We received 149 reported tags of the 657 tagged snakeheads across the survey period between 2022 and 2024. Of these, 67 were high-reward tags and 82 were standard tags. The vast majority of reported snakeheads had been harvested. However, four snakeheads with standard award tags were released alive by hook-and-line anglers, two of which had been caught by anglers targeting either Black Crappie (*Pomoxis nigromaculatus*) or Largemouth Bass (*Micropterus nigricans*) in Gunpowder River; the remaining two had been caught by anglers targeting Northern Snakehead in Gunpowder River and upper Chesapeake Bay. The majority of tags had been reported from Gunpowder River ($n = 66$) and evenly reported between Sassafras River ($n = 28$) and upper Chesapeake Bay (including Northeast River and Susquehanna River, $n = 26$); the fewest came from Elk River ($n = 16$), Bush River ($n = 12$), and Middle River ($n = 1$). Most fish (91%) were reportedly caught within the drainage that they were tagged, with 13 fish caught in a neighboring drainage and 1 fish caught in the neighboring Delaware Bay watershed.

Recreational bowfishers reported the harvest of 80 of the 149 tags with bows and two with a gig. Hook-and-line anglers captured and harvested 65 snakeheads. The fish harvested by bowfishing and gig were larger (average total length = 644 mm, standard error = 13; average mass = 3208 g, standard error = 234) than those harvested using hook and line (average total length = 599 mm, standard error = 15; average mass = 2546 g, standard error = 227). Two additional fish tagged in 2022

Table 2 Northern Snakehead *C.argus* tagged with high and standard reward tags in Chesapeake Bay (Maryland, United States) in 2022 and 2023 were reportedly harvested by various modes including bowfishing (B), gig (G), hook-and-line anglers (H–L), or reported in a fish lift (FL) at Conowingo Dam in order to compute reporting rate (λ), annual fishing mortality or exploitation (μ), and the % of fishing mortality owed to each mode of fishing.

Tag year	Rep year	Tags	λ	μ	% B or G	% H-L	%FL
2022	2023	270	0.54	19.1%	63%	37%	0%
	2024	242	0.26	17.8%	88%	12%	4%
2023	2024	415	0.54	22.0%	52%	43%	0%
2022/23	2024	657	0.43	20.3%	60%	40%	1%
Average	2024	438	0.41	20.0%	67%	32%	2%
Average	2023/24	354	0.48	19.5%	65%	34%	1%

(one high reward, one standard award) had been harvested and reported in 2024 by operators of a fish lift at Conowingo Dam on the lower Susquehanna River. These fish were excluded from reporting rate calculations because λ was assumed to be 1.0. Relative reporting of high and standard tags yielded an λ of 0.54 in 2023 and an average λ of 0.41 in 2024 (range: 0.26 to 0.54; average = 0.48) and was similar between those harvesting with bow or gig and with hook and line (Table 2).

After adjusting for reporting rate, annual fishing mortality estimates were similar between reporting years 2023 ($\mu_{2023} =$ 19.1%) and 2024 (average μ = 20.0%, standard error = 1.2). For the 2024 reporting year, whether the tagging year included just 2022,2023, or both 2022 and 2023 data, similar (but not identical) levels of annual fishing mortality occurred (Table 2), suggesting little bias related to tag loss or reporting among years. The majority of annual fishing mortality was partitioned to bowfishing and gigging (μ > 52%; average = 60.5%), with less owed to hook-and-line harvest (12% – 43%; average = 34.3%), and the least to the fish lift at Conowingo Dam (average = 1%) (Table 2).

Discussion

Harvest of Northern Snakehead in the recreational fishery of the upper Chesapeake Bay reduced both the numbers of total and large fish in populations. The majority of fish caught and reported had been harvested by hook-and-line anglers and bowfishers. As in hook-and-line fisheries, bowfishing harvest depended on effort (fishing > 5.5 hour; shooters > 5 people). These long trips were uncommon and many snakeheads were also harvested within a shorter duration. In addition to effort, bowfishing harvest depended on daily and seasonal climatic conditions during trips. More snakeheads were harvested during greater wind velocities, which possibly pushed boats further and faster to increase the probability of encountering a fish. People did not harvest many snakeheads when it was raining, which likely reduced visibility of fish. Harvest also varied with the number of snakeheads in the fishing area. More snakeheads were harvested during spring and fall, both seasons associated with reproduction (Odenkirk and Owens 2007) that involves active selection of vegetated habitat (Lapointe et al. 2010). Rainfall during spring and fall may also be associated with exploration behavior because Love and Newhard (2018) found that it related positively to the rate of colonization in Chesapeake Bay. Snakeheads pair themselves in predictable habitats for spawning and may become denser during these times. Northern Snakehead may also become denser during new or full moons, periods that also yielded greater harvest. Because new and full moons are associated with spring tides that cause lower, low tides, snakeheads could have become denser in channels of tidal streams as water drained from the wetlands. Lapointe et al. (2010) noted the occurrence of snakeheads in shallow and vegetated, stream-side habitats during low tide, which could increase density and the probability that a shooter would encounter a fish. These bowfishing patterns may also be applicable to hook-and-line angling; while analogous hook-and-line data were not available for analysis, season, habitat, and tide likely influenced harvest for that fishery because of their relationship to natural history.

Bowfishing has grown in popularity in the United States, in part because of its low entry cost and expanding opportunities (Scarnecchia and Schooley 2020). These opportunities have included agencies creating reservoirs with ideal conditions for shooting and maintaining species that lack possession limits. As with its gain in popularity, positive and negative consequences have been identified in management (Scarnecchia and Schooley 2020). Bowfishing provided a novel, essential service in reducing biomass of Northern Snakehead in the Chesapeake Bay watershed. One positive consequence of bowfishing was that it accounted for a greater percentage of annual fishing mortality than hook-and-line harvest. Another positive aspect of bowfishing was its harvest of larger fish than taken during fishing with a hook and line. Larger fish can be more easily seen and killed by bowfishers (Scarnecchia and Schooley 2020). The removal of larger adults could reduce recruitment because larger females produce more ova (Love 2024) and because bowfishing often harvests sexually mature fishes (Quinn 2010). Additionally, fewer mature adults in the population could increase mate searching time and have other recruitment-limiting effects. Such Allee effects have proven useful with invasive species management because they lower population persistence (Tobin *et al.* 2011).

Negative consequences of encouraging greater bowfishing effort include wanton waste and illegal fishing. After being shot during bowfishing, targeted fish have a high, near 100% probability of death (Montague *et al.* 2023). Illegally shot fishes that are protected by regulation or law have been reported broadly across the United States (Scarnecchia and Schooley 2020), including Maryland where Largemouth Bass *Micropterus nigricans* adults have been observed dead with holes through the body (pers. obs. JWL). Wanton waste occurs when gamefish or sportfish die without subsequent benefit. Nationwide attention from animal rights activists protested high levels of unregulated harvest for Cownose Ray during bowfishing tournaments, ultimately leading to a call for the ban of these tournaments (Kobell 2015) and prompting the development of a fishery management plan. Longnose Gar *Lepisosteus osseus* has also been wantonly abandoned at boat ramps and dirt roads (pers. obs., JWL), leading to more restrictive creel limits in the Chesapeake Bay watershed. During our study, Cownose Rays *Rhinoptera bonasus* (n = 1,166) and Longnose Gar (n = 560) were reportedly harvested using bowfishing, though the disposition of those fish is unknown. In general, the majority of fish reportedly harvested with bowfishing were not illegally shot and included non-native and unmanaged species: Blue Catfish *Ictalurus furcatus* (12,788 individuals), common carp *Cyprinus carpio* (n = 1,494), Goldfish *Cyprinus auratus* (n = 661), Grass Carp *Ctenopharyngodon idella*, (n = 4), and Flathead Catfish *Pylodictis olivaris* (n = 2). Consistent and massive outreach could stymie illegal fishing and wanton waste before it occurs. Significant effort has reduced unwanted mortality in popular sport fisheries (Siepker *et al.* 2007; Keretz *et al.* 2018; LaRouchelle *et al.* 2022) and arced angler behavior toward conservation practices (Gilliland *et al.* 2002). Because illegal fishing and wanton waste appear relatively rare, using outreach to limit them would benefit from local bowfishing communities being vigilant in self-policing.

Love and Genovese (2018) noted several ways MDNR has incentivized and promoted harvest of Northern Snakehead in Chesapeake Bay, including fishing awards, prizes, and recognition. When MDNR began tracking reports of snakeheads from the public, people who harvested and reported a snakehead qualified for entry into raffles for gift cards. As populations of snakeheads became established, MDNR incentivized harvest of large snakeheads with a newly created category for fishing challenge and state record recognition. The invasive fish category required people to harvest their fish to qualify for recognition. Additionally, MDNR provided awards and organized fishing derbies and tournaments aimed at educating the general public, encouraging harvest, and beneficial use of Northern Snakehead. These actions helped to inform the general public of the fishery as well as direct attention toward harvest, which helped to establish the public awareness necessitated for the work presented here. Other agencies have launched similar initiatives and assigned value to harvesting invasive species. As Lionfish *Pterois* spp. spread its distribution throughout the Atlantic Ocean and Gulf of Mexico, sponsored fishing derbies required harvest and removal of lionfish from reefs to support management and conservation goals (Hoag 2014). Assigning value to invasive fish harvest by investing in the culinary industry has also been done to create long-term harvest incentives (Smith *et al.* 2023). For example, significant investment into changing the name from Silver Carp or Bighead Carp to "Copi" aimed to encourage consumption (Garvey *et al.* 2024). Pasko and Goldberg (2014) cautioned against actions that assign value to an invasive fish because they can lead to unintended consequences, such as illegal introductions and calls to manage the species as a sustainable fishery. As invasive lionfish (*Pterois* spp.) becomes the focus of a culinary market, managing biomass optimally for both suppression and sustainability may become necessary (Bogdanoff *et al.* 2020). Additionally, encouraging harvest with deficient natural historical information on population growth may be counterproductive (Zipkin *et al.* 2009). Harvest of invasive common carp resulted population growth because of recruitment compensation (Weber *et al.* 2016). To date, Northern Snakehead has not increased in population size where intensively harvested (Odenkirk and Isel 2016; Newhard *et al.* 2019) and has a mix of natural history attributes that suggest its population will decline with the harvest of large adults (Love 2024).

Sources of annual fishing mortality other than recreational harvest exist for Northern Snakehead in Chesapeake Bay. Commercial harvest has increased from 0.45 kg in 2011 to 4,216 kg in 2024. No tagged snakeheads were reportedly harvested during commercial fishing. Commercial harvest was similar to that estimated for fish lift operations at Conowingo Dam in 2024 (2,084 adults x 2 kg/fish = 4,333 kg; unpublished data, JWL), which accounted for 1% of harvest. Therefore, commercial harvest may contribute a similar percentage to annual mortality. Agency boat electrofishing has also been used in targeted areas to harvest snakeheads. No tagged snakeheads were harvested during boat electrofishing for this work. Daytime boat electrofishing between 2019 and 2024 harvested between 1 and 9 snakeheads per trip with an average median of 4 (standard error = 1.9) (unpublished data, JWL), which would amount to an even smaller number of harvested snakeheads than commercial harvest throughout the year. While commercial and agency harvest contributed to annual fishing mortality, recreational harvest apparently contributed more. Within the recreational aspect of the fishery, bowfishing and gigging accounted for the majority of annual fishing mortality that approximated 20% in upper Chesapeake Bay. The target of 25% for fishing mortality has been associated with population declines (Newhard et al. 2019). Fishing and natural mortality (i.e., total annual mortality) for populations from Potomac River (Chesapeake Bay watershed) ranged between 22% and 43%, with fishing mortality for the same years ranging between 4% and 31%. Therefore, absent an increase in natural mortality, more and consistent work is needed to encourage harvest to increase fishing mortality.

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Supplementary Data

Supplementary Data available at *ICB* online.

Conflict of interest

The authors declare no conflicts of interest.

Data availability

The data underlying this article will be shared on request to the corresponding author.

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