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REGULAR ARTICLE

RELOCATION OF WESTERN PEARLSHELL BEFORE AND AFTER STREAM RESTORATION IN TINCUP CREEK, IDAHO

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ABSTRACT

Freshwater mussels can be negatively affected by heavy machinery during stream restoration projects, requiring mussels to be relocated from the project area to unaffected areas. We assessed recapture and survival of Western Pearlshell (*Margaritifera falcata*) relocated in Tincup Creek, Idaho before and after a stream restoration project. From 2018 to 2020, we searched 4,350 m of Tincup Creek before restoration and salvaged 1,213 Western Pearlshell. Mussels were measured, marked with shellfish tags, and relocated among 10 sites in previously restored reaches elsewhere in Tincup Creek. At the time of salvage, mussels ranged from 19 to 84 mm with 83% of the mussels $\geq$50 mm, and most mussels were found in run habitats (63%). We surveyed all sites for tagged mussels 1 to 3 yr after relocation. We recaptured tagged mussels at seven of the 10 sites, and the recapture rate was positively related to the number of relocated mussels and mussel size. Tag retention was high but varied among relocation years. Estimated survival after 3 yr was 69.9–87.4% at two sites, and detection probability was 60.3–62.9%. Estimated survival after 1 yr was 55.8–91.3% at four other sites. Survival was low at three sites, likely due to low numbers of relocated mussels or scarcity of suitable habitat, and survival decreased dramatically at one site (from 91.3% to 28.6%) in 2 consecutive years, likely due to beaver activity. Our results suggest that stream restoration created habitat suitable for Western Pearlshell, and relocation was a successful strategy for avoiding direct mortality associated with restoration activities.

KEY WORDS: *Margaritifera falcata,* freshwater mussels, shellfish tags, conservation planning, unionids, North America, translocation

INTRODUCTION

In recent decades, much effort has been dedicated to stream restoration to offset negative impacts of anthropogenic degradation on aquatic habitats (Bernhardt et al. 2005). These projects are usually focused on fishes and aim to enhance habitat availability and complexity. Benefits of stream restoration can include increased macroinvertebrate abundance, increased periphyton production, and enhanced reproductive success for target fishes (Mueller et al. 2014). Stream restoration projects also can improve habitat quality for freshwater mussels, which are among the most imperiled animals in North America (Ricciardi and Rasmussen 1999; Lydeard et al. 2004; Haag and Williams 2014). However, initial restoration activities can result in direct mussel mortality from heavy equipment, burial in sediments, or stranding in dewatered channels. Managers should consider negative impacts on mussels before initiating restoration projects and make efforts to minimize those effects (Blevins et al. 2017a).

Relocation is a common strategy for temporarily or permanently removing mussels from areas that will be affected by construction or other human activities (Cope and Waller 1995; Eveleens and Febria 2022). Mussel survival after relocation varies widely among projects (Cope and Waller 1995; Tiemann et al. 2016), but proper collecting and handling practices, as well as prior evaluation of habitat suitability and mussel density at the relocation site, can increase the chances of success (Bolden and Brown 2002; Luzier and Miller 2009). Careful documentation and monitoring of relocation projects

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can provide additional case studies for improving relocation methods and success (Cope and Waller 1995, Hamilton et al. 1997).

We assessed the success of relocating Western Pearlshell (*Margaritifera falcata*) in Tincup Creek, Idaho before and after a stream restoration project. Western Pearlshell is considered near threatened globally and imperiled and a species of greatest conservation need in Idaho (Blevins et al. 2017b; Idaho Department of Fish and Game 2017). The project required use of heavy machinery, which likely would have resulted in direct mussel mortality in the project area. We salvaged mussels from the project area, relocated them to 10 previously restored sites elsewhere in Tincup Creek, and assessed recovery, tag retention, and survival after relocation.

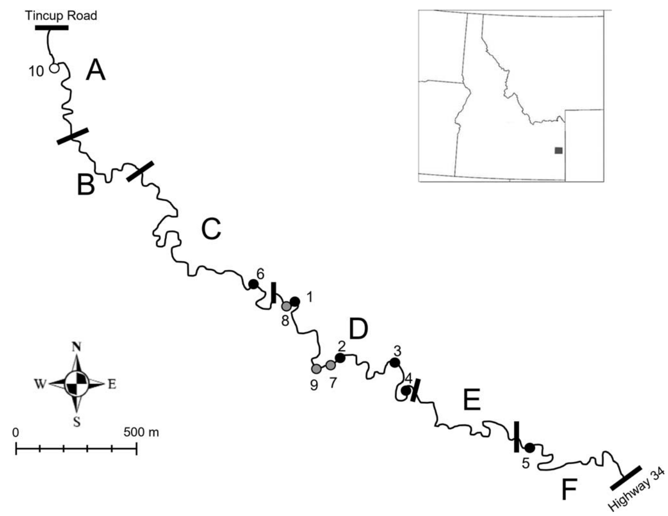

Figure 1. Map of the study sites in Tincup Creek, Idaho. Reaches (A-F) are delineated with thick black lines. Relocation sites are indicated by numbered dots; black dots represent sites to which mussels were relocated in 2018, gray dots represent relocation in 2019, and the white dot represents relocation in 2020.

METHODS

Study Area and Restoration Project

Tincup Creek is a 60-km-long tributary of the Salt River in the upper Snake River drainage in Bonneville and Caribou counties, Idaho. The stream flows east off the Caribou Range in the Caribou–Targhee National Forest and drops from 2,766 to 1,445 m in elevation from source to mouth. The hydrograph is typical of snowmelt-driven systems, having high spring flows followed by base flows for the remainder of the year.

Restoration of Tincup Creek was a collaborative project by Trout Unlimited, the U.S. Forest Service, and other groups; it was designed to improve habitat for Cuttthroat Trout (*Oncorhynchus clarkii*) and other aquatic species by addressing channel destabilization caused by prior removal of riparian vegetation. Specific actions included reconnecting historical meanders, planting willows in riparian areas, elevating riffles, and adding large woody debris. The project took place within a 6.5-km section of upper Tincup Creek from the Tincup Road bridge (U.S. Forest Service Road 117) downstream to the Highway 34 bridge (Fig. 1). Heavy equipment was used in the restoration and portions of the existing channel were dewatered, which prompted concern about the negative effects on Western Pearlshell (Blevins et al. 2017a). Restoration took place in phases from 2017 to 2020 in different reaches (Fig. 1). Restoration was completed in reaches D and F in 2017, Reach E in 2018, reaches A and B in 2019, and Reach C in 2020. Restoration of Reach A was originally scheduled to be completed in 2018 but was delayed until 2019.

Mussel Salvage

We did not salvage mussels from reaches D and F before restoration; however, mussels observed within these reaches during restoration prompted concerns about the impact of restoration on mussels in other reaches. Consequently, we salvaged mussels from reaches A and E in 2018, reaches A and B in 2019, and Reach C in 2020 before each reach was restored. Reach lengths were as follows: A, 843 m; B, 754 m; C, 1,849 m; and E, 928 m. Salvage occurred in all reaches in June and July at or near base flow; water temperatures were 8–18°C. We salvaged mussels by having two people search the entire reach in an upstream direction using plexiglass-bottomed view buckets. We carefully removed mussels from the substrate and placed them in mesh bags that remained in the stream during salvage. In each reach, we recorded the macrohabitat type (i.e., pool, riffle, or run) in which each mussel was found. Salvage in each reach required 45 to 96 person-hours.

We measured the length of each mussel from anterior end to posterior end and affixed two 8- × 4-mm polyethylene shellfish tags (model FPN8X4; Hallprint, Hindmarsh Valley, Australia) to the shell of each mussel with Loctite 60 Second Universal Glue (Henkel, Düsseldorf, Germany), which was allowed to dry for at least 30 s. The maximum time mussels were out of the water for measuring and tagging was 3 min.

Characterization of Mussel Habitat

In addition to recording the macrohabitat type where each mussel was found in each reach, we characterized Western Pearlshell habitat use during mussel salvage in reaches A and E in 2018 to guide subsequent relocation efforts in Tincup Creek. We divided each habitat unit where mussels were found into five equally spaced transects (perpendicular to flow) and measured the wetted width, three depths (at 25%, 50%, and 75% of channel width), and thalweg water velocity at each transect. We quantified substrate size in each transect using a modified pebble count (Wolman 1954), in which we measured the size of four substrate particles at equally spaced points across the transect (total = 20 particles/habitat unit) with a gravelometer (Wildco, Yulee, FL. USA).

Table 1. Number of Western Pearlshell (*Margaritifera falcata*) relocated from 2018 to 2020 and recaptured in 2019 to 2021 at 10 sites in Tincup Creek, Idaho. Not applicable (NA) indicates that the site was not surveyed for mussels that year.

Year Relocated	Reach	Site	Number Relocated	Recaptures in 2019	Recaptures in 2020	Recaptures in 2021
2018	D	1	28	0	0	NA
	D	2	22	0	0	NA
	D	3	117	64	68	61
	D	4	83	37	36	32
	F	5	62	0	0	NA
	C	6	96	NA	33	NA
2019	D	3	17	—	9	13
	D	7	64	—	NA	36
	D	8	51	—	28	9
	D	9	52	—	28	NA
2020	A	10	621	—	—	284

Mussel Relocation

After salvage and tagging, we relocated mussels to previously restored reaches of Tincup Creek. We relocated mussels to reaches C, D, and F in 2018, D in 2019, and A in 2020 (Table 1). We relocated mussels to one to seven sites within each reach (Reach A, one site; Reach C, one site; Reach D, seven sites; Reach F, one site). We chose relocation sites that had habitat types similar to those identified during salvage in reaches A and E (see Results), and we avoided livestock crossings. Sites were 20 to 30 m long; we placed mussels in these smaller areas to facilitate relocation and monitoring. However, site 10 was approximately 145 m long because of the high number of mussels relocated to this site. Relocation sites had a mean depth of 0.32 m (0.08 SD) and a mean thalweg velocity of 0.45 m/s (0.24 SD). Median substrate size generally was large gravel (32–64 mm), except for site 5, which had a median substrate size of small gravel (2–32 mm). We relocated mussels to each site in only 1 yr, except for site 3, to which we relocated mussels in 2018 and 2019.

We transported mussels to relocation sites in mesh bags placed in buckets with water; transit time was 10–30 min. Before placing mussels in the stream, we searched the site for resident mussels for about 30 min with a view bucket; we did not find resident mussels at any relocation site. We placed mussels in runs or riffles and avoided deep pools or low-flow areas. We placed relocated mussels on their side on the substrate surface and allowed them to burrow into the substrate; we did not attempt to bury the mussels to avoid damaging them (Blevins et al. 2017a). In areas with strong current, we placed mussels in pockets near large rocks or boulders to lessen the chances of dislodgement.

Postrelocation Surveys

We conducted mussel surveys at all relocation sites from 2019 to 2021 to evaluate relocation success. We surveyed each site one to three times (Table 1); surveys occurred 1 to 3 yr after relocation. We surveyed for mussels using plexiglass-bottomed view buckets throughout and within 100 m upstream and downstream of each site; search time at each site averaged 4 person-hours. We measured each mussel encountered and inspected it for the presence of tags. After the survey was completed, we released mussels where they were found within the relocation site. Mussels that were recaptured at site 6 in 2020 were moved to site 10 because restoration was scheduled for 2020 at that site.

Data Analysis

To determine the effect of mussel size on the probability of recapture after 1 yr, we used a generalized linear model with a binomial response in R (R Development Core Team 2018). We used recapture data collected in 2019, 2020, and 2021 that represented recaptures 1 yr after mussels had been relocated. Mussels that were not recaptured were given a value of 0, whereas mussels that were recaptured were given a value of 1. We determined the significance of mussel size on the probability of recapture using a drop-in-deviance test assuming a chi-squared distribution of deviances (Rasmussen and Belk 2012).

We estimated survival of relocated mussels using recapture data. We first estimated survival and detection probabilities for mussels at sites 3 and 4 because we surveyed those sites in 3 consecutive years (2019–2021). Our initial surveys found no resident mussels at any site before relocation (see previous), and all recaptured mussels were tagged. Therefore, we were unable to use simple mark–capture estimators that compare the proportions of marked and unmarked individuals. For sites 3 and 4, we estimated the abundance of surviving mussels at each site using the Schnabel estimator with 95% confidence intervals (CIs) estimated using the normal approximation (Krebs 1998). For the Schnabel estimator we used three sample occasions (2019, 2020, and 2021). The survey for recaptures in 2019 was considered the first sample occasion, and mussels captured in 2019 were considered captured for the first time for the Schnabel estimator. For 2020 and 2021, we considered mussels that had not been recaptured in previous sample occasions as "unmarked," whereas mussels that had been recaptured in previous sample occasions were considered "marked." We estimated survival of mussels at sites 3 and 4 by dividing estimated abundance and 95% CIs by the number of mussels originally relocated at each site. We estimated detection probability for sites 3 and 4 by dividing the number of mussels recaptured by the estimated abundance of surviving mussels. On the basis of the similarity of detection probabilities at sites 3 and 4 (see Results), we assumed that detection was similar at the other sites. We used the mean detection probability for sites 3 and 4 to estimate the number of surviving mussels at the other sites that only had one or two recapture occasions (sites 6–10).

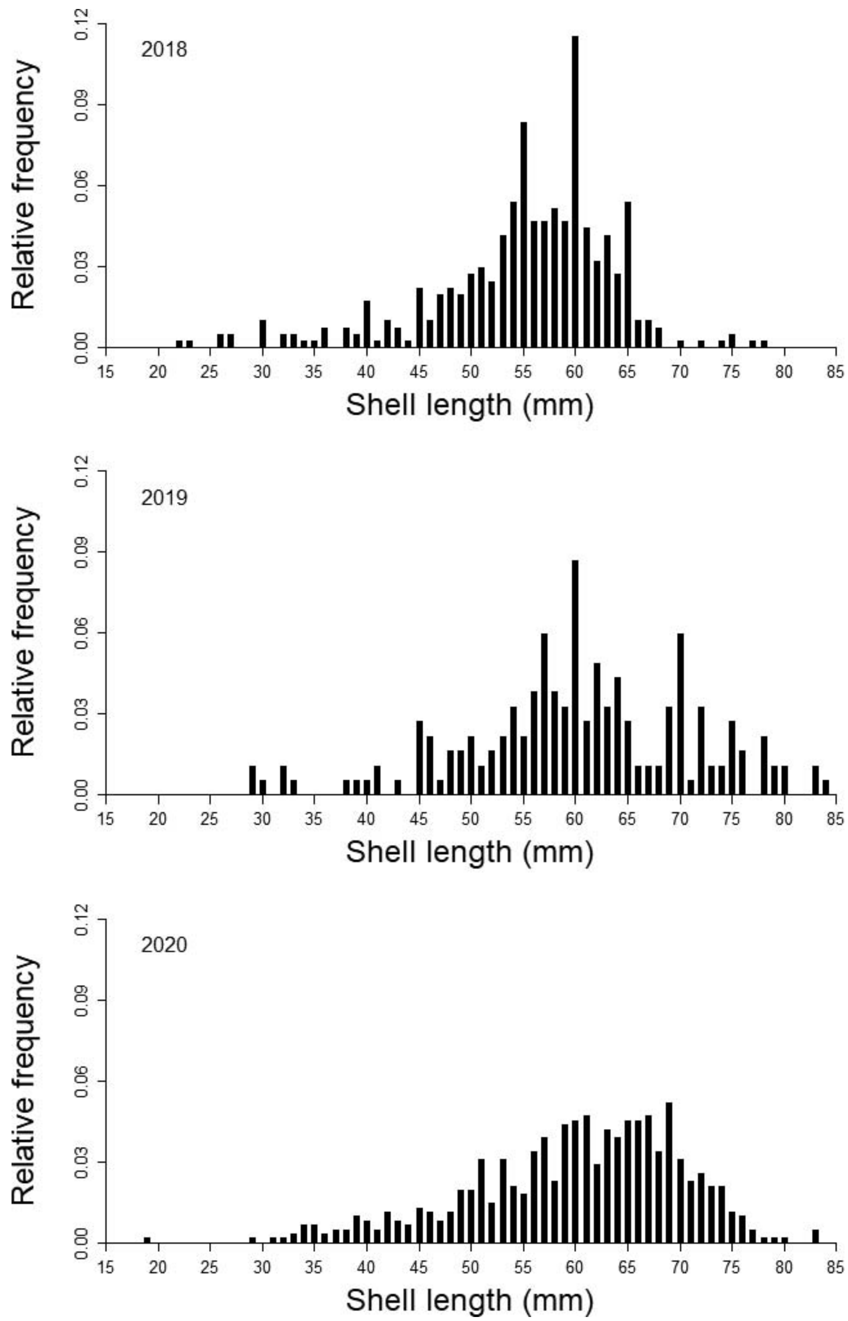

Figure 2. Size frequency distribution of Western Pearlshell (*Margaritifera falcata*) relocated in 2018 ($N = 408$ mussels), 2019 ($N = 184$ mussels), and 2020 ($N = 621$ mussels) in Tincup Creek, Idaho.

RESULTS

We salvaged and relocated a total of 1,213 Western Pearlshell from reaches A–C and E in Tincup Creek from 2018 to 2020. The size distribution of mussels at the time of salvage and relocation was similar among years; mussels were between 19 and 84 mm, and 80% of individuals were ≥50 mm (Fig. 2). Most Western Pearlshell (63%) were found in runs; 16% occurred in riffles and 21% in pools. Mussels in pools and riffles were often found in the short, runlike transition between riffles and pools where the channel was deeper than that found in the riffles, but the water velocity had not slowed completely to mean pool water velocity.

Mean channel depth in habitats where mussels were salvaged in 2018 was 40 cm ± 6.7 cm (SE) in Reach A and 29 cm ± 5.1 cm (SE) in Reach E. Mean thalweg water velocity in habitats where mussels were salvaged was 1.30 m/s ± 0.309 m/s (SE) in Reach A and 0.44 m/s ± 0.073 m/s (SE) in Reach E. Habitats where mussels were salvaged in both reaches had a similar mean substrate size (Reach A = 44 mm; Reach E = 48 mm) and the same median substrate size (32 mm).

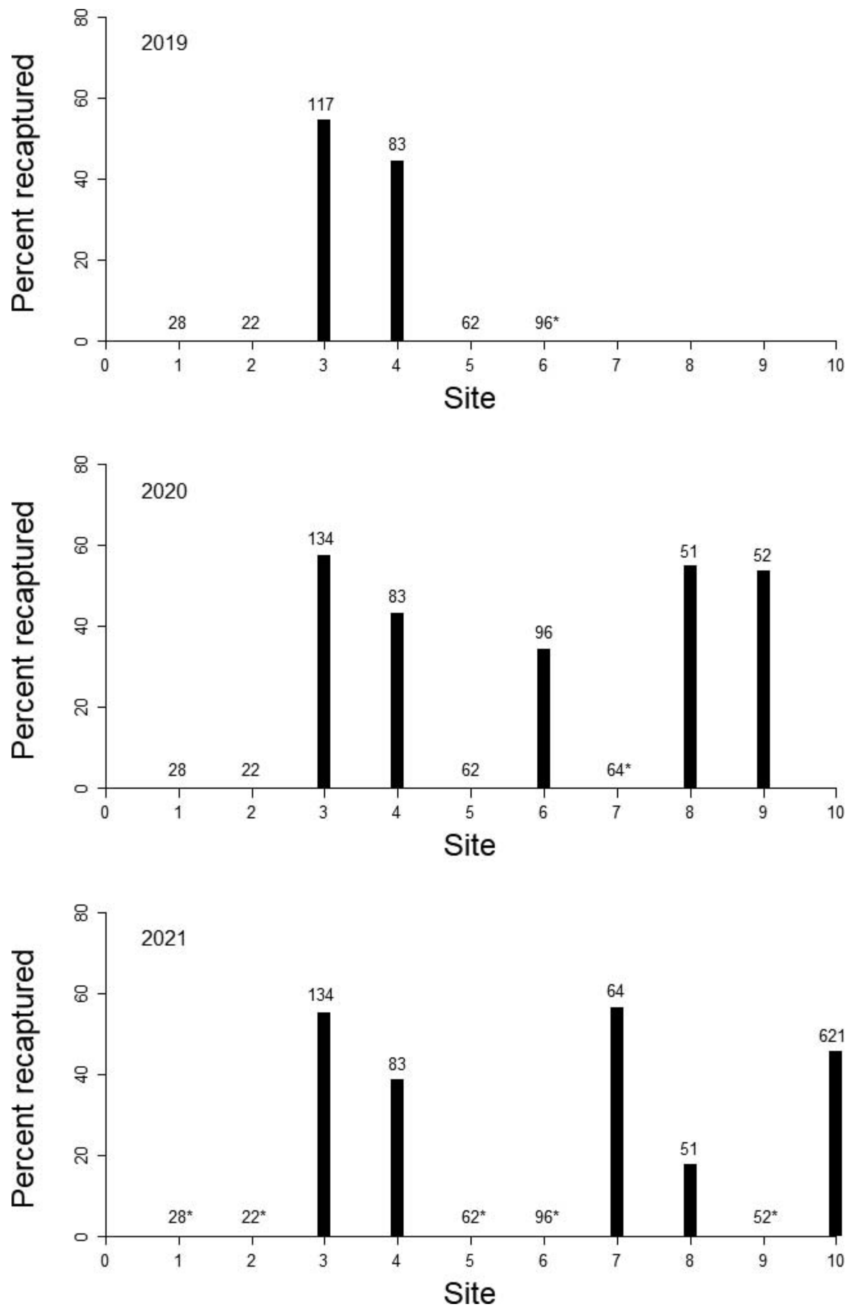

Figure 3. Percentage of Western Pearlshell (*Margaritifera falcata*) recaptured at relocation sites in Tincup Creek, Idaho in 2019, 2020, and 2021. Numbers above bars indicate the number of mussels relocated at each site. Note: the increase of mussels relocated at site 3 in 2020 reflects additional mussels relocated to the site in 2019 (see Table 1). An asterisk (*) indicates that the site was not surveyed for mussels during that year.

We recaptured Western Pearlshell at seven of the 10 sites to which mussels were relocated (Table 1; Fig. 3). At the sites that we sampled 1 yr after relocation (sites 1–5, 8–10), the number of recaptures was predicted remarkably well by the number of relocated mussels ($y = 0.468x - 4.695$, $R^2 = 0.983$, $P < 0.0001$), and the recapture rate after 1 yr was similar among sites at which mussels were recaptured (44.6–54.9%). Some mussels were recaptured in multiple years; we recaptured 71 mussels in 2 different years and 44 mussels in 3 different years. The recapture rate was similar between the first year and after 3 yr at sites 3 and 4, but it declined markedly at site 8 after 2 yr (17.7%). The probability of recapturing Western Pearlshell 1 yr after being relocated was positively related to mussel size ($\chi^2 = 51.32$; $P < 0.001$; Fig. 4). The few dead and tagged mussels we found were discovered only in 2021: two mussels from site 3 and three mussels from site 8.

Tag retention varied among years in which mussels were relocated (Table 2). For mussels relocated in 2018 and 2019, an average of 83.8% ± 5.9% (SE) retained both tags in each

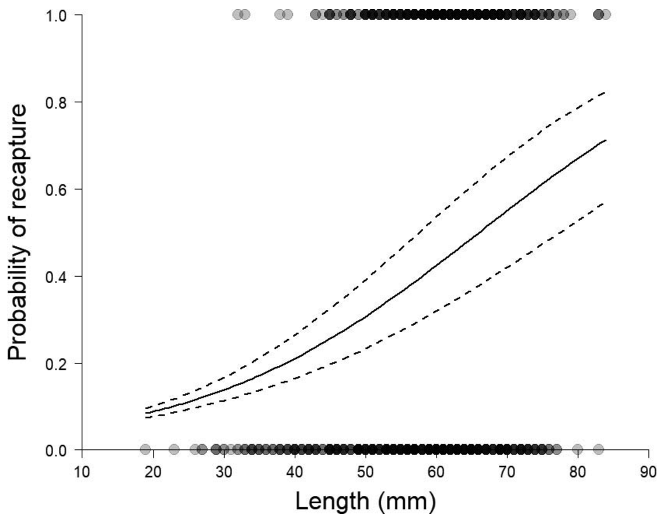

Figure 4. Probability of recapture of Western Pearlshell (*Margaritifera falcata*) as a function of mussel size 1 yr after relocation in Tincup Creek, Idaho. Recaptured mussels ($N = 157$) have a value of 1, whereas undetected mussels ($N = 146$) have a value of 0. Points are shaded on the basis of the number of individuals per point, with darker points representing a greater number of individuals. Equation of regression line is logit (recapture) = –3.35 + 0.051 × length. Error bars represent ±1 SE.

recapture event, 15.5 % ± 4.9% (SE) retained one tag, and only three mussels were found with no tags (<1%). However, only 52.2% of mussels relocated in 2020 retained both tags after 1 yr, 30.0% retained one tag, and 17.7% lost both tags. Mussels that had lost both tags retained glue on the shell; we did not find mussels without glue.

Estimated survival after 3 yr was 87.4% (95% CI = 73.0–98.3) at site 3 and 69.9% (54.9–96.1) at site 4. Detection probability was 62.9% ± 3.43% (SE) at site 3 and 60.3% ± 4.56% (SE) at site 4. On the basis of the mean recapture probability for sites 3 and 4 (61.6%), estimated survival of mussels after 1 yr was 55.8% at site 6, 74.2% at site 10, and 87.4% at site 9. Estimated survival after 2 yr was 91.3% at site 7. At site 8, estimated survival was 89.1% after 1 yr, but it decreased to 28.6% after 2 yr. The lack of recaptures in 2 yr of sampling at sites 1, 2, and 5 suggested that mussels did not survive after relocation to these sites.

Table 2. Retention of shellfish tags on Western Pearlshell (*Margaritifera falcata*) in Tincup Creek, Idaho 1 to 3 yr after relocation.

Year Relocated	Year Recaptured	Number of Mussels Recaptured	Number with Two Tags	Number with One Tag	Number with No Tags
2018	2019	101	90	11	0
	2020	136	120	16	0
	2021	105	82	21	2
2019	2020	65	50	14	1
	2021	61	53	8	0
2020	2021	276	144	83	49

DISCUSSION

Survival of relocated Western Pearlshell at most of our sites was high and comparable with survival rates reported in previous studies (71–93%, Tiemann et al. 2016). Earlier mussel relocations reported generally poorer survival (~50%; Cope and Waller 1995). We followed recent improvements in relocation protocols, such as avoiding extreme temperatures and overcrowding and keeping mussels moist (e.g., Blevins et al 2017a), which may have been responsible for high survival at most sites. Mussel mortality after relocation can be caused by handling stress during relocation or environmental factors at recipient sites. Mortality caused by handling stress is most likely to occur within the first year after relocation (Cope and Waller 1995). It is unlikely that low survival after 1 yr at sites 1, 2, and 5 was caused by handling stress because we used consistent relocation methods for all sites. The strong relationship we found between initial relocation number and recaptures suggests that the low recapture and survival rates at sites 1 and 2 were due simply to the low number of relocated mussels at those sites. Low survival at other sites may have been due to environmental factors. The low survival we observed at site 5 may have been due to the scarcity of suitable run habitat at that site. The abrupt decline in survival at site 8 between 2020 and 2021 may have been caused by construction of a beaver dam 100 m upstream, which rerouted the stream into an old channel and lowered current velocity at the relocation site by 2021.

Selection of suitable relocation sites is the most important consideration to be made before relocation (Dunn et al. 1999). Characteristics of sites that support healthy mussel assemblages, such as substrate composition and stability, stream size, surface geology, hydrological variability, and riparian vegetation, can be used to guide relocation site selection (e.g., Stober 1972; Vannote and Minshall 1982; Lewis and Riebel 1984; DiMaio and Corkum 1995; Morris and Corkum 1996). Our characterization of Western Pearlshell habitat use and subsequent selection of relocation sites on the basis of those criteria resulted in generally high mussel survival. Notably, we observed low survival at the site (5) that deviated most widely from our characterization of suitable habitat, which is similar to, and augments, previous characterizations for Western Pearlshell (Stober 1972; Vannote and Minshall 1982; Stone et al. 2004). We were unable to statistically test the relationship between relocation success and specific habitat variables, but our results demonstrate that careful consideration of habitat characteristics at relocation sites can lead to successful mussel relocation.

It is more difficult to anticipate other environmental factors during relocation site selection. Beavers are a natural and formerly abundant part of the ecosystem in streams that supported large Western Pearlshell populations (Humphries and Winemiller 2009), and beavers can have positive influences on mussel populations (Bylak et al. 2020). Future relocation efforts should weigh potential positive effects of beavers on overall stream health against localized negative effects, such as those we observed in our study. Other environmental factors such as drought and floods are difficult to predict, but selection of optimal habitats for relocation can maximize the chances that sites are resilient to those factors.

Our use of two shellfish tags/mussel was effective for short-term monitoring of relocation success, and >98% of mussels tagged in 2018 and 2019 retained at least one tag for as long as 3 yr. The lower tag retention we observed in 2020 may have been due to a combination of insufficient time for the glue to dry and placing a higher number of mussels in mesh bags after tagging, which may have dislodged tags. In addition to allowing sufficient time for the glue to dry, tag retention may be improved by placing mussels by themselves in water to provide additional time for the glue to cure before placing mussels in mesh bags or back in the stream (Lemarie et al. 2000). Nevertheless, 82% of mussels marked in 2020 retained at least one tag. Passive integrated transponder (PIT) tags can improve mussel detection, especially for small mussels, against which our sampling was biased (Kurth et al. 2007; Hua et al. 2015; Tiemann et al. 2016). However, PIT tags are also subject to loss, and these tags and associated equipment are more costly than shellfish tags.

To our knowledge, no previous studies have evaluated the effectiveness of stream restoration involving major channel reconfiguration in creating habitat suitable for mussels. Because all the potential relocation sites available to us were in previously restored reaches, we were not able to evaluate success of relocation into control reaches that were not restored. However, the high survival we observed at most sites indicates that newly restored habitats in Tincup Creek were suitable for Western Pearlshell. Continued monitoring is needed to determine the long-term success of Western Pearlshell relocation in Tincup Creek, but our initial results demonstrated that relocation was an effective conservation tool for avoiding direct mussel mortality associated with stream restoration.

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LITERATURE CITED

Bernhardt, E. S., M. A. Palmer, J. D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G. M. Kondolf, P. S. Lake, R. Lave, J. L. Meyer, T. K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005. Synthesizing U.S. river restoration efforts. Science 308:636–637.

Blevins, E., S. Jepsen, J. Brim Box, D. Nez, J. Howard, A. Maine, and C. O'Brien. 2017b. Extinction risk of western North American freshwater mussels: *Anodonta nuttalliana*, the *Anodonta oregonensis*/*kennerlyi* clade, *Gonidea angulata*, and *Margaritifera falcata*. Freshwater Mollusk Biology and Conservation 20:71–88.

Blevins, E., L. McMullen, S. Jepsen, M. Blackburn, A. Code, and S. H. Black. 2017a. Conserving the gems of our waters: Best management practices for protecting native western freshwater mussels during aquatic and riparian restoration, construction, and land management projects and activities. The Xerces Society for Invertebrate Conservation, Portland, Oregon. 108 pp. Available at https://xerces.org/publications/guidelines/conserving-gems-of-our-waters (accessed July 19, 2022).

Bolden, S. R., and K. M. Brown. 2002. Role of stream, habitat, and density in predicting translocation success in the threatened Louisiana pearlshell, *Margaritifera hembeli* (Conrad). Journal of the North American Benthological Society 21:89–96.

Bylak, A., J. Szmuc, E. Kukuła, and K. Kukuła. 2020. Potential use of beaver *Castor fiber* L., 1758 dams by the thick-shelled river mussel *Unio crassus* Philipsson, 1788. Molluscan Research 40:44–51.

Cope, W. G., and D. Waller. 1995. Evaluation of freshwater mussel relocation as a conservation and management strategy. Regulated Rivers: Research & Management 11:147–155.

DiMaio, J., and L. D. Corkum. 1995. Relationship between the spatial distribution of freshwater mussels (Bivalvia: Unionidae) and the hydrological variability of rivers. Canadian Journal of Zoology 73:663–671.

Dunn, H., B. E. Sietman, and D. E. Kelner. 1999. Evaluation of recent Unionid (Bivalvia) relocations and suggestions for future relocations and reintroductions. Pages 169–183 *in* R. A. Tankersley, D. I. Warmolts, G. T. Watters, B. J. Armitage, P. D. Johnson, and R. S. Butler, editors. Freshwater Mollusk Symposium Proceedings. Ohio Biological Survey, Columbus.

Eveleens, R. A., and C. M. Febria. 2022. A systematic review of the global freshwater mussel restoration toolbox. Aquatic Conservation: Marine and Freshwater Ecosystems 32:186–198.

Haag, W. R., and J. D. Williams. 2014. Biodiversity on the brink: An assessment of conservation strategies for North American freshwater mussels. Hydrobiologia 735:45–60.

Hamilton, H., J. B. Box, and R. M. Dorazio. 1997. Effects of habitat suitability on the survival of relocated freshwater mussels. Regulated Rivers: Research & Management 13:537–541.

Hua, D., Y. Jiao, R. Neves, and J. Jones. 2015. Use of PIT tags to assess individual heterogeneity of laboratory-reared juveniles of the endangered Cumberlandian combshell (*Epioblasma brevidens*) in a mark–recapture study. Ecology and Evolution 5:1076–1087. doi: 10.1002/ece3.1348.

Humphries, P., and K. Winemiller. 2009. Historical impacts of river fauna, shifting baselines, and challenges of restoration. BioScience 59:673–684.

Idaho Department of Fish and Game. 2017. Idaho State Wildlife Action Plan, 2015. Idaho Department of Fish and Game, Boise. Available at https://idfg.idaho.gov/swap (accessed July 19, 2022).

Krebs, C. J. 1998. Ecological Methodology, 2nd edition. Addison-Wesley-Longman, Boston. 620 pp.

Kurth, J., C. Loftin, J. Zydlewski, and J. Rhymer. 2007. PIT tags increase effectiveness of freshwater mussel recaptures. Journal of the North American Benthological Society 26:253–260.

Lemarie, D. P., D. R. Smith, R. F. Villela, and D. A. Weller. 2000. Evaluation of tag types and adhesives for marking freshwater mussels (Mollusca: Unionidae). Journal of Shellfish Research 19:247–250.

Lewis, J. B., and P. N. Riebel. 1984. The effect of substrate on burrowing in freshwater mussels (Unionidae). Canadian Journal of Zoology 62:2023–2025.

Luzier, C., and S. Miller. 2009. Freshwater Mussel Relocation Guidelines. Pacific Northwest Native Freshwater Mussel Workgroup. Available at https://www.fs.fed.us/r6/sfpnw/issssp/documents/planning-tools/cpt-ibi-mussel-relocation-guidelines-2009-09.pdf (accessed July 19, 2022).

Lydeard, C., R. H. Cowie, W. F. Ponder, A. E. Bogan, P. Bouchet, S. A. Clark, K. S. Cummings, T. J. Frest, O. Gargominy, D. G. Herbert, R. Hershler, K. E. Perez, B. Roth, M. Seddon, E. E. Strong, and F. G. Thompson. 2004. The global decline of nonmarine mollusks. Bioscience 54:321–330.

Morris, T. J., and L. D. Corkum. 1996. Assemblage structure of freshwater mussels in rivers with grassy and forested riparian zones. Journal of the North American Benthological Society 15:576–586.

Mueller, M., J. Pander, and J. Geist. 2014. The ecological value of stream restoration measures: An evaluation on ecosystem and target species scales. Ecosystem Engineering 62:129–139.

R Development Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. http://www.r-project.org (accessed July 19, 2022).

Rasmussen, J. E., and M. C. Belk. 2012. Dispersal behavior correlates with personality of a North American fish. Current Zoology 58:260–270.

Ricciardi, A., and J. B. Rasmussen. 1999. Extinction rates of North American freshwater fauna. Conservation Biology 13:1220–1222.

Stober, Q. J. 1972. Distribution and age of *Margaritifera margaritifera* (L.) in a Madison River (Montana, USA) mussel bed. Malacologia 11:343–350.

Stone, J., S. Barndt, and M. Gangloff. 2004. Spatial distribution and habitat use of the Western Pearlshell Mussel (*Margaritifera falcata*) in a western Washington stream. Journal of Freshwater Ecology 19:341–352.

Tiemann, J. S., M. J. Dreslik, S. J. Baker, and C. A. Phillips. 2016. Assessment of a short distance freshwater mussel relocation as viable tool during bridge construction projects. Freshwater Mollusk Biology and Conservation 19:80–87.

Vannote, R. L., and C. W Minshall. 1982. Fluvial processes and local lithology controlling abundance, structure, and composition of mussel beds. Proceedings of the National Academy of Sciences of the United States of America 79:4103–4107.

Wolman, M. G. 1954. A method for sampling coarse river-bed material. Transactions of the Geophysical Union 35:951–956.