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Lampricide Exposure in Mudpuppies (*Necturus maculosus*): Comparing Demographic Responses

Ryan B. Wagner[1] and William E. Peterman[2]

Since 1958, the lampricide 3-trifluoromethyl-4-nitrophenol (TFM) has been periodically used in nursery streams of the Great Lakes Region to control the invasive Sea Lamprey (*Petromyzon marinus*). Some treatments of streams containing Common Mudpuppies (*Necturus maculosus*), a species of large-bodied fully aquatic salamander found throughout the Great Lakes Region, have resulted in large amounts of mudpuppy mortality. However, the long-term consequences of mudpuppy mortality are not well understood. Following a TFM application in 1986, the mudpuppy population experienced an estimated 29% decline in the Grand River, Ohio. Since then, the Grand River has continued to be treated with TFM every three to five years. Mudpuppy population estimates suggest a slow to moderate decline over the last 32 years. In 2021 and 2022, we returned to the Grand River to estimate mudpuppy population size, survival, growth rates, and population demographics using mark–recapture methods. Following our first year of mark–recapture surveys, the US Fish and Wildlife Service treated the Grand River with TFM in April 2022. Despite observed mudpuppy mortality in the Grand River following TFM treatment, our population and survival estimates did not indicate decline following the 2022 TFM treatment. We also conducted a mark–recapture study at Alum Creek, a river that has never been treated with TFM. While differences in habitat and survey methods preclude direct comparison of the sites, we found little difference in population size or survival between sites. However, individual growth rates suggest that Grand River mudpuppies may reach sexual maturity at a younger age and attain a smaller adult size, patterns consistent with an exploited population. Smaller adults could have reduced fecundity, be more susceptible to predation, and have lower competitive ability, which may have consequences for long-term population persistence. Our study highlights the need for future studies to compare treated and untreated tributaries in the Great Lakes to address lingering concerns and long-term effects of TFM treatments.

AMPHIBIANS have experienced dramatic global declines during the last several decades with around one-third of species currently under threat of extinction (Stuart et al., 2004; Blaustein et al., 2011; Collins et al., 2019). Causes for these declines are varied and include habitat destruction (Kolozsvary and Swihart, 1999; Ray et al., 2002), road mortality (Hels and Buchwald, 2001), UV-B radiation (Blaustein et al., 1994), disease (Chatfield et al., 2012; Williams and Groves, 2014), invasive species (Kats and Ferrer, 2003), exploitation (Jensen and Camp, 2003), loss of genetic diversity (Rowe and Beebee, 2003; Frankham et al., 2010), climate change (Pounds et al., 1997; Walther et al., 2002), and pesticide exposure (Bonin et al., 1995; Gendron et al., 1997; Davidson, 2004; Davidson and Knapp, 2007; Brühl et al., 2013; Shojaei et al., 2021). Amphibians encounter pesticides from agricultural run-off and spray drift or through direct application to waters they inhabit. Exposure to many commercially available pesticides disrupts endocrine function, weakens the immune response, decreases body mass, affects time to metamorphosis, and increases mortality in amphibians (Bridges, 2000; Boone and Semlitsch, 2001; Hayes et al., 2006; Davidson and Knapp, 2007; Brühl et al., 2013).

One pesticide linked with amphibian mortality is 3-trifluoromethyl-4-nitrophenol (TFM; Kane et al., 1985; Kane and Johnson, 1989; Gabbadon and Chapman, 1996; Boogaard et al., 2003; Chellman et al., 2017; Matson, 2022). The US Fish and Wildlife Service uses TFM to control the invasive Sea Lamprey (*Petromyzon marinus*) in the Great Lakes and their tributaries (Applegate et al., 1961). TFM is applied to Sea Lamprey nursery streams on a three-to-five-year rotation and is highly toxic to Sea Lamprey ammocoetes while being less toxic to other aquatic organisms at the same concentrations (Wilkie et al., 2019). However, TFM treatments can still cause impacts on nontarget species, including being lethal to the Common Mudpuppy (Matson, 1990; Boogaard et al., 2003; Chellman et al., 2017; Matson, 2022; Wagner and Peterman, 2025).

The Common Mudpuppy is a large-bodied, fully aquatic salamander that inhabits both lentic and lotic environments across the eastern and central United States and southern Canada (Fig. 1). Mudpuppies are a long-lived species, with individuals known to live for over 30 years (Gendron, 1999). Mortality events consisting of up to hundreds of mudpuppies following some TFM applications have been documented (Gendron, 1999; Chellman et al., 2017). Examples include 528 mortalities reported in the Lamoille River, Vermont, 400 mortalities in the Serpent River, Ontario, and 200 mortalities in the Musquash River, Ontario following TFM applications (Gendron, 1999; Chellman et al., 2017). Mudpuppy mortality events have been recorded in 32% of Lake Superior tributaries and 36% of Lake Michigan tributaries following TFM treatment since the 1960s (Gilderhus and Johnson, 1980). Matson (1990) estimated a 29% decline of the mudpuppy population in the Grand River, Ohio following a TFM application in 1986, and Matson (2022) suggested the population may be experiencing a slow to moderate decline over the last 32 years.

Mudpuppy population declines have been documented recently in TFM-treated and untreated streams; however, the causes and extent of these declines are not well

[1] School of Biological Sciences, Washington State University, 14204 NE Salmon Creek Ave., Vancouver, Washington 98686; ORCID: 0009-0007-8690-1596; Email: ryan.wagner2@wsu.edu. Send correspondence to this address.
[2] School of Environment and Natural Resources, The Ohio State University, 2021 Coffey Rd., Columbus, Ohio 43201.
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Fig. 1. A mudpuppy salamander in profile (*Necturus maculosus*). Photographed at Alum Creek by Ryan Wagner.

understood (Matson, 2005; Hoffman et al., 2014). Mudpuppies are listed as a species of high conservation concern by the Northeast Partners in Amphibian and Reptile Conservation (NEPARC [Northeast Partners in Amphibian and Reptile Conservation], 2010). The species is endangered or locally extinct in Maryland, a species of special conservation need in Vermont, and threatened in Iowa and Illinois. They are listed as a species of concern in many states, including North Carolina, Indiana, Minnesota, Michigan, Indiana, Kansas, Tennessee, Alabama, Virginia, West Virginia, Pennsylvania, New York, and Connecticut, due in part to their susceptibility to lampricides and in combination with often limited population demographic information. The mudpuppy is ranked 14th among 39 amphibians of conservation concern by the Ohio Department of Natural Resources (Collins et al., 2019). However, no special status has been given to the mudpuppy in Ohio (Matson, 2013).

Currently, we lack the data to determine the status of mudpuppies in Ohio or the potential long-term impacts of TFM treatments on mudpuppy populations. If TFM treatments cause mortality of up to one-third of the population every three to five years, population decline or extirpation may ensue (Gendron, 1999; Matson, 2022). Boogaard (unpubl. report) suggested that a typical TFM treatment could pose a mortality risk to about 10% of adult mudpuppies and up to 100% of juvenile mudpuppies. Mudpuppy populations regularly exposed to TFM may show signals of exploitation, including population declines, increased growth rates, earlier reproduction, and skewed sex ratios (Healey, 1978; Davidson, 2004; Natusch and Lyons, 2012; Chellman et al., 2017; Monk et al., 2021).

We studied mudpuppy populations at two rivers in Ohio to better understand population size, survival, growth rates, and population demographics, as well as the potential effects of TFM applications (Fig. 2A). We conducted a mark–recapture study at the same site investigated by Matson (1990) in the Grand River, which is treated with TFM every three to five years. Federal biologists treated the Grand River with TFM in April 2022 after one pre-treatment year of mark–recapture surveys. We also conducted a mark–recapture study at a second stream, Alum Creek, immediately downstream of the tailwater of Alum Creek Reservoir, Ohio, which has never been treated with TFM and is not in the Lake Erie watershed. We estimated demographics of the two sites and before and after treatment of the Grand River to explore potential TFM impacts on mudpuppy populations in tributaries treated for invasive Sea Lamprey.

MATERIALS AND METHODS

Field sampling.—We conducted mark–recapture surveys during November–April from 2020–2023 in Alum Creek, immediately downstream of Alum Creek Reservoir (1,371 ha), Delaware County, Ohio, USA (Fig. 2C). Alum Creek Reservoir is a large US Army Corps of Engineers flood control impoundment with a popular sport fishery in the tailwater and further downstream due to the emigration of sport fish from the reservoir, particularly Muskellunge (*Esox masquinongy*) and Saugeye (*Sander vitreus* x *canadensis*). Alum Creek is a tributary of the Ohio River drainage system that has never been treated with TFM. River substrate is primarily artificial rip-rap and silt. We used a combination of trapping and spotlight surveys to capture mudpuppies along a 400-meter stretch of river. We trapped four consecutive nights each week during 2020–2022. We placed 40 collapsible Promar minnow traps, baited with canned dog food, along the river bottom approximately 5–10 m from shore and 10 m apart. Concomitantly with trapping, we conducted spotlight surveys five nights per week along the east bank of the study area during 2020–2023, where we captured mudpuppies by hand or with a dipnet as they moved around the river bottom. Weekly trapping and spotlighting are combined into single surveys in Table 1.

We conducted mark–recapture surveys during June–October from 2021–2022 in the Grand River, Lake County, Ohio (Fig. 2B). Our study site was the same stretch of the Grand River where Matson (1990) conducted field work 33 years prior. The Grand River is a tributary of the Lake Erie drainage system and is treated every three to five years with TFM.

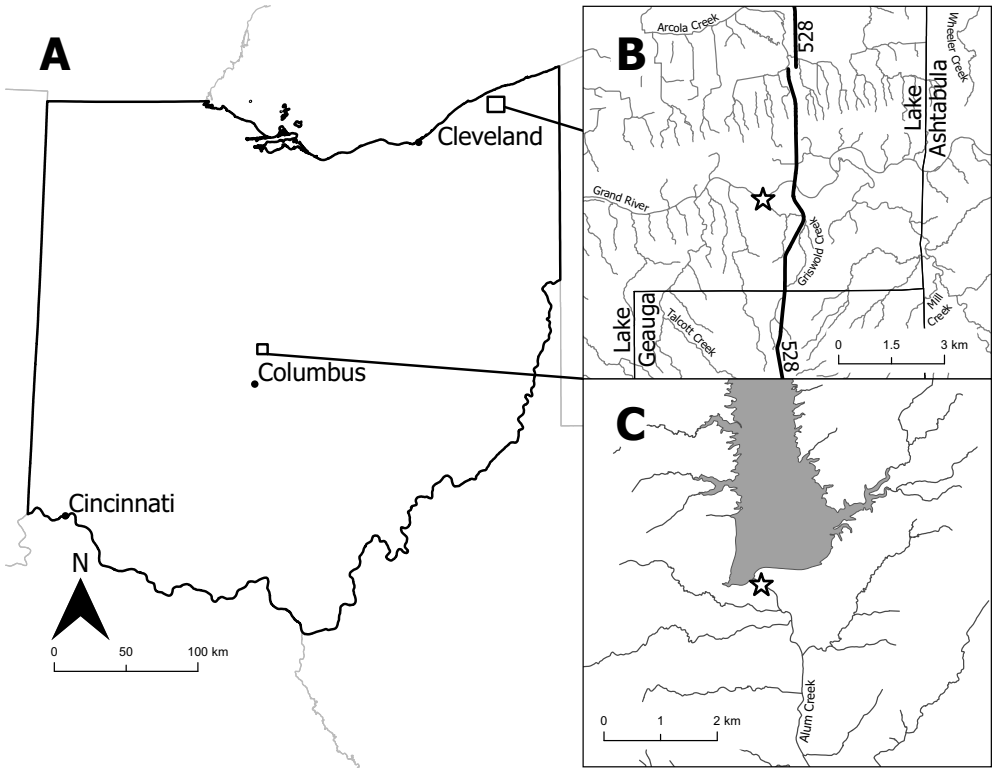


Fig. 2. Map of study area (A) Ohio, (B) the Grand River, and (C) Alum Creek.

Grand River substrate includes sand, gravel, cobble, large glacial erratics, and slabs of siltstone. We used seining and rock-flipping to capture mudpuppies along a 400-meter stretch of river. We conducted surveys once every three to four weeks to reduce impact on the habitat and animals. We used different survey techniques at Alum Creek and the Grand River due to habitat differences and to better compare our Grand River results to Matson (1990). These differences preclude direct comparison of demographic estimates between our two study sites.

We recorded total length (TL in mm) and snout–vent length (SVL in mm; using snake tubes to immobilize mudpuppies), mass (in g), and sex of each captured mudpuppy. To uniquely mark individuals, we injected an 8 mm passive integrated transponder (PIT) tag subcutaneously into the tail of each newly captured mudpuppy >100 mm total SVL. We used a chi-square test to examine differences in the distribution of sexes captured between years. For Alum Creek, we used a Kruskal-Wallis test to compare SVL of each sex across three years. For the Grand River, we used a Wilcoxon rank-sum test to compare the SVL of each sex between year 1 and year 2.

The US Fish and Wildlife Service treated 49.6 km of the Grand River between the Harpersfield Dam and Lake Erie on 29 April 2022. Liquid TFM is applied to the river at a precise concentration (dependent on water chemistry and flow) for a 12 h period. Our 400 m study area was within the treated stretch. We joined personnel from federal and state resource agencies including the US Fish and Wildlife Service, Ohio Department of Natural Resources, Ohio Environmental Protection Agency, Ohio State University, Cleveland State University, Cleveland Museum of Natural History, Lake County Metroparks, and citizen volunteers, to survey 20 km of the lower Grand River (representing less than half of the treated

Table 1. Sampling effort and total mudpuppy (*Necturus maculosus*) capture events using each survey method in Alum Creek for November 2020 to May 2021 (year 1), November 2021 to May 2022 (year 2), and November 2022 to May 2023 (year 3) and the Grand River for June 2021 to October 2021 (year 1) and June 2022 to October 2022 (year 2). Surveys for Alum Creek combine spotlighting and trapping, while surveys for the Grand River are seining. Parentheses contain individual mudpuppy count.

Site	Survey summary	Year 1	Year 2	Year 3
Alum Creek	Surveys	17	20	20
	Trapping	48 (33)	35 (21)	
	Spotlighting	143 (102)	257 (143)	159 (108)
	Incidental	9 (8)	0	0
	Recapture events	57 (42)	88 (72)	51 (47)
Grand River	Surveys	5	5	
	Seine	169 (103)	157 (94)	
	TFM mortality		45	
	Recapture events	66 (42)	63 (46)	

area) for nontarget fish and amphibian mortality. We collected dead mudpuppies and recorded TL, SVL, mass, and sex. All dead mudpuppies were checked for PIT tags and preserved as voucher specimens in the Cleveland Museum of Natural History.

Population size and survival.—To estimate detection probability (p) and abundance (N), we analyzed mudpuppy capture histories using an open population Jolly-Seber model in a Bayesian framework. Open populations allow for births, deaths, immigration, and emigration. Bayesian models were fit using jags v. 4.3.1 (Plummer, 2003) and run in R v. 4.3.1 (R Core Team, 2023) using the jagsUI package (Kellner, 2021). Parameters were estimated from normally distributed priors with a mean of 0 and precision of 1. Models did not include covariates on the demographic parameters. We ran population models on five Markov chain Monte Carlo (MCMC) chains for 180,000 iterations, 50,000 iterations in the adaptive phase, and a burn-in of 10,000, and a thinning rate of 25.

To estimate how apparent survival probability (phi) changed with SVL at each site, we estimated phi as a function of SVL within the Cormack-Jolly-Seber. The survival of individual i at time t was modeled as:

$$logit(phi_{i,t}) = \beta_0 + \beta_1 \times SVL_i$$

The prior distribution for β_0 was normally distributed with a mean of 0 and precision of 1, while β_1 parameter was normally distributed with a mean of 1 and precision of 0.25, in accordance with our general understanding that survival rates increase with size. Parameters were deemed meaningful if greater than 97.5% of the posterior density was on one side of zero. We ran survival models on five MCMC chains for 100,000 iterations, 5,000 iterations in the adaptive phase, and a burn-in of 10,000, and a thinning rate of 10.

Individual growth model.—We estimated individual growth using Fabens capture–recapture growth model (Fabens, 1965). The growth function for individual i at time t was defined as:

$$SVL0_{i,t} = SVL0_{i,t-1} + \left\{ L[SITE] - SVL0_{i,t-1} \times \left[1 - \exp\left(-K_{i,t} \times \frac{I}{365} \right) \right] \right\}$$

where asymptotic size L was allowed to differ by site and was estimated from a normally distributed prior with a mean of 290 mm and precision of 1 for Alum Creek and a normally distributed prior with a mean of 235 mm and a precision of 0.25 for the Grand River. These priors were based on our maximum recorded SVL for each site. We used a less precise prior for the Grand River to account for the possibility that our survey methods were biased against larger captures. $SVL0_{i,t}$ is the size at first capture and follows a uniform distribution with a minimum of 30 mm and maximum of 300 mm. We removed any observations where SVL at the final time step was less than SVL at the first time step, which would be because of measurement errors. K represents the individual growth rate, and I is the annual scaling interval between captures. We estimated K as a function of categorical site (Alum Creek or Grand River) based on observed change in SVL of recaptured individuals across sampling periods.

$$K_{i,t} = \beta_0 + \beta_1^{[k]} \times site_i$$

The β_0 parameter was estimated from a beta-distributed prior with shape parameters 2 and 10. The β_1 parameters were estimated from normally distributed priors with a mean of 0 and precision of 0.01. We evaluated the difference in K between Alum Creek and the Grand River by subtracting the two model coefficients, such that more positive values indicated larger growth coefficients. We treated the difference as significant if >97.5% of the posterior density was on one side of zero. Resulting curves were plotted against the minimum size at sexual maturity (130 mm SVL; Shoop, 1965) to estimate the age of sexual maturity for each population. We ran the growth model on five MCMC chains for 200,000 iterations with a burn-in of 25,000 and a thinning rate of 5. We considered models to have fully converged if all parameters had Gelman-Ruben (Rhat) statistics below 1.05 and visual inspection of MCMC chains indicated clear and consistent mixing.

RESULTS

At Alum Creek, we captured 416 individual mudpuppies (269 F, 119 M, 28 J) with a 32% recapture rate during 52 weeks of spotlight surveys and 3,412 trap nights from 2020 to 2023 (Table 1, Fig. 3). The number of male, female, and juvenile captures did not differ significantly between year 1 and year 2. The number of juvenile ($\chi^2 = 10.326$, $P = 0.001$) and female ($\chi^2 = 7.1212$, $P = 0.007$) captures were significantly lower in year 3 than in year 2. The number of male captures did not differ between year 2 and year 3. We captured 534 mudpuppies by hand or with net aided by spotlights. Only 83 mudpuppies were caught trapping. Trapping success was 0.021 mudpuppies per trap per night. Spotlighting capture success was 0.59 per search night. SVL of mudpuppies varied from 84–290 mm, and body mass varied from 15–361.5 g at Alum Creek (Fig. 4A). The Kruskal-Wallis test showed that captured male (Kruskal-Wallis $\chi^2 = 11.4$, df = 2, $P < 0.05$), female (Kruskal-Wallis $\chi^2 = 24.3$, df = 2, $P < 0.05$), and juvenile (Kruskal-Wallis $\chi^2 = 12.989$, df = 1, $P < 0.05$) mudpuppies had significantly different SVLs between years. Dunn's test for pairwise comparisons indicated that females from 2020–21 had significantly smaller SVLs than females from 2021–22 (Z = –4.46, $P < 0.05$), but no significant differences were found between 2021–22 and 2022–23 (Z = 0.08, $P > 0.05$). Males from 2020–21 had significantly smaller SVLS than males in 2021–22 (Z = –2.3, $P < 0.05$), but no significant differences were found between 2021–22 and 2022–23.

At the Grand River, we captured 197 individual mudpuppies (60 F, 28 M, 109 J) with a 40% recapture rate during ten seining surveys from 2021 to 2022 (Table 1, Fig. 5). The number of juvenile captures was significantly higher in year 2 ($\chi^2 = 5.02$, $P < 0.05$), and the number of female captures was close to significantly lower in year 2 ($\chi^2 = 3.82$, $P = 0.051$). Number of male captures did not differ between years ($\chi^2 = 0.05$, $P > 0.05$). SVL of mudpuppies varied from 30–235 mm and 6.5–255 g body mass at the Grand River (Fig. 4B). SVLs did not differ between years for any sex

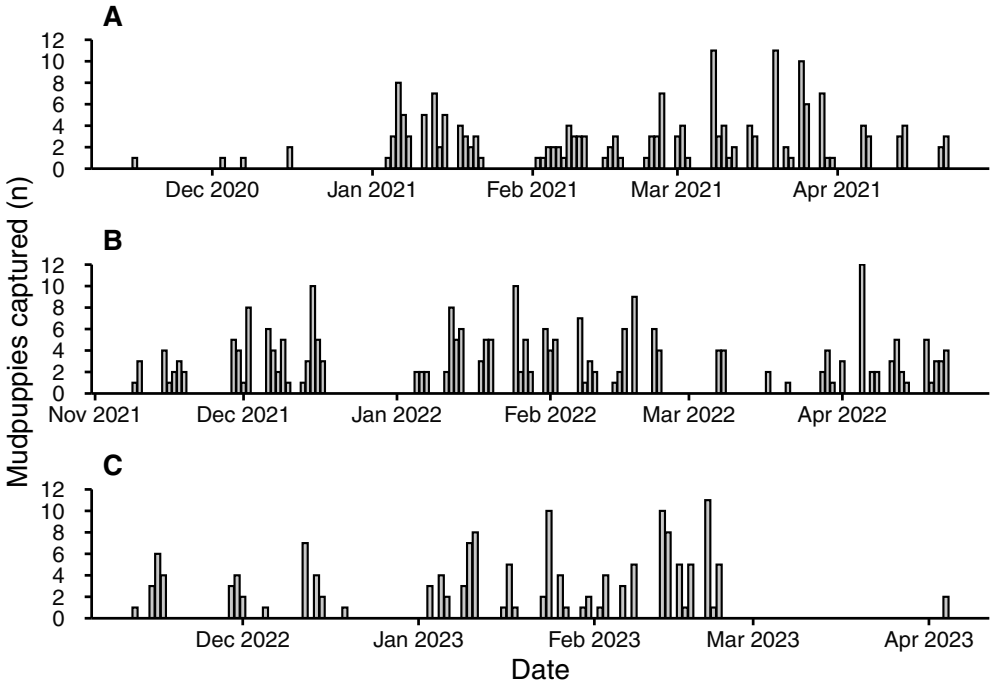


Fig. 3. Number of mudpuppies (*Necturus maculosus*) captured from trapping (four nights per week with no trapping in 2023) and spotlight surveys (five nights per week) at Alum Creek, Ohio, USA, during (A) November 2020 to May 2021 (year 1), (B) November 2021 to May 2022 (year 2), and (C) November 2022 to May 2023 (year 3). Mudpuppy captures (n) include same year recaptures.

(female: W = 2296, $P > 0.05$, male: W = 413.5, $P > 0.05$, juvenile: W = 2063.5, $P > 0.05$).

Population size and survival.—The estimated population size (*Nsuper*; total number of individuals that ever entered the study area during the sampling period) for the 400 m stretch of Alum Creek (hereafter Alum Creek) for year 1, 2, and 3 (Supplemental Tables S1–S3; see Data Accessibility), and the estimated population size for the 400 m stretch of the Grand River (hereafter the Grand River) in year 1 and 2 (Supplemental Tables S4–S5; see Data Accessibility) are reported in Figure 6 and Table 2. The average *Nsuper* difference between Alum Creek in year 1 and Alum Creek in year 2 was 198 (credible intervals: 19–337) individuals, and the

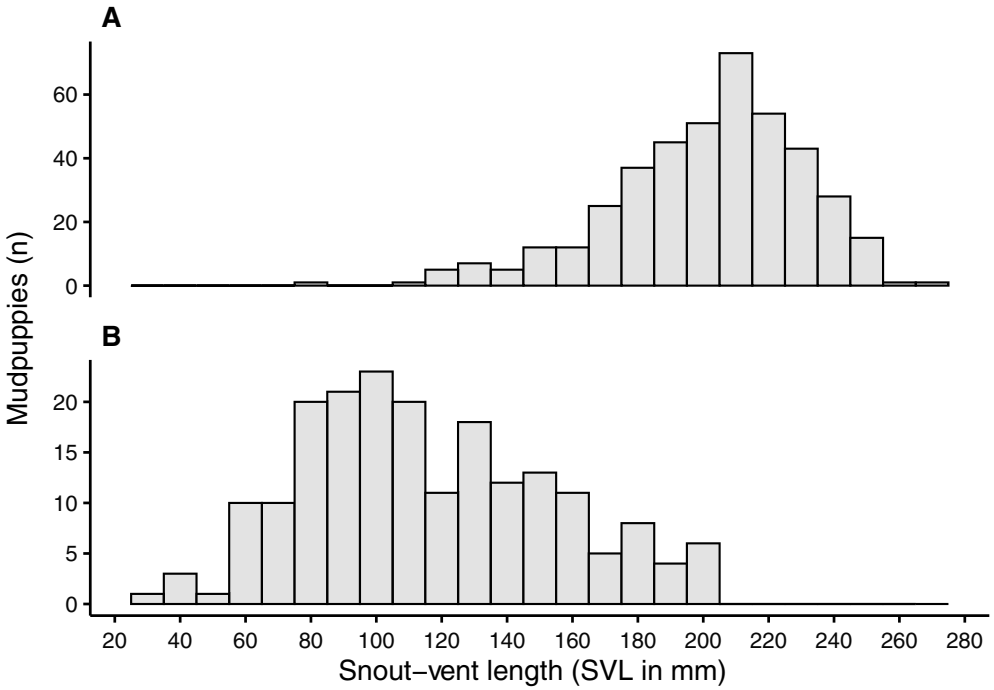


Fig. 4. Mudpuppy snout–vent length (mm) for (A) Alum Creek and (B) the Grand River.

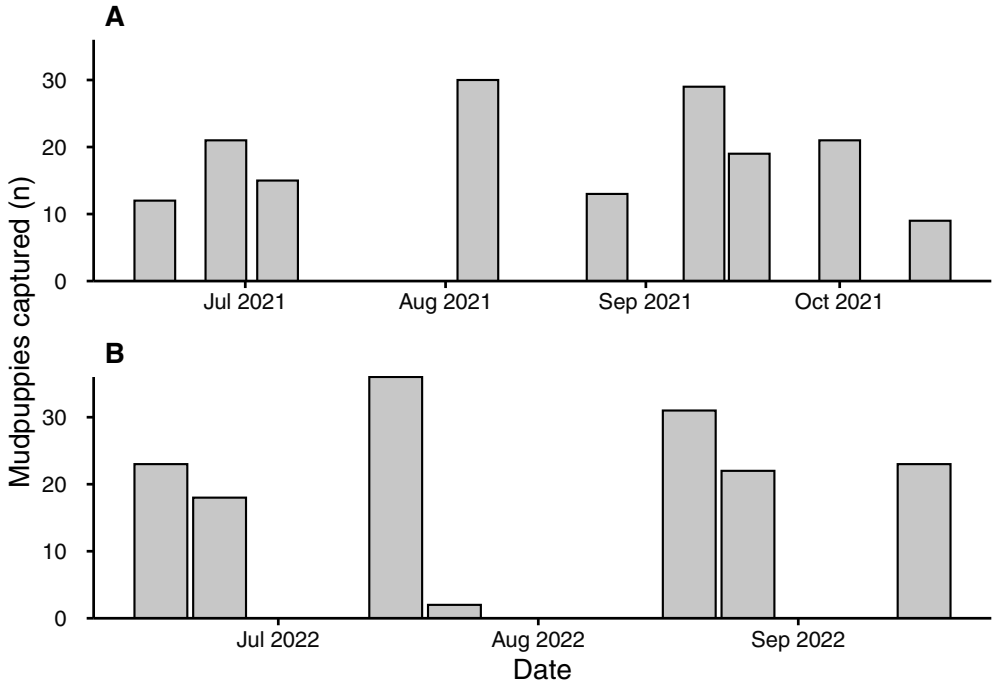


Fig. 5. Number of mudpuppies (*Necturus maculosus*) captured from seining surveys at the Grand River, Ohio, USA, during (A) June 2021 to October 2021 (year 1) and (B) June 2022 to October 2022 (year 2). Mudpuppy captures (n) include same year recaptures.

probability that the Alum Creek population was greater in year 2 was 99%. The average difference between Alum Creek in year 2 and Alum Creek in year 3 was 64 individuals (–59–206), and the probability that the Alum Creek population was greater in year 2 was 85%. The average difference in population size for the Grand River in year 1 and the Grand River in year 2 was 14 individuals (–306–312), and the probability that the Grand River population was smaller in year 2 was 53%.

Apparent yearly survival probability at Alum Creek was 0.28 (0.21–0.35; Fig. 7A; Table 3; Supplemental Table S6; see Data Accessibility), and apparent yearly survival probability at the Grand River was 0.24 (0.15–0.43; Fig. 7B; Table 3). Survival increased with SVL at both sites. Probability of capture at Alum Creek was 0.08 (0.06–0.10) in year 1, 0.09 (0.08–0.1) in year 2, and 0.14 (0.11–0.17) in year 3 (Table 3; Supplemental Table S6; see Data Accessibility). The probability of capture at the Grand River was 0.13 (0.05–0.42) in year 1 and 0.17 (0.08–0.26) in year 2 (Table 2; Supplemental Table S7; see Data Accessibility).

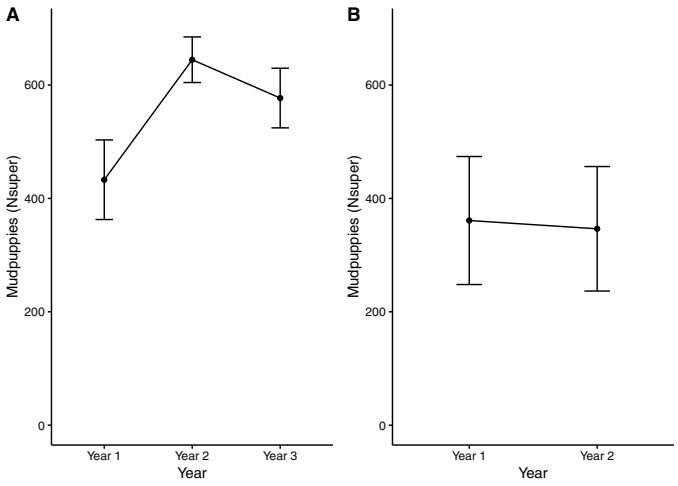


Fig. 6. Population size estimates with 95% credible intervals: (A) Alum Creek for November 2020 to May 2021 (year 1), November 2021 to May 2022 (year 2), and November 2022 to May 2023 (year 3) and (B) Grand River for June 2021 to October 2021 (year 1) and June 2022 to October 2022 (year 2).

Individual growth estimates and time to maturity.—Starting from a hatchling SVL of 14.5 mm, 50% of juvenile mudpuppies at Alum Creek are expected to reach the minimum size of sexual maturity (130 mm SVL; Shoop, 1965) at around 7 years and a maximum size of approximately 290 mm SVL at around 30 years. At the Grand River, 50% of juvenile mudpuppies are expected to reach the minimum size of sexual maturity after 5 years and a maximum size of approximately 235 mm SVL at around 15 years (Fig. 8).

TFM treatment.—During the post-TFM treatment surveys, we recovered 45 dead mudpuppies, ranging in total length from 46–330 mm ($\bar{x}$ = 127 ± 66 mm) and a mass of 0.5–270 g ($\bar{x}$ = 20.5 ± 40.7 g; Table 1). Based on our sample, juveniles accounted for more than 94% of the mortality. None of the dead mudpuppies recovered contained PIT tags.

DISCUSSION

We estimated population size, survival rate, and growth curves for two mudpuppy populations in Ohio. Compared with other mudpuppy studies, we had high capture and recapture rates for both sites across years. Despite our intensive and successful effort to capture large numbers of mudpuppies, our population size estimates had wide and broadly overlapping credible intervals between years. Because of this

Table 2. Mean parameter estimates ± standard deviation for the Jolly-Seber population model parameterizations for mudpuppies at Alum Creek in year 1, 2, and 3 and the Grand River in year 1 and 2. The parameters are variance (sigma2), mean capture probability (mean.p), inclusion probability (psi), mean survival (mean.phi), and super population size (Nsuper).

	Alum Creek Year 1	Alum Creek Year 2	Alum Creek Year 3	Grand River Year 1	Grand River Year 2
sigma2	0.16 ± 0.19	0.04 ± 0.06	0.09 ± 0.13	1.79 ± 1.07	1.06 ± 0.88
mean.p	0.08 ± 0.02	0.09 ± 0.01	0.14 ± 0.03	0.13 ± 0.08	0.17 ± 0.09
psi	0.68 ± 0.11	0.92 ± 0.06	0.9 ± 0.08	0.59 ± 0.19	0.56 ± 0.18
mean.phi	0.85 ± 0.03	0.81 ± 0.03	0.53 ± 0.07	0.80 ± 0.07	0.74 ± 0.09
Nsuper	432.95 ± 70.19	644.64 ± 40.21	577.08 ± 52.61	361.04 ± 112.92	346.44 ± 109.81

uncertainty in population size, we had limited ability to identify changes between years.

In 1987, Matson (1990) estimated a population size of 803 (556–1,118) mudpuppies per km in the Grand River prior to TFM treatment, and in 1988, 333 (280–397) mudpuppies per km following TFM treatment at the site. We extrapolated our population estimates for our 400 m study area to 1 km to compare with Matson (1990). Our projected Grand River population size in 2021 is 850 (460–1,470) mudpuppies per km, and in 2022, 708 (482–1,365) mudpuppies per km following TFM treatment. Matson's (1990) pretreatment estimates squarely lie within our 95% credible interval for Grand River population size, and our mean estimated population is comparable to Matson (1990), suggesting mudpuppy populations may have some resiliency to TFM. To detect a clear population trend, more sampling over a longer time period would be required, such as that conducted by Matson (2022). Our Grand River density estimates were comparable to the Alum Creek density estimates (798–1,740 mudpuppies per km).

Apparent survival did not differ between pre- and post-TFM treatment at the Grand River or between the Grand River and Alum Creek despite differences in sampling. Survival increased with SVL at both sites, but because apparent survival probability combines true mortality and permanent emigration, these results are difficult to interpret. Our extremely low survival rate estimates for small mudpuppies likely underestimates true survival. Juvenile mudpuppies may be more prone to disperse outside of the study area (Cushman, 2006). Developing a better understanding of juvenile mudpuppy behavior and movement would help tease apart mortality and dispersal. High apparent survival probability among sexually mature individuals is expected, given higher site fidelity compared to juveniles (Matson, 2005) and because mudpuppies can exceed 29 years in age (Bonin et al., 1995; Gendron, 1999). Adult mudpuppies also appear to be more resistant to TFM-induced mortality (Boogaard et al., 2003; Chellman et al., 2017).

Our monthly survival estimates (extrapolated from yearly estimates) were 0.88 (0.81–0.93) for the Grand River and 0.98 (0.95–0.99) for Alum Creek. To our knowledge, the only other study that estimated mudpuppy apparent survival was Chellman and Parrish (2010), which reported monthly survival was 0.87–0.88 for males and 0.87 for

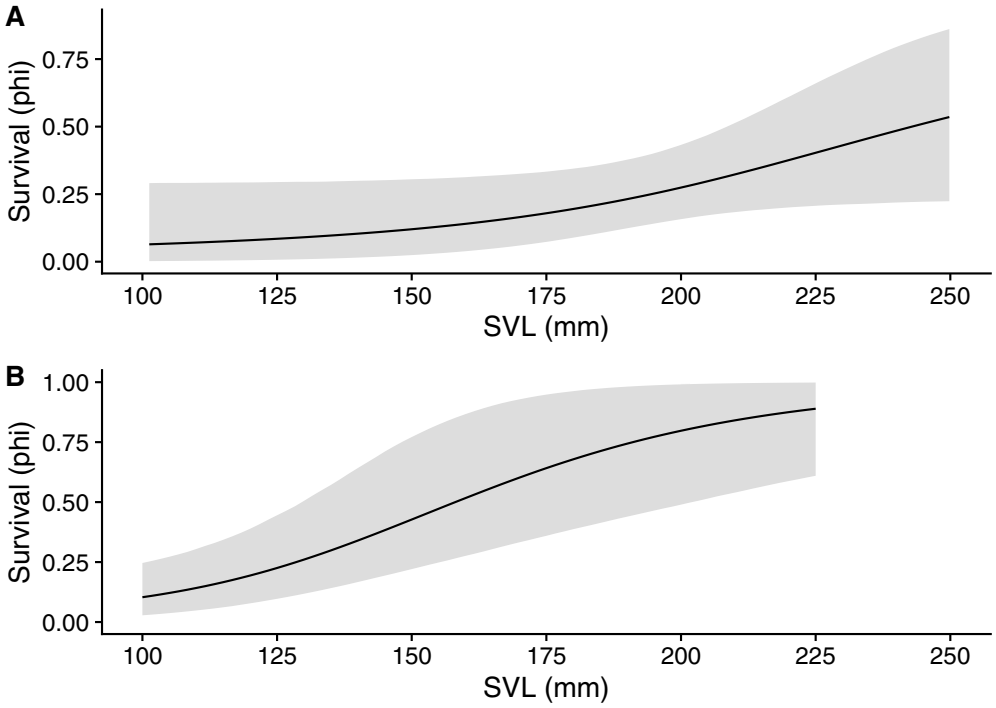


Fig. 7. Estimated survival with 95% credible intervals across a range of mudpuppy snout–vent lengths (mm) at (A) Alum Creek and (B) Grand River.

Table 3. Mean parameter estimates ± standard deviation for the Cormack-Jolly-Seber survival model parameterizations for mudpuppies at Alum Creek and the Grand River. The parameters are intercept (beta0), effect of SVL (beta1), mean capture probability (mean.p), mean survival (mean.phi), and standard deviation (sigma_time_p, sigma_ind_p).

	Alum Creek	Grand River
beta0	−0.96 ± 0.37	−1.24 ± 0.51
beta1	0.64 ± 0.37	1.59 ± 0.58
mean.p	0.04 ± 0.01	0.17 ± 0.05
mean.phi	0.28 ± 0.07	0.24 ± 0.09
sigma_time_p	0.69 ± 0.17	0.85 ± 0.4
sigma_ind_p	0.37 ± 0.21	0.88 ± 0.31

females in the Lamoille River, Vermont, another system that has been treated with TFM at intervals since 2009. Our monthly mudpuppy survival estimates for the Grand River exactly corresponded with those of Chellman and Parrish (2010).

The Grand River mudpuppy population exhibited more rapid growth trajectories than Alum Creek mudpuppies, potentially resulting in earlier maturation and a smaller estimated maximum adult size. Matson (2022) provides evidence that the Grand River mudpuppy population has experienced a 50 mm decline in average total length from 1987–2018 for individuals greater than 99 mm. Smaller body size can lead to lower fecundity, higher predation, and diminished competitive ability in other aquatic species (Salthe, 1969; Kaplan and Salthe, 1979; Berven, 1981; Formanowicz and Brodie, 1993). Smaller individuals can occur when energy is shifted away from growth and toward increased metabolic costs to enhance survival (Rowe et al., 1998). Rowe et al. (1998) found that tadpoles reared in polluted environments experience stunted growth and development because of an increased maintenance cost. Body size influences physiological performance, predator–prey interactions, life-history characters, ecological patterns, and evolutionary trajectories (Arendt, 2011). Exploited populations may exhibit increased growth rates, earlier reproduction, and skewed sex ratios (Healey, 1978; Natusch and Lyons, 2012; Monk et al., 2021). These ontological and reproductive changes may help offset increased mortality; however, compensatory life history changes may be unable to overcome long-term population impacts, due to the apparent minimum time it takes for mudpuppies to mature, which is typically estimated to be anywhere between five and ten years (Bishop, 1926; Gendron, 1999), with males likely attaining maturity at a younger age and smaller size than females (Bishop, 1941).

Numerous site-level differences and survey methods could contribute to the differences observed between sites. Trapping, rock flipping, and dip netting are all known to bias in favor of adult mudpuppies (Matson, 1990; Gendron, 1999; Chellman et al., 2017). Seining is an effective way to sample the smaller size classes as well as adults (Matson, 1990). Rock flipping and seining are not feasible in Alum Creek because of the rip-rap substrate. However, because of the size of PIT tags, we did not tag any animals smaller than 100 mm TL in either population. We found night spotlight surveys to be a highly effective survey technique where

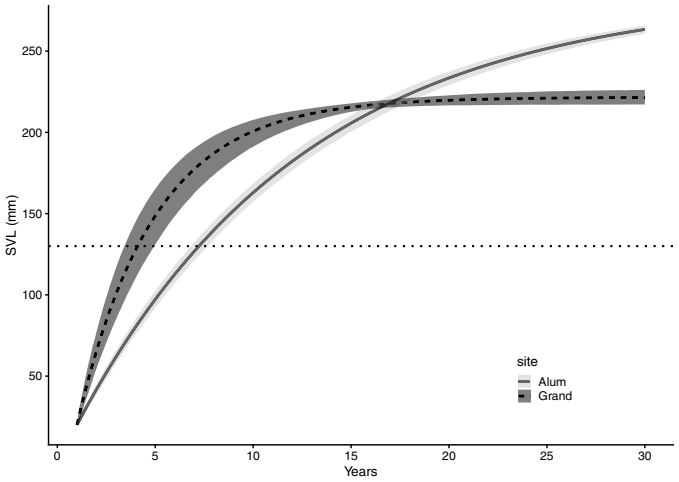


Fig. 8. Asymptotic growth curves with 95% credible intervals, indicating the time it would take mudpuppies to reach 130 mm snout–vent length (literature-based minimum size at sexual maturity) in Alum Creek and in the Grand River.

water is shallow and clear. Time of year may also influence capture rates because mudpuppy activity increases in the winter months (Shoop and Gunning, 1967). Despite this, we did not survey the Grand River in the winter because of dangerous conditions (high flow) and because Matson (1990) found success using seines at this site.

Our low trap rate was consistent with previous studies. Chellman et al. (2017) reported capture and recapture probabilities <0.04. Many studies suggest that mudpuppies are not available for capture during the warmer months of the year (Gendron et al., 1997; Chellman et al., 2017). We observed no mudpuppies in Alum Creek before 8 November. However, we captured mudpuppies in the Grand River using seining and rock flipping during the summer (June–September). This suggests under certain environmental conditions, mudpuppies remain accessible to surveyors during the summer. Matson (2022) also reported consistent success capturing mudpuppies during summer months.

We found lower mudpuppy mortality following TFM treatment than has been reported in other studies. TFM applications are typically applied at 1.2–1.5X minimum lethal concentration (MLC; 3–3.75 mg/L) for Sea Lamprey (Brege et al., 2003; McDonald and Kolar, 2007). Laboratory studies suggest that 1.44X MLC (3.6 mg/L) causes 50% mortality (LC50) for adult mudpuppies. LC50 occurs at lower concentrations for lamprey and mudpuppies with TFM/1% niclosamide, a commonly used mixture for its increased effectiveness for killing ammocoetes with less TFM. In two lab trials, Boogaard et al. (2003) found LC50 for mudpuppies to be 2.11 mg/L with TFM and 2.15 mg/L with TFM/1% niclosamide mixtures.

In free-flowing streams, 0.84–2.64X MLC (2.1–6.6 mg/L) can result in extensive mudpuppy mortality (Matson, 1990; Boogaard et al., 2003). The TFM concentration at the Grand River study site in 2022 averaged 0.96X MLC (2.4 mg/L) for nine hours. The highest concentration recorded in the river was 1.6X MLC (4 mg/L). In 2017, 218 dead mudpuppies were found in the Grand River following TFM treatment. The highest TFM concentration recorded in the river that year was over 2.4X MLC (6 mg/L; USFWS, unpubl. data). Chellman et al. (2017) reported collecting over 500 dead mudpuppies

from the visible portions of the Lamoille River in 2009, with an average reported TFM concentration of 1.2 MLC.

TFM concentration alone may not be informative of risk to nontarget species because TFM toxicity also depends on pH, alkalinity, and temperature (Bills et al., 2003; Hepditch et al., 2019; Hlina et al., 2021; Schueller et al., 2023). For example, juvenile Lake Sturgeon (*Acipenser fulvescens*) are more susceptible to TFM than adults, and their vulnerability decreases with increased pH and alkalinity (Hepditch et al., 2019). Future studies should aim to understand how mudpuppies of different ages vary in their susceptibility to TFM under variable concentrations, pH, and alkalinity.

Stress from courtship and breeding may increase mudpuppy susceptibility to TFM (Gendron, 1999; Boogaard et al., 2003). TFM applications typically occur in the fall (October) and early spring (late April) when mudpuppies are breeding and producing eggs, respectively. Much of the mudpuppy's life history, including seasonal movements, habitat use, population structure, dispersal ability, and fine-scale distribution, remain unknown (McDaniel et al., 2009; Murphy, 2016). Filling these gaps in our knowledge of mudpuppy ecology is essential to assess where and when mudpuppies are at greatest risk from TFM.

Boogaard (unpubl. report) suggested a typical TFM treatment can cause about 10% mortality among adult mudpuppies and up to 100% mortality among juvenile mudpuppies. Chellman et al. (2017) found that 70% of observed mudpuppy mortalities were juveniles following TFM treatment, which is consistent with our estimate that juveniles comprised 94% of the observed mudpuppy mortality. Boogaard (unpubl. data) found the LC50 was 2.4X greater for adult mudpuppies than Sea Lamprey, and 1.6x greater for juvenile mudpuppies than Sea Lamprey. Other studies have found similar vulnerability of juveniles and adults to TFM (Matson, 1990; Gendron, 1999). If adult mudpuppies are less susceptible to TFM, then studies based on adult population size and survival may find a lag in the effects of TFM. High levels of reproduction and recruitment in aquatic salamanders are necessary to maintain population stability (Freake and DePerno, 2017). High mortality among juvenile mudpuppies during TFM treatments may risk long-term population declines in areas, such as the Grand River, that receive lampricide treatments on 3–5 year cycles, which is a shorter interval than the typical duration required for mudpuppies to reach maturity.

Continued long-term monitoring of mudpuppy populations in areas impacted and unimpacted by TFM is essential to understanding long-term impacts of TFM in aquatic ecosystems. While we found no indication that mudpuppy populations have declined over the last 30 years, the ability to predict long-term population trends from only a few years of data is limited. A long-term study of the Grand River population by Matson (2022) found a slow to moderate decline over the last 32 years. This emphasizes the importance of consistent long-term population monitoring. Population declines for long-lived species like mudpuppies may be delayed following environmental perturbations because adults can persist even when there is little or no recruitment. Targeted hatchling surveys could be used to quantify recruitment, supplement adult mark–recapture surveys, and reveal potential effects of TFM on this life stage. Long-term population trajectories based on current demographic conditions, such as those produced by population viability analyses, can better capture risk faced by a population and be used to identify proximate causes of population decline (Wagner and Peterman, 2025).

DATA ACCESSIBILITY

Supplemental material is available at https://www.ichthyologyandherpetology.org/h2024078. Unless an alternative copyright or statement noting that a figure is reprinted from a previous source is noted in a figure caption, the published images and illustrations in this article are licensed by the American Society of Ichthyologists and Herpetologists for use if the use includes a citation to the original source (American Society of Ichthyologists and Herpetologists, the DOI of the *Ichthyology & Herpetology* article, and any individual image credits listed in the figure caption) in accordance with the Creative Commons Attribution CC BY License.

AI STATEMENT

The authors declare that no AI-assisted technologies were used in the design and generation of this article and its figures.

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LITERATURE CITED

Applegate, V. C., J. H. Howell, J. W. Moffett, B. G. H. Johnson, and M. A. Smith. 1961. Use of 3-trifluormethyl-4-nitrophenol as a selective sea lamprey larvicide. Great Lakes Fishery Commission Technical Report No. 1. Great Lakes Fishery Commission, Ann Arbor, Michigan.

Arendt, J. D. 2011. Size-fecundity relationships, growth trajectories, and the temperature-size rule for ectotherms. Evolution 65:43–51.

Berven, K. A. 1981. Mate choice in the wood frog, *Rana sylvatica*. Evolution 35:707–722.

Bills, T. D., M. A. Boogaard, D. A. Johnson, D. C. Brege, R. J. Scholefield, R. W. Westman, and B. E. Stephens. 2003. Development of a pH/alkalinity treatment model for applications of the lampricide TFM to streams tributary to the Great Lakes. Journal of Great Lakes Research 29:510–520.

Bishop, S. C. 1926. Notes on the habits and development of the mudpuppy *Necturus maculosus* (Rafinesque). New York State Museum Bulletin 268:5–60.

Bishop, S. C. 1941. The salamanders of New York. New York State Museum Bulletin 324:1–365.

Blaustein, A. R., B. A. Han, R. A. Relyea, P. T. J. Johnson, J. C. Buck, S. S. Gervasi, and L. B. Kats. 2011. The complexity of amphibian population declines: understanding

the role of cofactors in driving amphibian losses. Annals of the New York Academy of Sciences 1223:108–119.

Blaustein, A. R., D. B. Wake, and W. P. Sousa. 1994. Amphibian declines: judging stability, persistence, and susceptibility of populations to local and global extinctions. Conservation Biology 8:60–71.

Bonin, J., J.-L. DesGranges, C. A. Bishop, J. Rodrigue, A. Gendron, and J. E. Elliott. 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., T. D. Bills, and D. A. Johnson. 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. Journal of Great Lakes Research 29:529–541.

Boone, M. D., and R. D. Semlitsch. 2001. Interactions of an insecticide with larval density and predation in experimental amphibian communities. Conservation Biology 15:228–238.

Brege, D. C., D. M. Davis, J. H. Genovese, T. C. McAuley, B. E. Stephens, and R. W. Westman. 2003. Factors responsible for the reduction in quantity of the lampricide, TFM, applied annually in streams tributary to the Great Lakes from 1979 to 1999. Journal of Great Lakes Research 29(Supp. 1):500–509.

Bridges, C. M. 2000. Long-term effects of pesticide exposure at various life stages of the southern leopard frog (*Rana sphenocephala*). Archives of Environmental Contamination and Toxicology 39:91–96.

Brühl, C. A., T. Schmidt, S. Pieper, and A. Alscher. 2013. Terrestrial pesticide exposure of amphibians: an underestimated cause of global decline? Scientific Reports 3:1135.

Chatfield, M. W. H., P. Moler, and C. L. Richards-Zawacki. 2012. The amphibian chytrid fungus, *Batrachochytrium dendrobatidis*, in fully aquatic salamanders from southeastern North America. PLoS ONE 7:e44821.

Chellman, I. C., and D. L. Parrish. 2010. Developing methods for sampling mudpuppies in Vermont tributaries of Lake Champlain. Final Report. State Wildlife Grants Program, Vermont Fish and Wildlife, Waterbury, Vermont.

Chellman, I. C., D. L. Parrish, and T. M. Donovan. 2017. Estimating mudpuppy (*Necturus maculosus*) abundance in the Lamoille River, Vermont, USA. Herpetological Conservation and Biology 12:422–434.

Collins, M. K., S. F. Spear, J. D. Groves, L. A. Williams, and S. R. Kuchta. 2019. Searching for a salamander: distribution and habitat of the mudpuppy (*Necturus maculosus*) in southeast Ohio using eDNA as a rapid assessment technique. The American Midland Naturalist 182:191–202.

Cushman, S. A. 2006. Effects of habitat loss and fragmentation on amphibians: a review and prospectus. Biological Conservation 128:231–240.

Davidson, C. 2004. Declining downwind: amphibian population declines in California and historical pesticide use. Ecological Applications 14:1892–1902.

Davidson, C., and R. A. Knapp. 2007. Multiple stressors and amphibian declines: dual impacts of pesticides and fish on yellow-legged frogs. Ecological Applications 17: 587–597.

Fabens, A. J. 1965. Properties and fitting of the von Bertalanffy growth curve. Growth 29:265–289.

Formanowicz, D. R., and E. D. Brodie. 1993. Size-mediated predation pressure in a salamander community. Herpetologica 49:265–270.

Frankham, R., S. E. J. D. Ballou, D. A. Briscoe, and J. D. Ebel. 2010. Introduction to Conservation Genetics. Cambridge University Press, Cambridge.

Freake, M. J., and C. S. DePerno. 2017. Importance of demographic surveys and public lands for the conservation of eastern hellbenders *Cryptobranchus alleganiensis alleganiensis* in southeast USA. PLoS ONE 12:e0179153.

Gabbadon, P. W., and F. A. Chapman. 1996. Use of the lampricide 3-trifluoromethyl-4-nitrophenol (TFM) to control tadpoles in warmwater ornamental fish ponds. The Progressive Fish-Culturist 58:23–28.

Gendron, A. D. 1999. Status report on the mudpuppy, *Necturus maculosus*. Report to Reptile and Amphibian Subcommittee, Committee on the Status of Endangered Wildlife in Canada, Wildlife Canada, Québec.

Gendron, A. D., C. A. Bishop, R. Fortin, and A. Hontela. 1997. In vivo testing of the functional integrity of the corticosterone-producing axis in mudpuppy (Amphibia) exposed to chlorinated hydrocarbons in the wild. Environmental Toxicology and Chemistry 16:1694–1706.

Gilderhus, P. A., and B. G. H. Johnson. 1980. Effects of sea lamprey (*Petromyzon marinus*) control in the Great Lakes on aquatic plants, invertebrates, and amphibians. Canadian Journal of Fisheries and Aquatic Sciences 37:1895–1905.

Hayes, T. B., P. Case, S. Chui, D. Chung, C. Haeffele, K. Haston, M. Lee, V. P. Mai, Y. Marjuoa, J. Parker, and M. Tsui. 2006. Pesticide mixtures, endocrine disruption, and amphibian declines: are we underestimating the impact? Environmental Health Perspectives 114(Supp. 1):40–50.

Healey, M. C. 1978. The dynamics of exploited lake trout populations and implications for management. The Journal of Wildlife Management 42:307–328.

Hels, T., and E. Buchwald. 2001. The effect of road kills on amphibian populations. Biological Conservation 99:331–340.

Hepditch, S. L. J., L. R. Tessier, J. M. Wilson, O. Birceanu, L. M. O'Connor, and M. P. Wilkie. 2019. Mitigation of lampricide toxicity to juvenile lake sturgeon: the importance of water alkalinity and life stage. Conservation Physiology 7:coz089.

Hlina, B. L., O. Birceanu, C. S. Robinson, H. Dhiyebi, and M. P. Wilkie. 2021. The relationship between thermal physiology and lampricide sensitivity in larval sea lamprey (*Petromyzon marinus*). Journal of Great Lakes Research 47:S272–S284.

Hoffman, A. S., J. R. Robb, and B. E. Fisher. 2014. Recent records for mudpuppies (*Necturus maculosus*) in Indiana with notes on presumed declines throughout the Midwest. Proceedings of the Indiana Academy of Science 123:1–6.

Jensen, J. B., and C. D. Camp. 2003. Human exploitation of amphibians: direct and indirect impacts, p. 199–213. *In*: Amphibian Conservation. R. D. Semlitsch (ed.). Smithsonian Books, Washington, DC.

Kane, A. S., and D. L. Johnson. 1989. Use of TFM (3-trifluoromethyl-4-nitrophenol) to selectively control frog larvae in fish production ponds. The Progressive Fish-Culturist 51:207–213.

Kane, A. S., T. M. Stockdale, and D. L. Johnson. 1985. 3-trifluoromethyl-4-nitrophenol (TFM) control of tadpoles in culture ponds. The Progressive Fish-Culturist 47:231–237.

Kaplan, R. H., and S. N. Salthe. 1979. The allometry of reproduction: an empirical view in salamanders. The American Naturalist 113:671–689.

Kats, L. B., and R. P. Ferrer. 2003. Alien predators and amphibian declines: review of two decades of science and the transition to conservation. Diversity and Distributions 9:99–110.

Kellner, K. 2021. jagsUI: a wrapper around "rjags" to streamline "JAGS" analyses. https://CRAN.R-project.org/package=jagsUI

Kolozsvary, M. B., and R. K. Swihart. 1999. Habitat fragmentation and the distribution of amphibians: patch and landscape correlates in farmland. Canadian Journal of Zoology 77:1288–1299.

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. 2005. *Necturus maculosus* (Rafinesque, 1818). Mudpuppy, p. 870–871. *In*: Amphibian Declines: The Conservation Status of United State Species. M. J. Lannoo (ed.). University of California Press, Berkeley and Los Angeles.

Matson, T. O. 2013. Common Mudpuppy *Necturus maculosus maculosus* (Rafinesque 1818), p. 407–424. *In*: Amphibians of Ohio. R. A. Pfingsten, J. G. Davis, T. O. Matson, G. J. Lipps, Jr., D. Wynn, and B. J. Armitage (eds.). Ohio Biological Survey, Columbus, Ohio.

Matson, T. O. 2022. The impacts of long-term, episodic applications of the lampricide TFM on the common mudpuppy (*Necturus maculosus maculosus*) in a northeast Ohio stream. Ohio Biological Survey Notes 11:14–24.

McDaniel, T. V., P. A. Martin, G. C. Barrett, K. Hughes, A. D. Gendron, L. Shirose, and C. A. Bishop. 2009. Relative abundance, age structure, and body size in mudpuppy populations in southwestern Ontario. Journal of Great Lakes Research 35:182–189.

McDonald, D. G., and C. S. Kolar. 2007. Research to guide the use of lampricides for controlling sea lamprey. Journal of Great Lakes Research 33(Supp. 2):20–34.

Monk, C. T., D. Bekkevold, T. Klefoth, T. Pagel, M. Palmer, and R. Arlinghaus. 2021. The battle between harvest and natural selection creates small and shy fish. Proceedings of the National Academy of Sciences of the United States of America 118:e2009451118.

Murphy, M. O. 2016. Population genetic structure of *Necturus maculosus* in central and eastern Kentucky. Unpubl. M.S. thesis, University of Kentucky, Lexington, Kentucky. https://uknowledge.uky.edu/biology_etds/33

Natusch, D. J. D., and J. A. Lyons. 2012. Exploited for pets: the harvest and trade of amphibians and reptiles from Indonesian New Guinea. Biodiversity and Conservation 21:2899–2911.

NEPARC (Northeast Partners in Amphibian and Reptile Conservation). 2010. Northeast amphibian and reptile species of regional responsibility and conservation concern. Northeast Partners in Amphibian and Reptile Conservation (NEPARC) Publication 2010-1.

Plummer, M. 2003. JAGS: a program for analysis of Bayesian graphical models using Gibbs sampling, p. 1–10. *In*: Proceedings of the 3rd International Workshop on Distributed Statistical Computing (DSC 2003), Vienna, 20–22 March 2003.

Pounds, J. A., M. P. L. Fogden, J. M. Savage, and G. C. Gorman. 1997. Tests of null models for amphibian declines on a tropical mountain. Conservation Biology 11:1307–1322.

R Core Team. 2023. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Ray, N., A. Lehmann, and P. Joly. 2002. Modeling spatial distribution of amphibian populations: a GIS approach based on habitat matrix permeability. Biodiversity and Conservation 11:2143–2165.

Rowe, C. L., O. M. Kinney, R. D. Nagle, and J. D. Congdon. 1998. Elevated maintenance costs in an anuran (*Rana catesbeiana*) exposed to a mixture of trace elements during the embryonic and early larval periods. Physiological Zoology 71:27–35.

Rowe, G., and T. J. C. Beebee. 2003. Population on the verge of a mutational meltdown? Fitness costs of genetic load for an amphibian in the wild. Evolution 57:177–181.

Salthe, S. N. 1969. Reproductive modes and the number and sizes of ova in the urodeles. The American Midland Naturalist 81:467–490.

Schueller, J. R., M. A. Boogaard, C. A. Kirkeeng, N. A. Schloesser, S. L. Wolfe, A. J. Lettenberger, T. C. King-Heiden, and J. A. Luoma. 2023. Seasonal differences in larval sea lamprey (*Petromyzon marinus*) sensitivity to the pesticide TFM. Journal of Great Lakes Research 50:102248.

Shojaei, N., S. Naderi, E. Yasari, and N. Moradi. 2021. Exposure to common pesticides utilized in northern rice fields of Iran affects survival of non-target species, *Pelophylax ridibundus* (Amphibia: Ranidae). Environmental Science and Pollution Research 28:33557–33569.

Shoop, C. R. 1965. Aspects of reproduction in Louisiana *Necturus* populations. The American Midland Naturalist 74:357–367.

Shoop, C. R., and G. E. Gunning. 1967. Seasonal activity and movements of *Necturus* in Louisiana. Copeia 1967:732–737.

Stuart, S. N., J. S. Chanson, N. A. Cox, B. E. Young, A. S. L. Rodrigues, D. L. Fischman, and R. W. Waller. 2004. Status and trends of amphibian declines and extinctions worldwide. Science 306:1783–1786.

Wagner, R. B., and W. E. Peterman. 2025. Population viability analysis for the common mudpuppy: assessing potential impacts of TFM lampricide bycatch. Animal Conservation. DOI: 10.1111/acv.12989

Walther, G.-R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. C. Beebee, J.-M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. Nature 416:389–395.

Wilkie, M. P., T. D. Hubert, M. A. Boogaard, and O. Birceanu. 2019. Control of invasive sea lampreys using the piscicides TFM and niclosamide: toxicology, successes & future prospects. Aquatic Toxicology 211:235–252.

Williams, L. A., and J. D. Groves. 2014. Prevalence of the amphibian pathogen *Batrachochytrium dendrobatidis* in Eastern Hellbenders (*Cryptobranchus a. alleganiensis*) in Western North Carolina, USA. Herpetological Conservation and Biology 3:454–467.