

Assessing Mussel Survival and Growth as Steps Before Reintroductions to the Cuyahoga River, Ohio, USA

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ABSTRACT. Few rivers in the United States are more infamous than Ohio's Cuyahoga River. Its waters, which were once characterized as oozing—not flowing—in the 1960s became the impetus for the Clean Water Act of 1972 following publicity on a series of fires. Returning fauna to the Cuyahoga River has become a major focus especially of the Cuyahoga Valley National Park (CUVA), which notes that fish populations and water quality have improved but that no natural recovery of freshwater mussels has occurred even within extensive protected parklands. Collaborating with multiple stakeholders, pilot projects tested whether the river is satisfactory for mussel survival and growth. In the first round of testing, adult *Ortmanniana ligamentina* (muckets) from a nearby river were inserted into wire cages spread across 3 locations within the Cuyahoga River, and their survival was monitored over a period of 70 days. A second round of testing examined the survival and growth of hatchery-reared 1-year old *Lampsilis siliquoidea* (fatmuckets) inserted into small mesh silos placed in 5 locations within the Cuyahoga River over a period of 105 days. The second set of tests also measured the survival of resident mussels in a control location in the Grand River, Ohio, where mussels are abundant. Almost all of the adult *O. ligamentina* mussels survived, except where sediment inundated the enclosures, and the survival of the juvenile *L. siliquoidea* mussels approached 60% with 16% linear growth in a 105 day period, matching results at the control site. Thus, water quality and food resources, which were also assessed by chemical and particulate analysis, appeared sufficient to consider reintroducing mussels to selected sites within the Cuyahoga River.

Key words: conservation, habitat, stream, Unionidae, sedimentation

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INTRODUCTION

Across most aquatic and marine systems, healthy shellfish communities are needed to decrease the occurrence of eutrophication events, provide bedload stabilization, increase overall habitat structure, and release nutrients from the sediment through bioturbation (Soto and Mena 1999; Gutiérrez et al. 2003; Spooner and Vaughn 2006). Freshwater mussels (Unionidae) are critical regulators of ecosystem function in rivers, cycling nutrients between the benthos and water column by first pedal feeding in sediments, then filtering as much as 1 liter of water through their ciliated gills each hour (Pusch et al. 2001). During the filtration process bacteria, phytoplankton, and dissolved organic materials are converted into fecal pellets, which are subsequently deposited into the stream bottom (Kryger and Riisgard 1988;

Vaughn 2018; Campos et al. 2022), where they often provide shelter to small invertebrates (Vaughn and Hakenkamp 2001; Vaughn et al. 2008; Strayer 2014). In turn, mussels are a food source for fish, muskrats and otters (Stearns and Serfass 2011; Edelman et al. 2015; Cmeil et al. 2018; Clark et al. 2022). Reintroducing mussels into rivers from whence they have previously been extirpated (lost locally) may also provide these ecosystems with a chance to restart or renew the many integral functions and cycles that mussels help mediate (Haag and Williams 2014).

In the mid-twentieth century, the lower Cuyahoga River died ecologically (Davis 1951; Atwell et al. 2023). An extensive 1968 survey located only two fish species and four invertebrate species at just one of 23 testing locations; all 22 others lacked fish, mussels and detectable levels of other invertebrates

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(Simpson et al. 1969). The story behind this death and what caused it is infamous—packed with intentional pollution, anoxic zones from dams, and heavy flows of wastewater (Orr 1969)—yet it would take a news story in June 1969 about a river literally catching on fire to finally propel the action (DiMento and Oshio 2010) that led to the creation of the federal Environmental Protection Agency and the Clean Water Act of 1972 (USEPA 2024), followed in 1974 by the creation of the Cuyahoga Valley National Recreation Area, now Cuyahoga Valley National Park, or CUVA (National Geographic 2015).

Since the creation of the EPA, the passage of the Clean Water Act, and the creation of the CUVA, the water quality in the Cuyahoga River has improved (McManus et al. 2023), and small numbers of freshwater mussels, which have long been recognized as indicators of river health (Ortmann 1909), are occasionally found. A survey conducted by Smith et al. (2002) reported finding several live mussel specimens across the 40 kilometers of river located within the CUVA, including two *Potamilus alatus* (pink heelsplitters), a *Pyganodon grandis* (giant floater), and a *Quadrula quadrula* (maple leaf). The team also reported finding evidence, in the form of shells, of the presence of additional mussel species, including *Potamilus fragilis* (fragile papershell) and *Fusconaia flava* (Wabash pigtoe). A recent reconnaissance survey in 2023 by the Northeast Ohio Regional Sewer District (NEORSD) confirmed the presence of mussels at 1 site downstream of CUVA, but searches in 2016 at bridge access points upstream totaled just 1 live mussel (Andrikanich 2020). These results indicate that mussel populations are not recovering naturally.

Reintroducing mussels requires an extensive multistep process (Norris et al. 2022), which CUVA began by soliciting input from an array of sources: the U.S. Army Corp of Engineers (USACE), Ohio Environmental Protection Agency (OEPA), Ohio Department of Natural Resources (ODNR), United States Fish and Wildlife Services, Ohio State University, Ohio Department of Transportation, University of Toledo, NEORSD, Edge Engineering and Science, Cleveland State University, Otterbein University, EnviroScience, and Lawhon and Associates. Based on OEPA surveys from 2017–2019, all Cuyahoga

River sites (excepting a dam pool) featured 12.5 kilometers of “Exceptional Warmwater Habitat.” Over 40 fish species have been documented (OEPA 2023), including the host fishes for many species of mussels that several studies based on historical records suggest may be some of the top candidates for reintroduction (Tevesz et al. 2002; Schwartz and Trimboth 2023): *Ortmanniana ligamentina* (mucket), *Fusconaia flava* (Wabash pigtoe), *Lampsilis siliquoidea* (fatmucket), *Potamilus fragilis* (fragile papershell), *Potamilus alatus* (pink heelsplitter), and *Quadrula quadrula* (maple leaf).

To test mussel survival and growth, individuals deemed sensitive to environmental conditions were deployed within enclosures at CUVA, first adult (3–6 year old) *O. ligamentina* in summer 2021 and second, juvenile *L. siliquoidea*, a species widespread regionally (Krebs et al. 2010). Although largely extirpated from most of Ohio and elsewhere in the Mississippi River drainage (MDNR 2023) in the early 20th century, *O. ligamentina* remains common in the Grand River, a nearby river in Ohio that has exceptional mussel diversity (Huehner et al. 2005; Watters et al. 2009).

METHODS AND MATERIALS

Survival of Adult Mussels in Cages

A total of 43 *Actinonaias ortmanniana ligamentina* mussels were collected from the Grand River (Latitude: 41.172, Longitude: -81.572) on the morning of July 27, 2021, and transported to the Cuyahoga River in buckets of river water with battery-powered bubblers. The collected mussels were relocated to wire cages placed at designated sites across three locations along the Cuyahoga River (Fig. 1A): (a) Grether at 41.169, -81.572, (b) Lock 25 at 41.179, -81.578 and (c) Columbia Run at 41.276, -81.578. All wire cages were filled to an initial density of 4 to 5 mussels per cage. Sites were selected to try to minimize public interference as a walking/bike trail extends along the Cuyahoga River throughout the park and north into Cleveland, Ohio, and public kayaking is frequent.

The wire mesh cages (Fig. 1B and 1C) were used for the purpose of exposing mussels to sediment (Haag et al. 2019). Sandy and mixed-gravel substrates were chosen at depths where cages would stay submerged if flow rates dropped below 8 m³/s based on USGS National Water Dashboard monitoring station



Figure 1. Mussels in the Cuyahoga River (A) were housed at 3 sites for adult *Ortmanniana ligamentina* (muckets) in 2021, labelled a-c, and 5 sites for juvenile *Lampsilis siliquoidea* (fatmuckets) in 2022, labelled 1–5, with one control site in the Grand River for the silo study. Cages were placed on firm substrate (B) that exposed mussels to sediment (C). Mussel silos were constructed of cement and PVC piping (D), which quickly became camouflaged in the river by mud, moss, and algae (E).

for Jaite, Ohio, site number 04206425 (<https://waterdata.usgs.gov/monitoring-location/USGS-04206425/#dataType=continuous-00065-0&period=P7D&showFieldMeasurements=true>), yet also enable access at river flow rates up to 15 m³/s, a range spanning normal flow variation. Cages were monitored every two weeks over 70 days, as well as after every storm during this period, as conditions allowed, to ensure the cages were still attached and that cages did not become buried in sediment. Mussels were returned to the Grand River on October 5, 2021, early enough to meet state permit requirements on minimum water temperature for handling freshwater mussels.

Survival and Growth of Young Mussels in Silos

Juvenile (1-year-old) hatchery-raised *L. siliquoidea* (N=312) were transplanted into the Cuyahoga River in summer 2022, and their survival and growth was then monitored for 105 days. These mussels were propagated and shipped cool (between 10° C and 18° C) overnight to the CUVA from the Genoa National Fish Hatchery (USFWS). Because the origin of glochidia (larval mussels) were adult females collected from the Wisconsin River, these experimental individuals were retrieved from both rivers upon completion of the study.

Upon arrival, juvenile mussels were housed in plastic bags within buckets of Cuyahoga River water to acclimate them to new water conditions

and ambient temperature by doubling the amount of water in each bag three times over the course of an hour. Mussels remained one night in buckets with bubblers to aerate water before placement in the river within silos the following day.

Each silo (Fig. 1D) was constructed of PVC pipe and quick-dry cement as per Barnhart (2020). The first silo was assembled under the guidance of the Columbus Zoo and Aquarium, and 30 more were constructed at the CUVA. Each housed a 12.7 cm diameter, 7.6 cm length cylindrical plexiglass removable chamber constructed using Schedule 40 PVC pipe with ends of mesh screen. Chambers were secured into the cement casing with zip ties. The convex shape utilizes the Bernoulli effect to draw a continuous flow of water through each chamber, providing mussels access to nutrients from river water and a predicted low risk of clogging from sandy sediments (Barnhart et al. 2007). Each was labelled on the cement dome with a unique number 1–31 and on a laminated tag attached to the handle that indicated use in a scientific study to deter vandalism. The weight and shape of the silos allowed them to blend in with the bottom of the river within 1–2 weeks (Fig. 1E).

Ten juvenile mussels were ensconced within each silo (N=31) and monitored across 5 sites in the Cuyahoga River and at one control site in the Grand River (Lat./Long. coordinates in Table 1) during the 105 days from June 8, 2021 to September 21, 2022 (Fig. 1A). Sites were chosen by tactile assessment of

habitat suitability for mussels that targeted stable gravel substrate, less sand and silt to avoid clogging, moderately fast flowing water, and ease of access. To contrast variation within the CUVA, effort was made to space five sites evenly with consideration of proximity to major tributaries. Five silos were installed per site, but one extra silo (#31) with 12 remaining mussels was added at the southernmost location, site 5. At each site, mussel silos were placed along an upstream-to-downstream transect across 40 m at Site 1, 100 m at Site 2, 110 m at Site 3, 50 m at Site 4, 150 m at Site 5, and 45 m at the Grand River control site, all dependent on local conditions. The lowest-numbered silo at each location contained a HOBO data logger pendant to record hourly temperature trends for the duration of the study.

Mussels were measured before and after placement to estimate growth as a measure of water suitability (Buddensiek 1995). Juvenile mussels were photographed next to a dime for scale as a batch to limit handling time (Ohlman and Pegg 2020). Shell measurements were later made using Image J (Schneider et al. 2012). Length was measured as the longest possible line parallel to the hinge.

Collecting water quality data

To characterize abiotic conditions experienced by mussels at each deployment site, flow rates were monitored at the closest USGS stations, which were Jaite (04206425) for the Cuyahoga River and Painesville (04212100) for the Grand River. On July 14, 2022 and September 14, 2022 water quality was assessed at each site using a YSI® ProQuatro water meter and quad sensor cable. The quad sensor cable has probes for pH, specific conductance, dissolved oxygen, and NO_3^- . Water samples for suspended particulate volume, which represents available food (Fogleman et al. 2023), were collected 3 times, on August 3, August 22 and September 23, and sent to the Genoa Fish Hatchery for analysis. All samples were collected from center stream, just below the surface using a 50 ml centrifuge tube, which was put on ice in the dark and express mailed.

Silos were examined after three high-water events (June 9, July 6, and July 18, 2022) when flows exceeded $25 \text{ m}^3/\text{s}$, or about 3x normal rates, to ensure silo locations were stable and to examine whether sediment accumulated inside any chambers. When sediment was present, chambers were

gently rinsed in the river and the silo was replaced. Given the goal of testing water quality and food resources, the silos at Rockside were moved to a less-sandy location as a cluster across 4 m at the initial check in week 1. Survival and growth were examined at all sites on August 1, 2022, the midpoint, after which mussel silos were returned to the river, and at the end point on September 21, 2022.

Copper assessment

Copper was assayed by the methods of EPA report number 200.7 for trace elements (USEPA 1994). At the field test conclusion, the tissue of three juvenile *L. siliquoidea* survivors from each silo from the Cuyahoga River and five from each silo from the Grand River were placed in 1.5 ml microfuge tubes, flash frozen in liquid nitrogen, and stored in a -80°C freezer at NEORSD. Due to small size, tissues of all mussels per silo were pooled before tissue was dried for 2 weeks at 60°C and analyzed.

Data Analysis

Upstream to downstream trends in water quality metrics were assessed by linear regression. Variation in mussel length and survival over time at Cuyahoga River sites and between Cuyahoga River and the Grand River control site applied the rstatix package version 0.7.0 (R Coreteam version 4.2.1) for Wilcoxon rank sum tests and paired contrasts. Descriptive data visualization was produced in the ggplot2 package (version 3.3.6)

RESULTS

The survival rate of adult *Ortmanniana ligamentina* was 97% (or 42 of 43 mussels) one month into the water quality test in cage enclosures and 96% or 24 of 25 mussels at completion where cages were undisturbed and the substrate was firm (all at site c, Fig. 1A). Growth of adult mussels over 70 days, however, was negligible. Variation in mussel loss at the end related to differential impacts to specific cages and not to different mussels within cages. At site “b,” one cage was found empty, placed on an unofficial trail used for fishing that runs parallel to the site. Three other cages had been moved to shallow water, and these cages were subsequently transferred upstream to site “c” to avoid further vandalism. While this movement confounded assessment, unstable sandy substrate and deposition had already required cages to be reset

within site “b” after rain events. Substrate erosion and deposition were also observed at site “a” where all four cages there had anchors washed out and were recovered empty in a small backwater area. Survival therefore equated to 56% allowing for all causes of loss, putatively vandalism and sediment, but only one mussel from an intact cage died.

Mussel survival of juvenile *Lampsilis siliquoides* in the Cuyahoga River silo sites (48%) essentially matched the 50% survival at the Grand River control site (Fig. 2A) based on $\alpha = 0.05$. Survival varied among Cuyahoga River sites (Wilcoxon test, $p=0.05$), but significance was limited to one pairwise contrast between the most northern site 1 and the most upstream site 5, where only about 25% survived ($p = 0.027$). Mortality was over dispersed among silos within sites (mean = 4.79; variance = 8.44), with six silos showing 100% mortality, putatively from sediment inundation apparent at a halfway check point when 29 of the 31 silos were located and examined (5 silos then and a sixth later at site 2). Therefore, the cause was not related to water quality specific to a site. The other missing silo, once found, contained live mussels and remained unopened until final collection. If survival of these six sediment-impacted silos was excluded from the

final tally, mean survival was 62%. All five silos in the control Grand River site contained live mussels.

During the 105 days mussels were housed in silos in the river, they initially grew slowly (<1% increase in shell length at the midpoint), but thereafter, average shell length increased from a mean of 17.9 to 20.9 mm or about 16% (Fig. 2B). A trend for more rapid growth existed in more downstream sites. Mussels at sites 1 and 2 grew more compared to those at the Grand River control site (Wilcoxon rank sum test; $p < 0.001$ and 0.033 respectively), and this more rapid growth at site 1 compared to the Grand River was apparent by the midpoint measurements on length (paired test, $p < 0.001$).

Coincident with patterns in growth, particulate matter as a proxy for food availability showed a similar and significant increasing pattern downstream ($\hat{y} = 0.23X + 2.78$, $p=0.039$), but there was not a clear difference between the higher-particulate Cuyahoga River sites and the Grand River site where both growth and particulate counts were intermediate (Table 1). In the Cuyahoga River, water temperature rose slightly for sites further downstream, a pattern echoed by the slower movement and warmer waters of the Grand River

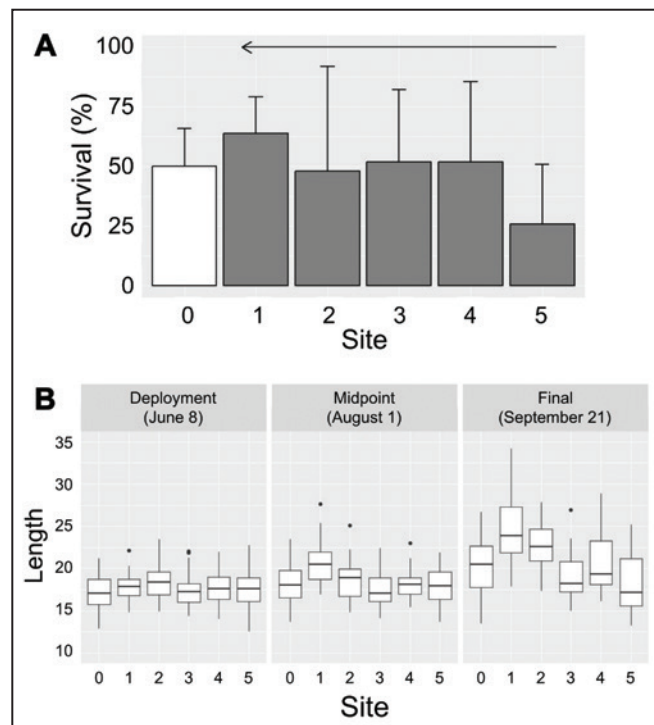


Figure 2. Success of juvenile mussels at 5 sites in the Cuyahoga River in comparison to controls (site 0, white) placed in the Grand River, Ohio: (A) survival of juvenile mussels in silos across sites where the arrow represents water flow direction and (B) their shell length distributions in mm (box plots).

Table 1

Mean water quality (standard deviation) and mussel tissue copper concentrations at each deployment site numbered from farthest north, or downstream (1) to south, upstream (5). The Grand River is used as a control because this neighboring river has a diverse mussel fauna. Each reported characteristic was measured twice, except particulates were measured thrice at each site during the study, and all sampled individuals per site were pooled for copper analysis.

Site	Coordinates latitude longitude	Particulates ($\mu\text{m}^3 \text{ mL}^{-1}$) $\times 10^{-6}$	Water Temp ($^{\circ}\text{C}$) pH	Specific Conductance ($\mu\text{S}/\text{cm}$)	Dissolved Oxygen (mg/L)	NO_3 (mg/L)	Copper (mg/kg dry wt)	
Control Grand	41.7265	2.10 ¹	23.1	8.04	258	8.96	1.18	19.8
	-81.1832	(0.93)	(1.0)	(0.14)	(72)	(0.11)	(0.44)	
1. Rockside	41.3888	2.62	22.1	8.14	705	8.29	4.64	25.8
	-81.6291	(0.24)	(1.8)	(0.06)	(25)	(1.15)	(1.41)	
2. Fitzwater	41.3570	2.42	21.4	8.09	698	8.50	4.58	23.0
	-81.5981	(1.23)	(1.6)	(0.02)	(33)	(0.08)	(NA) ²	
3. Boston	41.2626	1.90	20.9	8.09	727	8.92	6.16	28.2
	-81.5593	(0.78)	(1.6)	(0.08)	(39)	(0.11)	(0.80)	
4. Langes Run	41.2169	1.70	20.7	7.83	750	7.93	6.22	36.7
	-81.5601	(0.23)	(0.8)	(0.03)	(29)	(0.09)	(0.01)	
5. Grether	41.1719	1.85	20.1	7.76	724	7.81	5.83	35.3
	-81.5736	(0.87)	(0.7)	(0.04)	(4)	(0.65)	(1.01)	

¹ Value for the Grand River was adjusted based on missing data at the third sampling period. Particulate matter generally declined over time.

² NA (not applicable) indicates where only a single measurement was obtained

(USGS data). Across sites, pH hovered around 8 (range 7.73–8.18). Dissolved oxygen was usually above 8 and always above 7 mg/L. Other standard assays of stream quality suggested all sites were acceptable for mussels, although conductivity, NO_3 , and mussel tissue copper concentrations all registered consistently higher in the Cuyahoga River than in the Grand River.

DISCUSSION

Water in the Lower Cuyahoga River now supports both adult and juvenile freshwater mussels, a huge change following implementation of the Clean Water Act in 1972 (Davis 1969; Orr 1969). Improvements to ecosystem connectivity followed removal of a low-head dam, although combined sewage overflow remains an occasionally reported issue for public recreational use. Natural recovery of fish and macroinvertebrates, however, suggest such overflows are not a major limiting factor for the biological community (OEPA 2023). Therefore, even with only two mussel species tested,

opportunities to bring back mussel diversity and abundance exist.

Reestablishment of diverse historical mussel assemblages (Dean 1890, Tevesz et al. 2002) may now begin at selected sites in the lower Cuyahoga River to accelerate recovery already shown for multiple groups (Brown and Olive 1995), but most notably fish (Cannon et al. 2016; NEORS 2021; OEPA 2023). A juvenile survival rate of 46%, however, was lower than expected based on the results of other studies that held mussels short-term. Survival as reported in Doua et al. (2021) ranged from 50% to 100%, with a mean of 80%, and a study by Haag et al. (2019) on 6-month old *Lampsilis cardium* housed in silos obtained 90% average survival and in cages, 68% average survival across 40 streams. In the present study, one concern of unknown consequence was use of the smallest mussels from a large, reared cohort. This was not designed with intent, but was applied based on mussel availability. Yet survival was reasonable where sediment did not inundate silos.

Silos are typically more resistant to becoming packed with sediment than cages. Lower overall survival rate may be explained by sediment packing, but the hope in species reintroduction is that mussels would be able to unbury themselves and reach the surface for filter feeding. Generally, deeper and varied sediments enhance mussel habitat (Sansom et al. 2022), as burrowing is a normal component of mussel behavior throughout the year (Schwalb and Pusch 2007).

The challenge is to screen among identifiable risks as the first mussels are introduced. Both survival and growth followed an increasing and advantageous trend moving from upstream to downstream in the Cuyahoga River coincident with warmer temperature and greater particulate volume. Although warmer temperatures and reduced water flow did not result in increased growth at the Grand River site, food (particulate) availability there remained at an intermediate level among measurements. Streamflow can be negatively correlated with growth (Schöne et al. 2007; Rypel et al. 2009), while temperature variation can explain more than 50% of the variability in mussel growth (Kendall et al. 2010; Schöne et al. 2004). *Lampsilis siliquoidea* grows faster in streams than in lacustrine environments perhaps by primarily incorporating a combination of terrestrial carbon sources and bacteria (Bartsch et al. 2017). A cleaner yet anthropogenically impacted Cuyahoga River may continue to provide more nutrients to mussels than is common for the few pristine rivers that remain, even though these high-quality habitats are used to set environmental targets. Conductivity and NO_3 concentration are often measured in anthropogenically affected rivers, both of which were higher in the Cuyahoga River than the Grand River. However, the reported levels may have no direct negative impact on mussel health at common environmental levels (Moore and Bringolf 2020). Both traits show somewhat higher levels in Tinkers Creek (OEPA 2021), the largest tributary of the lower Cuyahoga River, and this stream supports a small but stable assemblage of mussels (Atwell et al. 2023).

Water quality in the Cuyahoga River appears acceptable across all sites, as expected for rivers that support mussels. Mussel loss from incidental burial impacts survival as a threshold outcome, unrelated to water or sediment chemistry (Haag et al. 2019).

Storms necessitated both cages and silos to be checked, and in some instances, relocated. Rain in urban watersheds may come with sewage overflow, impervious surface run off, and rapid increases in flow velocity, creating vast sediment transportation and widening the stream bed (Bevan et al. 2018; Bodeck et al. 2021). This effect is recognized by the park service as they frequently armor the stream banks to prevent erosion, which likely affects stream flow and shear stresses (Piégay et al. 2016).

The present results from cages and silos possess value for convincing state and federal agencies that the Cuyahoga River is ready for a biotic investment as mussels become available for translocation and for rearing juveniles that will be freely released. Such an investment is no trivial task. As freshwater mussel species are declining globally and much of the current restoration work has focused on species of conservation concern, demonstrating success with common generalist species may help direct focus on enhancing ecosystem function, a step beyond basic conservation (Aldridge et al. 2023). Determining success may take 10 years, but across the world, each community needs to begin assessing what is possible in their local watersheds, and thus we offer one blueprint to begin.

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