Check for updates

Animal Conservation

ZSL

Animal Conservation. Print ISSN 1367-9430

Population viability analysis for the common mudpuppy: Assessing potential impacts of TFM lampricide bycatch

R. B. Wagner & W. E. Peterman

School of Environment and Natural Resources, The Ohio State University, Columbus, Ohio, USA

Keywords
Necturus maculosus; Sea Lamprey; Lampricide; PVA; Population Model; Pesticide Bycatch; TFM.

Correspondence
Ryan B. Wagner, School of Environment and Natural Resources, The Ohio State University, 2021 Coffey Rd, Columbus, OH 43201, USA.
Email: ryan.wagner2@wsu.edu

Editor: Jeff Johnson
Associate Editor: Thomas Tscheulin

Received 14 May 2024; accepted 26 August 2024

doi:10.1111/acv.12989

Abstract

Bycatch is one of the leading threats facing aquatic organisms, worldwide. Pesticide bycatch can occur when nontarget species are incidentally killed during chemical application targeting noxious species. The common mudpuppy (*Necturus maculosus*) is a river-dwelling salamander that is susceptible to bycatch from 3-trifluoromethyl-4-nitrophenol (TFM) applications. However, the long-term consequences of TFM bycatch on mudpuppy populations are not well understood. We used population viability analysis to reveal potential impacts of TFM application on a mudpuppy population in Ohio's Grand River under plausible bycatch scenarios. We found that the population was more sensitive to increased juvenile mortality and rapid declines occurred when both adults and juveniles were impacted at high bycatch rates (≥5% of the population) or more frequent TFM intervals (≥5 years). Our results suggest that continued use of TFM could pose a risk to mudpuppy population persistence if bycatch occurs at moderate to high levels and affects both juveniles and adults. Future TFM use and management decisions should be directed with these potential nontarget impacts in mind.

Introduction

Bycatch, or the incidental take of nontarget species, is a global biodiversity issue (Lewison *et al*., 2011). Imperiled species can rapidly decline when subject to bycatch pressure resulting in reduced long-term population viability. Fisheries' bycatch has been linked with population declines for several imperiled marine organisms including sea turtles, marine mammals, and seabirds (Lewison *et al*., 2004). Bycatch is particularly devastating for long-lived species that mature late in life, have low reproductive output, and have high adult survival. Even slight increases in mortality of sensitive age classes can have large population-level effects (Lewison *et al*., 2004). Bycatch research has primarily focused on large, marine vertebrates, but bycatch can be an issue for freshwater species as well. Understanding the effects of bycatch in freshwater systems is pertinent because freshwater environments are among the most imperiled ecosystems on earth, with a proportionally greater number of at-risk species (Raby *et al*., 2011; Collen *et al*., 2014). Freshwater environments are subject to bycatch from fisheries but also nontarget mortality from pesticides targeting noxious species.

The lampricide 3-trifluoromethyl-4-nitrophenol (TFM) has been used to control sea lamprey (*Petromyzon marinus*) in the Great Lakes of North America since 1958 (Applegate, Howell, & Moffett, 1961). Over 170 Great Lakes tributaries are treated with TFM on average once every 4 years (Christie & Goddard, 2003). TFM kills sea lamprey by decoupling mitochondrial oxidative phosphorylation (Wilkie, Holmes, & Youson, 2007; Birceanu *et al*., 2011), thus starving the body of ATP and leading to death (Wilkie *et al*., 2007). TFM concentrations 3–5 times higher than required to kill larval sea lampreys are tolerated by most fish (Applegate & King Jr, 1962; Boogaard, Bills, & Johnson, 2003) because they can detoxify and excrete the chemical (Clarke, George, & Burchell, 1991). However, commonly used dosages of TFM are still known to cause nontarget mortality in many freshwater species (Dermott & Spence, 1984; Boogaard *et al*.,2003).

Large-scale die-offs of nontarget species following TFM application have been known since the 1960s (Gilderhus & Johnson, 1980), and abundances of certain macroinvertebrates have declined within TFM treated streams (Dermott & Spence, 1984). Particularly susceptible groups include turbellarians, snails (*Physa*), and aquatic earthworms (*Tubifex*) (Rye, 1967; DuBois & Plaster, 1993). Aquatic insect larvae vary in their sensitivity, with black flies, mayflies, stoneflies, and caddisflies being highly susceptible (Torblaa, 1968; Gilderhus & Johnson, 1980). The early life stages of the lake sturgeon (*Acipenser fulvescens*) are also sensitive to TFM.

Furthermore, TFM is used as a selective amphibicide to control bullfrog larvae in aquaculture (Kane & Johnson, 1989).

Mass mortality of the common mudpuppy, a species of large-bodied, fully aquatic salamander, has been documented following TFM application (Gendron, 1999). Over 500 dead mudpuppies were recovered in the Lamoille River, Vermont, 400 dead mudpuppies were recovered in the Serpent River, Ontario, and 200 dead mudpuppies were recovered in the Musquash River, Ontario following TFM applications (Gendron, 1999). Matson (1990) reported a mudpuppy population decline of 29% between 1987 and 1988 in the Grand River, Ohio, following TFM application and suggested that four applications within 12 to 20 years could result in population declines of 75%. Mudpuppy mortality following TFM application has been recorded in 32% of Lake Superior tributaries and 36% of Lake Michigan tributaries since the 1960s (Gilderhus & Johnson, 1980).

Mudpuppies may be susceptible to bycatch because they are long-lived species, have low reproductive output, and have high adult survival (Matson, 1990; Wagner, 2023). Due to the documented impacts of TFM on mudpuppies immediately following TFM applications, lampricide concentrations have been reduced in Ohio due to concerns over mudpuppy sensitivity and declines (McLaughlin, Ellen Marsden, & Hayes, 2003). McLaughlin *et al*. (2003) suggested mudpuppies have regularly recovered from impacts of TFM and that the Lake Erie population growth trajectory has not declined. Other publications have asserted that the sea lamprey control program does not pose long-term consequences for nontarget species such as mudpuppies (McLaughlin *et al*., 2003; Gaden *et al*., 2021), but empirical evidence for such claims is limited.

In the absence of rigorous impact assessments or long-term monitoring, other methods for understanding the plausible impacts of bycatch are needed. Population viability analysis (PVA) can be used to explore plausible impacts of bycatch on mudpuppy populations. PVAs use demographic data to simulate the probability that a population will decline or become extinct because of anthropogenic threats (Akçakaya & Sjögren-Gulve, 2000; Beissinger & McCullough, 2002). PVAs can be used to examine the efficacy of alternative management strategies and identify conservation actions needed to ensure long-term population persistence (Reed *et al*., 2002; Radchuk *et al*., 2016; Chaudhary & Oli, 2020). In particular, stage-based PVAs have been used to study the impact of drought, habitat loss, and conservation strategies for several amphibian populations (Trenham & Shaffer, 2005; Pellet, Maze, & Perrin, 2006; Unger, Sutton, & Williams, 2013; Auffarth *et al*., 2017; Davis, Lohr, & Dale Roberts, 2019; Crawford *et al*., 2022; Andersen, Jang, & Borzée, 2023). However, the demographics of many amphibian species, including the common mudpuppy, are not well understood. One mudpuppy population for which recent demographic data exists is the Grand River, a tributary of Lake Erie. Wagner (2023) estimated population size, survival rate, and demographics for the Grand River mudpuppy population in 2021 and 2022. This population is regularly exposed to TFM on a 3- to 5-year cycle, presenting an opportunity to assess TFM impact on mudpuppies using PVAs.

We developed PVAs to better understand mudpuppy population dynamics in the Grand River and to assess how varying and differential bycatch mortality rates affect population trajectories. Our objectives were to (i) construct a stage-based population model for the mudpuppy to examine population sensitivity to stochastic events, (ii) compare population sensitivity to increased levels of adult and juvenile mortality, and (iii) forecast future population viability over a 100-year period with scenarios varying in the proportion of the population removed from TFM bycatch. Results of this study can inform conservation and management decision-making for TFM use where mudpuppy populations are present.

Materials and methods

Baseline models

A baseline population model of the mudpuppy population in the Grand River, Ohio, was constructed using Vortex, an individual-based population simulation program (version 10.0.7.9; Lacy & Pollak, 2013). VORTEX simulates a population by stepping through a series of events that describe an annual cycle of a typical sexually reproducing, diploid organism: mate selection, reproduction, mortality, increment of age by 1 year, migration among populations, removals, supplementation, and truncation to the carrying capacity. Vortex uses demographic population data to simulate deterministic and stochastic effects on wildlife populations. Demographic parameters such as birth and death rates include some random annual and environmental variation (Lacy & Pollak, 2013). To model environmental variation, each demographic parameter was assigned a distribution with a mean and standard deviation. Annual fluctuations in probabilities of reproduction and mortality are modeled as binomial distributions (Lacy & Pollak, 2013).

The demographic parameters and values used to construct the baseline model are detailed in Table 1. Population demographic estimates were obtained from Wagner (2023) or the literature. Each scenario was simulated 1000 times, over 100 years, with a one-year time step, to explore long-term population trends and allow for multi-generational effects to be observed. Population extinction was defined as occurring when only one sex remained. Long-term viability was defined in the models as the probability of extinction (PE) of <0.01.

Juvenile survival rates of mudpuppies are not well understood, although juvenile survival is typically low for amphibians (Unger *et al*., 2013; Wagner, 2023). We constructed a baseline population scenario in which juvenile survival increased with age from 25 to 70% (SD 10%). This scenario is based on demographic estimates from Wagner (2023) and is consistent with low juvenile survival estimates found for other aquatic salamanders (Unger *et al*., 2013). To examine the effect that increasing juvenile survival would have on bycatch impacts, we constructed an optimistic population

14691795, 0, Downloaded from https://zslpublications.onlinelibrary.wiley.com/doi/10.1111/acv.12989 by Ryan Wagner - Washington State University , Wiley Online Library on [25/09/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 1 Population parameters used in VORTEX simulation models for population projection and PVA of Grand River common mudpuppies

Parameter	Value	Reference
Reproductive system	Polygynous	
Age of first offspring – females (years)	6	Bishop (1926)
Age of first offspring – males (years)	6	Bishop (1926)
Max. # of progeny/brood	125	Matson (2013)
Max. # of broods/year	1	Matson (2013)
Sex ratio at birth	50% females	Matson (2013)
Sex ratio at adulthood	66% females	Wagner (2023)
Density-dependent reproduction	Not included	
Inbreeding depression	Not included	
Maximum lifespan and maximum age of reproduction (years)	30	Bonin et al. (1995)
Proportion of adult females breeding (SD due to environmental variation)	0.50 (.10)	Matson (2013)
Age 0–1 mortality for both sexes (SD due to environmental variation)	Baseline: 0.75 (0.10) Optimistic: 0.55 (0.10)	Wagner (2023)
Age 1–2 mortality for both sexes (SD due to environmental variation)	B: 0.70 (0.10) O: 0.55 (0.10)	Wagner (2023)
Age 2–3 mortality for both sexes (SD due to environmental variation)	B: 0.60 (0.10) O: 0.50 (0.10)	Wagner (2023)
Age 3–4 mortality for both sexes (SD due to environmental variation)	B: 0.50 (0.10) O: 0.50 (0.10)	Wagner (2023)
Age 4–5 mortality for both sexes (SD due to environmental variation)	B: 0.40 (0.10) O: 0.40 (0.10)	Wagner (2023)
Age 5–6 mortality for both sexes (SD due to environmental variation)	B: 0.30 (0.10) O: 0.30 (0.10)	Wagner (2023)
Age 6+ mortality for both sexes (SD due to environmental variation)	B: 0.01 (.03) O: 0.01 (.03)	Wagner (2023)
Initial population size (*N*)	340	Wagner (2023)
Catastrophe effects	Not included	
Carrying capacity (K)	500	
SD in K due to environmental variation	Not included	

B, baseline scenario; O, optimistic scenario.

scenario in which juvenile survival increased with age from 45%–70% (SD 10%).

Bycatch rates

To assess the vulnerability of the population to bycatch, we modeled 1, 2.5, 5, 10, 17, and 29% bycatch of the initial population size occurring every 5 years over a 100-year simulation for all age classes. Bycatch mortality was incorporated as a pre-determined number of mudpuppies removed from the population every 5 years. These bycatch rates were chosen to simulate relatively low (1–2.5%), moderate (5–10%), and high bycatch rates (17–29%), which are realistic impacts on mudpuppy populations from TFM (Matson, 1990; Wagner, 2023).

Age-structured bias in bycatch mortality

Some studies have suggested that juvenile mudpuppies are more susceptible to TFM than adults (Matson, 1990; Boogaard *et al*., 2003; Chellman, Parrish, & Donovan, 2017). To explore the effect of a skewed distribution of bycatch across age classes, we modeled (i) equal bycatch of adults and juveniles, (ii) 100% juvenile bycatch, and (iii) 30% adult and 70% juvenile bycatch.

Sensitivity analysis

We conducted sensitivity analyses in Vortex to assess the relative effect 1% incremental increases in mortality (up to a 10% increase) for adults and juveniles would have on the population size and growth. We used the baseline scenario with a 5% bycatch rate to test how increasing proportion of adults impacts population viability. We also used the baseline scenario with 30% adult and 70% juvenile mortality and a 5% bycatch rate to test how frequency of application (1–10 years) impacts population viability.

Results

The baseline scenario and optimistic scenario resulted in stable populations and no risk of extinction within 100 years (Fig. 1, Table 2). Sensitivity analysis using the baseline scenario resulted in a lower population growth rate and greater decline in population size for increased juvenile mortality compared to increased adult mortality (Fig. 2, Table 2). Increased proportion of adult mortality and increased frequency of bycatch events increased the risk of extinction (Figs. 3 and 4, Table 2).

14691795, 0, Downloaded from https://zslpublications.onlinelibrary.wiley.com/doi/10.1111/acv.12989 by Ryan Wagner - Washington State University , Wiley Online Library on [25/09/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

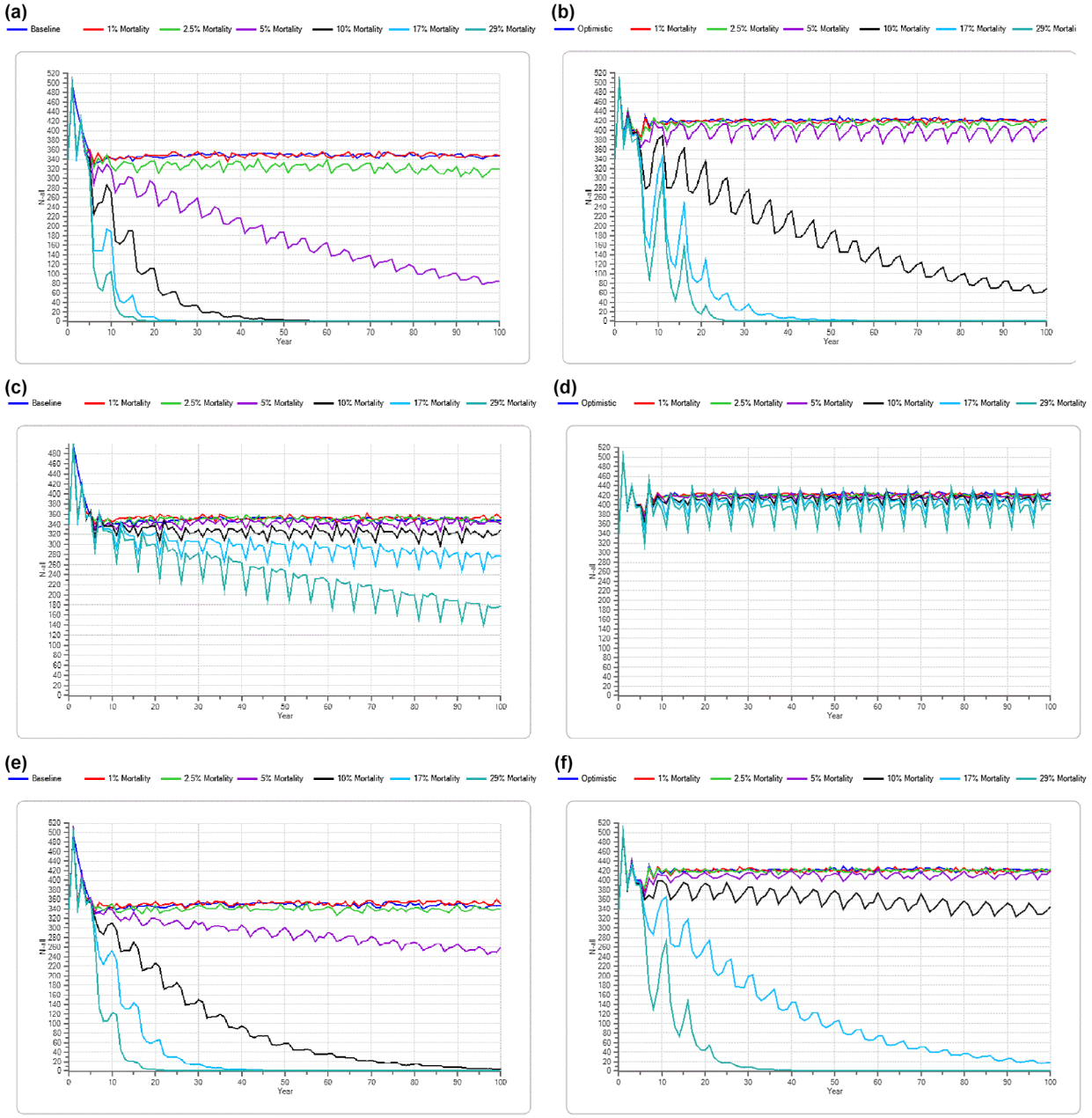


Figure 1 (a, c and e) Baseline population viability model (stable population). (a and b) Bycatch is equally distributed among adults and juveniles. (c and d) Bycatch is only juveniles. (e and f) Bycatch is distributed 30% adult and 70% juvenile. TFM application occurs once every 5 years.

Simulations of bycatch rates exhibited negative effects on population size, growth rates, and time to extinction. Under the baseline population scenario, 5% mortality and above resulted in a high probability of extinction when adult mortality was included. When only juvenile mortality was included, 17% mortality and above resulted in a high probability of extinction (Fig. 1). When a 5% bycatch rate affected at least 20% adults or occurred at four-year intervals, the probability of extinction greatly increased (Figs. 3 and 4, S2 and S3). Under the optimistic population scenario, 10% mortality and above resulted in a high probability of extinction when adult mortality was included (Fig. 1, Table 2). When only juvenile mortality was included, the probability of extinction was zero, although the population abundance greatly fluctuated when mortality was 17% or more (Fig. 1, Table 2).

14691795, 0, Downloaded from https://zslpublications.onlinelibrary.wiley.com/doi/10.1111/acv.12989 by Ryan Wagner - Washington State University , Wiley Online Library on [25/09/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 2 Simulated bycatch scenarios across TFM treatment regimens and possible impacts

Scenario	Bycatch (%)	TFM frequency (years)	Age classes	Annual population growth rate (*r*)	Population size at 100 years	Probability of extinction (%)	Mean time to extinction (years)
Baseline	0	NA	NA	0.07 ± 0.6	348 ± 125	0	NA
Baseline	1	5	All	0.08 ± 0.7	353 ± 121	0	NA
Baseline	2.5	5	All	0.06 ± 0.7	337 ± 123	5	NA
Baseline	5	5	All	0.02 ± 0.7	282 ± 136	67	70
Baseline	10	5	All	**−0.06 ± 0.8**	**0**	**100**	**24**
Baseline	17	5	All	**−0.13 ± 0.9**	**0**	**100**	**16**
Baseline	29	5	All	**−0.17 ± 1**	**0**	**100**	**15**
Baseline	1	5	Juveniles only	0.08 ± 0.7	344 ± 123	0	NA
Baseline	2.5	5	Juveniles only	0.08 ± 0.7	346 ± 122	0	NA
Baseline	5	5	Juveniles only	0.07 ± 0.7	344 ± 116	0	NA
Baseline	10	5	Juveniles only	0.05 ± 0.7	326 ± 121	0	NA
Baseline	17	5	Juveniles only	0.04 ± 0.7	287 ± 130	6	NA
Baseline	29	5	Juveniles only	0.02 ± 0.7	102 ± 120	26	NA
Baseline	1	5	30% Adults 70% Juveniles	0.08 ± 0.7	353 ± 124	0	NA
Baseline	2.5	5	30% Adults 70% Juveniles	0.07 ± 0.7	343 ± 125	0	NA
Baseline	5	5	30% Adults 70% Juveniles	0.04 ± 0.7	317 ± 130	53	NA
Baseline	10	5	30% Adults 70% Juveniles	**−0.01 ± 0.7**	**185 ± 142**	**99**	**40**
Baseline	17	5	30% Adults 70% Juveniles	**−0.07 ± 0.7**	**0**	**100**	**21**
Baseline	29	5	30% Adults 70% Juveniles	**−0.14 ± 0.7**	**0**	**100**	**16**
Optimistic	0	NA	NA	0.16 ± 0.6	424 ± 92	0	NA
Optimistic	1	5	All	0.15 ± 0.6	421 ± 94	0	NA
Optimistic	2.5	5	All	0.14 ± 0.6	421 ± 94	0	NA
Optimistic	5	5	All	0.12 ± 0.6	404 ± 111	0	NA
Optimistic	10	5	All	**0.04 ± 0.6**	**108 ± 182**	**68**	**71**
Optimistic	17	5	All	**−0.02 ± 0.8**	**0**	**100**	**26**
Optimistic	29	5	All	**−0.06 ± 0.9**	**0**	**100**	**21**
Optimistic	1	5	Juveniles only	0.16 ± 0.6	425 ± 96	0	NA
Optimistic	2.5	5	Juveniles only	0.15 ± 0.6	424 ± 92	0	NA
Optimistic	5	5	Juveniles only	0.15 ± 0.6	427 ± 91	0	NA
Optimistic	10	5	Juveniles only	0.14 ± 0.6	409 ± 98	0	NA
Optimistic	17	5	Juveniles only	0.13 ± 0.6	407 ± 97	0	NA
Optimistic	29	5	Juveniles only	0.11 ± 0.6	400 ± 98	0	NA
Optimistic	1	5	30% Adults 70% Juveniles	0.16 ± 0.6	422 ± 94	0	NA

14691795, 0, Downloaded from https://zslpublications.onlinelibrary.wiley.com/doi/10.1111/acv.12989 by Ryan Wagner - Washington State University , Wiley Online Library on [25/09/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 2 Continued.

Scenario	Bycatch (%)	TFM frequency (years)	Age classes	Annual population growth rate (*r*)	Population size at 100 years	Probability of extinction (%)	Mean time to extinction (years)
Optimistic	2.5	5	30% Adults 70% Juveniles	0.16 ± 0.6	418 ± 96	0	NA
Optimistic	5	5	30% Adults 70% Juveniles	0.13 ± 0.6	424 ± 93	0	NA
Optimistic	10	5	30% Adults 70% Juveniles	0.1 ± 0.6	403 ± 167	13	>100
Optimistic	17	5	30% Adults 70% Juveniles	**0.02 ± 0.6**	**256 ± 0.6164**	**95**	**41**
Optimistic	29	5	30% Adults 70% Juveniles	**−0.04 ± 0.8**	**0**	**100**	**21**

The mean annual population growth rate, population size at the end of 100-year simulation, probability of extinction, and mean time to extinction are reported for each scenario. Bold indicates values from scenarios that have a negative impact on population viability.

Discussion

Detecting bycatch-related population declines can be difficult because of uncertainty in population size and bycatch rates. Population viability analysis allows us to model plausible bycatch scenarios and their effects on population growth rates. The baseline PVA scenario suggested that the Grand River mudpuppy population was stable given current demographic estimates. However, the baseline scenario and the optimistic scenario suggest the population could decline or be extirpated within the next 100 years if TFM application occurs at least every 4 years, causes ≥5% mortality, and includes at least 20% adults. To ensure no extinction risk under the baseline scenario when bycatch mortality affects 30% adults and 70% juveniles, bycatch must occur at greater than four-year intervals and cause no more than 5% mortality. Alternatively, juvenile survival rate must be increased by 20% in year one, 15% in year two, and 10% in year three (optimistic scenario) (Fig. 5).

Sensitivity analysis found that the population growth rate is more affected by juvenile mortality than adult mortality. While population growth rates for long-lived species are usually most dependent on adult survival (Sæther & Bakke, 2000; Stahl & Oli, 2006), some studies have suggested similar effects of juvenile mortality (Sergio *et al*., 2011). Long-lived species require sufficient juvenile survival for population stability (Heppell, Caswell, & Crowder, 2000; Sergio *et al*., 2011). Eastern hellbender populations, for example, have declined due in part to low juvenile survival (Unger *et al*., 2013). However, real potential for extinction in our mortality simulations occurred when both adults and juveniles were impacted.

Wagner (2023) estimated low apparent survival rates for juvenile mudpuppies consistent with other studies of juvenile amphibian survival (Anderson, Hassinger, & Dalrymple, 1971; Blaustein *et al*., 1997). However, apparent survival combines survival and emigration, and actual estimates of juvenile mudpuppy survival may be higher than those reported. Low juvenile recapture rate and difficulty monitoring nests make obtaining precise estimates of juvenile survival difficult. We chose to model PVAs using survival between 25 and 70% for juvenile age classes to estimate a stable baseline population. PVAs with lower juvenile survival could not sustain the observed population of 340 individuals reported by Wagner (2023).

Because of the naturally high variability of juvenile survival, focusing management actions on increasing this demographic parameter may be the most feasible method for improving mudpuppy population viability (Mortensen & Reed, 2016; Manlik, 2019; Zamora-Nasca & Lambertucci, 2022). The current interval between TFM applications (3–5 years) is shorter than the typical mudpuppy generation time of 6 years (Gendron, 1999). Increasing the application interval could allow juvenile mudpuppies to reach adult size, thereby reducing their vulnerability to TFM applications. However, reaching the high rates of survival used in our optimistic scenario may be difficult or impossible given our poor understanding of juvenile mudpuppy life history.

Matson (1990) estimated a population size of 803 (556–1188) mudpuppies per km in the Grand River prior to TFM treatment, and in 1988, 333 (280–397) mudpuppies per km following TFM treatment, a decline of 29%. Other studies also suggest high levels of mudpuppy bycatch can occur following TFM treatment. Chellman *et al*. (2017) reported 500 dead mudpuppies from 5% of the treated area in the Lamoille River, Vermont. It is unclear what percentage of the population this represents. Systematic bycatch surveys following TFM applications are essential to quantifying the extent of impact. Mudpuppy population persistence, and indeed persistence of any nontarget species, should not be assumed without population monitoring.

Bycatch rates that did not result in population declines in our PVAs could still be a risk to mudpuppy population

14691795, 0, Downloaded from https://zslpublications.onlinelibrary.wiley.com/doi/10.1111/acv.12989 by Ryan Wagner - Washington State University , Wiley Online Library on [25/09/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

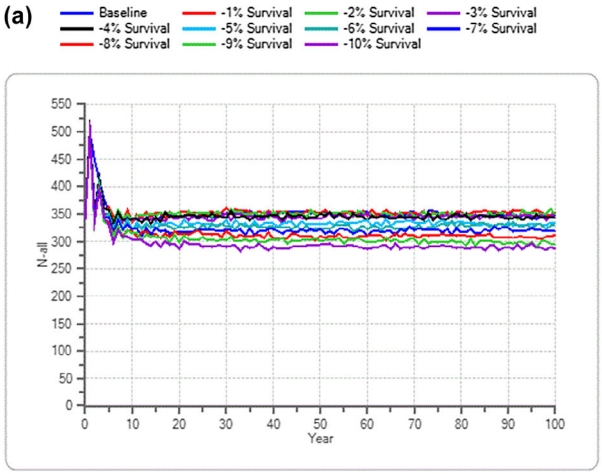


Figure 2 (a) Sensitivity analysis with incremental decrease of adult survival up to 10% (no increase in juvenile mortality). (b) Sensitivity analysis with incremental decrease of juvenile survival up to 10% (no increase in adult mortality).

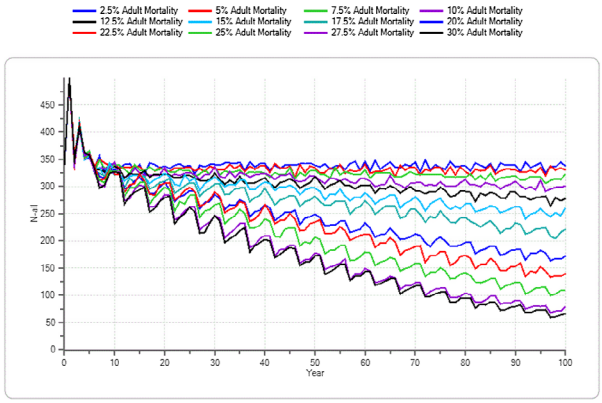


Figure 3 Baseline population viability model (stable population). TFM application occurs once every 5 years. Bycatch is 5% of the population distributed in increasing proportion of adults up to 30% adult and 70% juvenile.

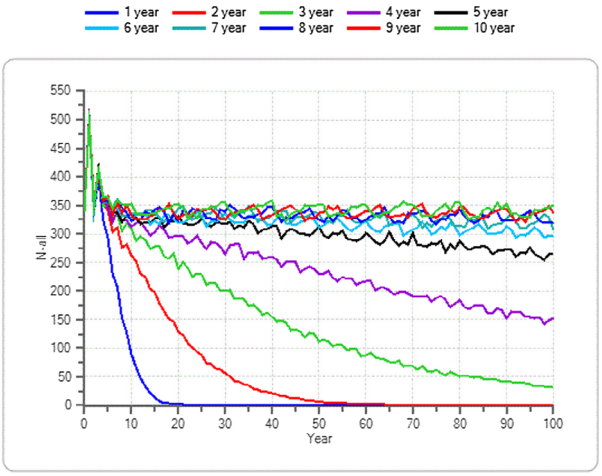


Figure 4 Baseline population viability model. Bycatch is 5% of the population distributed 30% adult and 70% juvenile. TFM application occurs once every 1–10 year.



Figure 5 Common mudpuppy in profile (*Necturus maculosus*).

viability if combined with other threats. Habitat loss and degradation because of siltation from agricultural runoff has been suggested to contribute to mudpuppy population declines (Braswell & Ashton, 1985). Mass die-offs of thousands or tens of thousands of mudpuppies from botulism and water mold have also been recorded in Lake Erie (Matson, 2013)). Quantifying the effects of these environmental perturbations on mudpuppy population size and carrying capacity is an important next step for future population viability analyses. Metapopulation modeling using combined species distribution models and connectivity mapping could be used to find carrying capacity of population patches and possible migration between patches.

Mudpuppy populations appear to have limited resiliency to harvest, and increased mortality caused by TFM threatens population persistence. The results of our PVAs clearly demonstrate that moderate (≥5%) rates of mortality due to TFM bycatch could drive mudpuppy population declines or lead to extirpation. However, we estimated that low levels of bycatch (1–2.5% mortality) do not lead to long-term population declines. The current Grand River population appears to have

14691795, 0, Downloaded from https://zslpublications.onlinelibrary.wiley.com/doi/10.1111/acv.12989 by Ryan Wagner - Washington State University , Wiley Online Library on [25/09/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

recovered from the 1988 TFM application and bycatch (Wagner, 2023). However, the Grand River mudpuppy population shows evidence of exploitation, including reduced body size and possible compensatory growth compared to another TFM-free mudpuppy population (Wagner, 2023), which suggests TFM is not environmentally benign (McLaughlin *et al*., 2003; Gaden *et al*., 2021). Despite these potential impacts, a few systematic surveys to quantify nontarget mortality have occurred immediately following treatments, and even less is known regarding the long-term consequences of nontarget mortality. Our study suggests that long-term monitoring and detailed studies of nontarget populations may be warranted to fully understand the impacts of TFM.

Acknowledgments

This work was funded by the Ohio Division of Wildlife. We thank T. Matson and G. Orr for their guidance and field assistance. We also thank two anonymous reviewers for helpful comments on an earlier version of this manuscript.

Authors' contributions

R. B. Wagner and W. E. Peterman conceived of the ideas and designed methodology; R. B. Wagner collected the data; R. B. Wagner and W. E. Peterman analyzed the data; R. B. Wagner and W. E. Peterman led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Conflict of interest

The authors declare no conflict of interest.

References

Akçakaya, H.R. & Sjögren-Gulve, P. (2000). Population viability analyses in conservation planning: an overview. *Ecol. Bull.* **48**, 9–21.

Andersen, D., Jang, Y. & Borzée, A. (2023). Influence of landscape and connectivity on anuran conservation: population viability analyses to designate protected areas. *Anim. Conserv.* **26**, 381–397.

Anderson, J.D., Hassinger, D.D. & Dalrymple, G.H. (1971). Natural mortality of eggs and larvae of Ambystoma *T. tigrinum*. *Ecology.* **52**, 1107–1112.

Applegate, V.C. & King, E.L., Jr. (1962). Comparative toxicity of 3-trifluormethyl-4-nitrophenol (TFM) to larval lampreys and eleven species of fishes. *Trans. Am. Fish. Soc.* **91**, Article 4–Article 345.

Applegate, V.C., Howell, J.H. & Moffett, J.W. (1961). *Use of 3-trifluormethyl-4-nitrophenol as a selective sea lamprey larvicide*. Ann Arbor, MI: Great Lakes Science Center.

Auffarth, J., Krug, A., Proehl, H. & Jehle, R. (2017). A genetically-informed population viability analysis reveals conservation priorities for an isolated population of *Hyla arborea*. *Salamandra.* **53**, 15.

Beissinger, S.R. & McCullough, D.R. (2002). *Population viability analysis*. Chicago: University of Chicago Press.

Birceanu, O., McClelland, G.B., Wang, Y.S., Brown, J.C.L. & Wilkie, M.P. (2011). The lampricide 3-trifluoromethyl-4-nitrophenol (TFM) uncouples mitochondrial oxidative phosphorylation in both sea lamprey (*Petromyzon marinus*) and TFM-tolerant rainbow trout (*Oncorhynchus mykiss*). *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* **153**, 342–349.

Bishop, S.C. (1926). *Notes on the habits and development of the mud-puppy Necturus maculosus (Rafinesque) (No. 268)*. University of the State of New York.

Blaustein, A.R., Kiesecker, J.M., Chivers, D.P. & Anthony, R.P. (1997). Ambient UV-B radiation causes deformities in amphibian embryos. *Proc. Natl. Acad. Sci. USA.* **94**, 13735–13737.

Bonin, J., DesGranges, J.L., Bishop, C.A., Rodrigue, J., Gendron, A. & Elliott, J.E. (1995). Comparative study of contaminants in the mudpuppy (Amphibia) and the common snapping turtle (Reptilia), St. Lawrence River, Canada. *Archives of Environmental Contamination and Toxicology* **28**, 184–194.

Boogaard, M.A., Bills, T.D. & Johnson, D.A. (2003). Acute toxicity of TFM and a TFM/niclosamide mixture to selected species of fish, including Lake sturgeon (*Acipenser fulvescens*) and mudpuppies (*Necturus maculosus*), in laboratory and field exposures. *J. Great Lakes Res.* **29**, 529–541.

Braswell, A.L. & Ashton, R. (1985). Distribution, ecology, and feeding-habits of *Necturus-lewisi* (brimley). *Brimleyana.* **10**, 13–35.

Chaudhary, V. & Oli, M.K. (2020). A critical appraisal of population viability analysis. *Conserv. Biol.* **34**, 26–40.

Chellman, I.C., Parrish, D.L. & Donovan, T.M. (2017). Estimating mudpuppy (*Necturus maculosus*) abundance in the Lamoille River, Vermont, USA. *Herpetol. Conserv. Biol.* **12**, 422–434.

Christie, G.C. & Goddard, C.I. (2003). Sea Lamprey International Symposium (SLIS II): advances in the integrated management of sea Lamprey in the great lakes. *J. Great Lakes Res.* **29**, 1–14.

Clarke, D.J., George, S.G. & Burchell, B. (1991). Glucuronidation in fish. *Aquat. Toxicol.* **20**, Article 1–2.

Collen, B., Whitton, F., Dyer, E.E., Baillie, J.E.M., Cumberlidge, N., Darwall, W.R.T., Pollock, C., Richman, N.I., Soulsby, A.-M. & Böhm, M. (2014). Global patterns of freshwater species diversity, threat and endemism. *Glob. Ecol. Biogeogr.* **23**, 40–51.

Crawford, B.A., Maerz, J.C., Terrell, V.C.K. & Moore, C.T. (2022). Population viability analysis for a pond-breeding amphibian under future drought scenarios in the southeastern United States. *Glob. Ecol. Conserv.* **36**, e02119.

Davis, R.A., Lohr, C.A. & Dale Roberts, J. (2019). Frog survival and population viability in an agricultural landscape with a drying climate. *Popul. Ecol.* **61**, 102–112.

Dermott, R. & Spence, H. (1984). Changes in populations and drift of stream invertebrates following lampricide treatment. *Can. J. Fish. Aquat. Sci.* **41**, 1695–1701.

14691795, 0, Downloaded from https://zslpublications.onlinelibrary.wiley.com/doi/10.1111/acv.12989 by Ryan Wagner - Washington State University , Wiley Online Library on [25/09/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

DuBois, R.B. & Plaster, S.D. (1993). Effects of lampricide treatment on macroinvertebrate drift in a small, softwater stream. *Hydrobiologia.* **263**, 119–127.

Gaden, M., Brant, C., Stedman, R.C., Cooke, S.J., Young, N., Lauber, T.B., Nguyen, V.M., Connelly, N.A. & Knuth, B. (2021). Shifting baselines and social license to operate: challenges in communicating sea lamprey control. *J. Great Lakes Res.* **47**, S800–S808.

Gendron, A.D. (1999). Status report on the Mudpuppy, *Necturus maculosus*. Committee on the Status of Endangered Wildlife in Canada.

Gilderhus, P. & Johnson, B. (1980). Effects of sea lamprey *Petromyzon marinus* control in the Great Lakes on aquatic plants, invertebrates, and amphibians. *Can. J. Fish. Aquat. Sci.* **37**, 1895–1905.

Heppell, S.S., Caswell, H. & Crowder, L.B. (2000). Life histories and elasticity patterns: perturbation analysis for species with minimal demographic data. *Ecology.* **81**, 654–665.

Kane, A.S. & Johnson, D.L. (1989). Use of TFM (3-trifluoromethyl-4-nitrophenol) to selectively control frog larvae in fish production ponds. *Prog. Fish Cult.* **7**, 207–213.

Lacy, R.C. & Pollak, J.P. (2013). *VORTEX: A stochastic simulation of the extinction process. Version 10*. Brookfield: Chicago Zoological Society.

Lewison, R., Crowder, L., Read, A. & Freeman, S. (2004). Understanding impacts of fisheries bycatch on marine megafauna. *Trends Ecol. Evol.* **19**, 598–604.

Lewison, R., Soykan, C., Cox, T., Peckham, H., Pilcher, N., LeBoeuf, N., McDonald, S., Moore, J., Safina, C. & Crowder, L. (2011). Ingredients for addressing the challenges of fisheries bycatch. *Bull. Mar. Sci.* **87**, 235–250.

Manlik, O. (2019). The importance of reproduction for the conservation of slow-growing animal populations. In *Reproductive sciences in animal conservation*: 13–39. Comizzoli, P., Brown, J.L. & Holt, W.V. (Eds.) Vol. **1200**. Cham: Springer International Publishing.

Matson, T.O. (1990). Estimation of numbers for a riverine necturus population before and after TFM lampricide exposure. *Kirtlandia.* **45**, 33–38.

Matson, T.O. 2013. Necturus maculosus. In *Amphibians of Ohio*: 407–424. R. Pfingsten, J.G. Davis, T. Matson, G. Lipps Jr, D. Wynn, and B. Armitage, (Eds.). Ohio Biological Survey, Columbus.

McLaughlin, R.L., Ellen Marsden, J. & Hayes, D.B. (2003). Achieving the benefits of sea lamprey control while minimizing effects on nontarget species: conceptual synthesis and proposed policy. *J. Great Lakes Res.* **29**, 755–765.

Mortensen, J.L. & Reed, J.M. (2016). Population viability and vital rate sensitivity of an endangered avian cooperative breeder, the white-breasted thrasher (*Ramphocinclus brachyurus*). *PLoS One.* **11**, e0148928.

Pellet, J., Maze, G. & Perrin, N. (2006). The contribution of patch topology and demographic parameters to population viability analysis predictions: the case of the European tree frog. *Popul. Ecol.* **48**, 353–361.

Raby, G.D., Colotelo, A.H., Blouin-Demers, G. & Cooke, S.J. (2011). Freshwater commercial bycatch: an understated conservation problem. *Bioscience.* **61**, 271–280.

Radchuk, V., Oppel, S., Groeneveld, J., Grimm, V. & Schtickzelle, N. (2016). Simple or complex: relative impact of data availability and model purpose on the choice of model types for population viability analyses. *Ecol. Model.* **323**, 87–95.

Reed, J.M., Mills, L.S., Dunning, J.B., Jr., Menges, E.S., McKelvey, K.S., Frye, R., Beissinger, S.R., Anstett, M.-C. & Miller, P. (2002). Emerging issues in population viability analysis. *Conserv. Biol.* **16**, 7–19.

Rye, R.P. (1967). Acute toxic effects of two lampricides to twenty-one freshwater invertebrates. *Trans. Am. Fish. Soc.* **105**, 322–326.

Sæther, B.-E. & Bakke, Ø. (2000). Avian life history variation and contribution of demographic traits to the population growth rate. *Ecology.* **81**, 642–653.

Sergio, F., Tavecchia, G., Blas, J., López, L., Tanferna, A. & Hiraldo, F. (2011). Variation in age-structured vital rates of a long-lived raptor: implications for population growth. *Basic Appl. Ecol.* **12**, 107–115.

Stahl, J.T. & Oli, M.K. (2006). Relative importance of avian life-history variables to population growth rate. *Ecol. Model.* **198**, 23–39.

Torblaa, R.L. (1968). *Effects of lamprey larvicides on invertebrates in streams*. Marquette: US Department of the Interior, Bureau of Commercial Fisheries.

Trenham, P.C. & Shaffer, H.B. (2005). Amphibian upland habitat use and its consequences for population viability. *Ecol. Appl.* **15**, 1158–1168.

Unger, S.D., Sutton, T.M. & Williams, R.N. (2013). Projected population persistence of eastern hellbenders (*Cryptobranchus alleganiensis alleganiensis*) using a stage-structured life-history model and population viability analysis. *J. Nat. Conserv.* **21**, 423–432.

Wagner, R. (2023). *Tale of two mudpuppy populations: impacts of TFM on Ohio's second largest salamander.* Master's Thesis, The Ohio State University.

Wilkie, M.P., Holmes, J.A. & Youson, J.H. (2007). The lampricide 3-trifluoromethyl-4-nitrophenol (TFM) interferes with intermediary metabolism and glucose homeostasis, but not with ion balance, in larval sea lamprey (*Petromyzon marinus*). *Can. J. Fish. Aquat. Sci.* **64**, 1174–1182.

Zamora-Nasca, L.B. & Lambertucci, S.A. (2022). Domestic dog-wildlife interactions and support for pet regulations in protected areas. *Biol. Conserv.* **273**, 109705.

Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Supporting information.

14691795, 0, Downloaded from https://zslpublications.onlinelibrary.wiley.com/doi/10.1111/acv.12989 by Ryan Wagner - Washington State University , Wiley Online Library on [25/09/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License