RESTORATION MONITORING

A Get-Started Guide

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Preface

Every year Trout Unlimited volunteers and professional staff dedicate thousands of hours and millions of dollars towards restoring coldwater habitats across the country. Projects range from small, local efforts to watershed-scale endeavors.

Stream restoration, which is really about reestablishing the ecological function of degraded streams and rivers, is a relatively young discipline. As such, the science of stream restoration is evolving by iteration, assessment, and adaptive management. Monitoring, or measuring restoration success, plays a crucial role in this evolution (Roni et al. 2018). Despite this crucial role, nationally only about 10% of projects are assessed or monitored (Bernhardt et al. 2005), and only those that have been monitored are driving our scientific understanding of ecological function and of what does and does not work.

Over the past couple of decades Trout Unlimited's efforts have, through the growing expertise of our restoration staff and the assistance of an army of dedicated volunteers, begun to leave an impressive restoration footprint across the United States. Given this state of affairs, we endeavored to create an approachable but informative guide to restoration monitoring. The goal of this guide[1] is to provide restoration practitioners with basic strategies and tools for evaluating the benefits (or, or in some cases, lack thereof) of their work (Figure 1).

We organized the guide into several sections. It leads with a discussion about the critical decision of *if* and *when* to monitor. It follows with an introduction to types of monitoring and associated tradeoffs with each. The guide then walks through a stepwise framework for designing a monitoring program. Each step-based sub-section introduces a key monitoring concept, draws on relevant examples, and ends with a short list of recommended resources for further reading and deeper understanding. The guide ends with a discussion about the many potential challenges to restoration monitoring. Considering these challenges in advance can help with the decision to monitor and the design of a monitoring plan. Moreover, by thinking through a plan and flagging potential pitfalls, we reduce our chances of encountering these obstacles and limitations down the road.

We included a number of TU case studies at the back of the document (Appendix A. Restoration Monitoring Case Studies). Even these case studies fall short of meeting all of our idealistic recommendations for monitoring. However, the cases studies illustrate both the real-life complexities and key considerations when setting out to monitor restoration success.

Trout Unlimited is inextricably linked to the science-based field of restoration. Monitoring is critical to ensure that the science is current and our restoration techniques relevant and effective. Further, monitoring can help TU staff and volunteers tell our story to supporters, funders, and other restoration practitioners. Nevertheless, the essence of our message is not to monitor without question. Rather, we encourage staff to consider thoughtfully if and how to monitor and to commit to monitoring only when we can commit to doing it well.

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[1] It is our hope that this will be a dynamic document that will evolve as our understanding of stream restoration and monitoring evolves

Figure 1. Trout Unlimited staff and volunteers implement hundreds of instream (top) and riparian (bottom) restoration projects each year.

1. Introduction

Trout Unlimited has put millions of dollars towards the restoration of streams and rivers over the last few decades. Clearly, we have had a substantial impact. But how do we demonstrate our restoration successes and – just as importantly – learn from our restoration failures? Is a simple tally of projects completed or dollars spent a good measure of success? Does installing a fish habitat improvement structure or signing an instream flow agreement indicate success? Most scientists would answer "no" to these questions. So, then, how do we quantify the success of a restoration project?

In a science-based field like restoration, information typically comes from data, and data result from monitoring[2]. But data also need context, and that context is framed by the goals and objectives of restoration. Monitoring then becomes a means by which we can evaluate, document, and communicate our restoration successes (or failures). Moreover, monitoring becomes a critical element in helping move the science of restoration forward.

Unfortunately, research has shown that many stream restoration projects are not monitored adequately enough to determine whether they were successful (i.e., effective), and this is especially true of small, low-cost projects (<1-km and <$45,000)(Bernhardt et al. 2005; Rolls et al. 2013). More importantly, less than half of restoration projects are associated with measurable goals and objectives, which makes monitoring a moot point because data cannot be related back to clear definitions of success. Because so much money is expended on stream and river restoration in the United States (over $1 billion/year) some have argued that funding and permitting entities should require accountability through monitoring (Bernhardt et al. 2007).

2. If and When to Monitor

Although it would be ideal to evaluate the success of each and every restoration project, it is neither necessary nor feasible to do so. Monitoring might be especially important if a restoration project incorporates new or common but unvalidated techniques, if a project is high-profile and involves threatened or endangered species, or if a funder requires it. At the same time, we should consider organizational strategy. With restoration practitioners working across the country, Trout Unlimited staff and volunteers have great opportunities to share with and learn from one another. If staff have monitored numerous fish passage projects in Colorado and Montana, it might be less important to replicate those studies in Utah or Wyoming, on similar streams, or for the same or similar species. On the other hand, if volunteers are planning to in the future install numerous rock-drop structures in Washington, it might be even more important to learn about the effectiveness of rock-drop structures previously installed in California and Oregon. By documenting effectiveness through monitoring, we can help one another make informed decisions about restoration and avoid redundancy in monitoring similar types of projects.

While strategic learning is an important consideration of monitoring, it is not the only consideration. Opportunity, or lack thereof, also influences the decision to monitor. For

[2] The word "monitoring" can invoke many different thoughts, but monitoring is often defined as collecting systematic observations over space and time for the purpose of evaluating something

example, convenient project sites, available funds, and enthusiasm of partners make it easier to develop, initiate, and execute a monitoring plan. Because lack of funding and/or support can derail even the best-laid plans, it is also important to consider long-term availability of these resources. Monitoring can also be a grant requirement. If you commit to an outcome of "more fish in two years," for instance, some funders will request to see the evidence.

Also, restoration projects can arise quickly and opportunistically. Short, fast-paced processes leave little or no time to collect pre-project data from which a baseline can be established for future comparison. If pre-project data are not available or cannot be collected, it is worth considering whether any degree of monitoring will yield good information (see "4. Steps for Effective Monitoring" below).

Overall, the decision of whether or not to monitor a restoration project depends on a number of factors. Restoration practitioners should consider monitoring projects when it will be feasible and instructive to do so but should consider opting out when there is little to be gained and effort and resources can be better spent elsewhere. Commit to doing it, doing it well and reporting it out, or simply just opt out.

3. Types of Monitoring and Adaptive Management

Monitoring has been classified in numerous ways (Table 1). Here we touch briefly on three types of monitoring: 1) implementation monitoring (*was the project constructed as it was designed?*), 2) effectiveness monitoring (*did we see the desired, often near-term, effects?*) and 3) validation monitoring (*did we see the physical and/or biological outcomes?*)(Roni 2005a). We then focus on the role of monitoring in adaptive management, that is, an iterative and structured way to "learn by doing" (Walters and Holling 1990).

Table 1. Various types of monitoring (Roni 2005a).

Monitoring Type	Frequency[a]	Duration[b]	Intensity[c]
Implementation	Variable	Duration of project	Low
Trend	Low	Long	Low to moderate
Baseline	Low	Short to medium	Low to moderate
Effectiveness	Medium to high	Short to medium	Medium
Project	Medium to high	Duration of project	Medium
Validation	High	Medium to long	High
Compliance	High	Medium to long	Medium

[a]how frequently over time monitoring occurs (e.g., every 5 years)
[b]the total length of time monitoring occurs (e.g., from 2001 to 2025)
[c]the rigor of monitoring when it occurs (e.g., number of sites monitored, or measurements taken)

Implementation monitoring

Implementation monitoring consists, in part, of simply ensuring a project was constructed according to its design. Monitoring could range from comparison of pre- and post-project photos to comparison of an engineer's design to an "as-built" survey. An as-built survey might reveal, for example, whether instream habitat structures meet design criteria, such as proper spacing, anchoring, and elevation, or whether a reconstructed stream channel meets the designed pattern and profile.

Figure 2. Fish passage barrier on the South Fork Little Colorado River, Arizona that protects an Apache Trout population from non-native trout downstream. These barriers are often designed to withstand certain flows and be effective for certain periods of time.

Although implementation monitoring is often completed immediately after project construction, it can also include periodic inspection to evaluate if a project *continues* to function as originally designed and constructed. Although projects are often designed to withstand a specific flow event (e.g., the 25-year flood), streams and rivers are naturally dynamic. If streamflows exceed design standards, then project infrastructure could be negatively affected by higher than planned channel scour or sediment and debris transport. Thus, implementation monitoring can entail monitoring project infrastructure to determine if maintenance is needed. Questions could arise regarding how long a project should be monitored and who should do the monitoring. Engineered projects (e.g., fish passage barriers) often have a design life that is expressed in years (Figure 2), and that timeframe can define and guide implementation monitoring efforts.

Consider an example wherein a restoration practitioner installs large wood to increase the frequency of complex pools, with hopes of ultimately eliciting a positive response in Coho Salmon abundance. Implementation monitoring might entail log counts to verify that enough were installed to meet the project design, but it would not address matters of either pool complexity or salmon density. Implementation monitoring is relatively easy to conduct and often satisfies fundamental reporting criteria, but it yields little if any information about the physical and biological efficacy of a restoration project.

Figure 3. A field crew captures(top) and processes (bottom) fish at an electrofishing monitoring site on the Bear River, Utah.

Effectiveness monitoring

Effectiveness monitoring is the process by which we collect information about the physical outcomes of a restoration project and compare them back to project goals and objectives. Moreover, effective monitoring tells us whether a project was successful in eliciting desired physical effects. Picking up on the large wood-Coho Salmon example, it might be reasonable to hypothesize that large wood-related increases in pool depth and complexity led to increases salmon density, but observations of physical change are not evidence in themselves of a change in salmon density. Moreover, effectiveness monitoring provides crucial information with respect to project success but will not elucidate whether the ultimate project goal or outcome has been achieved.

Validation monitoring

The goal of validation monitoring is to evaluate whether the ultimate, desired outcomes of a project were achieved. This often but not always pertains to a biological (e.g., fish-related) project goal. Following through on the large wood-Coho Salmon example, validation monitoring could entail some form of fish sampling to determine whether additions of wood and associated changes in habitat elicited an increase in salmon density or abundance (e.g., Figure 3). Validation monitoring is the most difficult and intensive to conduct, and thus not always practical, but it yields the most meaningful answers.

Adaptive management

For projects implemented over large watersheds and/or with objectives that would be realized over years or decades, monitoring can be part of a decision-making process called *Adaptive Management* (Figure 4). Adaptive management integrates monitoring data into a decision-making process and provides a formal means by which a project can be evaluated (Figure 4). Course corrections can be implemented, if necessary, to change certain aspects of the restoration work before too much time and money are spent on an undesirable result (Figure 4). Adjustment without structured prediction of outcomes and testing of those outcomes is just trial and error, which has a lower learning potential and can lead to bad decisions (Allen et al. 2011; Bouwes et al. 2016).

A great example of adaptive management is illustrated in the 30-year restoration of the Blackfoot River, Montana (Pierce et al. 2019). Pool forming habitat structures were installed in two streams: one a valley-confined, moderate gradient (>2%) stream (Rosgen B channel), and the other an unconfined, low gradient (<2%) stream (Rosgen C channel). Short-term effectiveness monitoring data showed that pool habitat increased in both streams, from 1% pre-restoration to 14% post-restoration. However, after a ~50-year flood, only 85% of structures were retained and retention differed both with channel and structure type (Schmetterling and Pierce 1999). The implementing agency, Montana Fish, Wildlife, and Parks, used monitoring data and an adaptive management framework to detect failures and change restoration practices, and, over the long-term, observed concomitant increases in trout abundance through validation monitoring (Pierce et al. 2019).

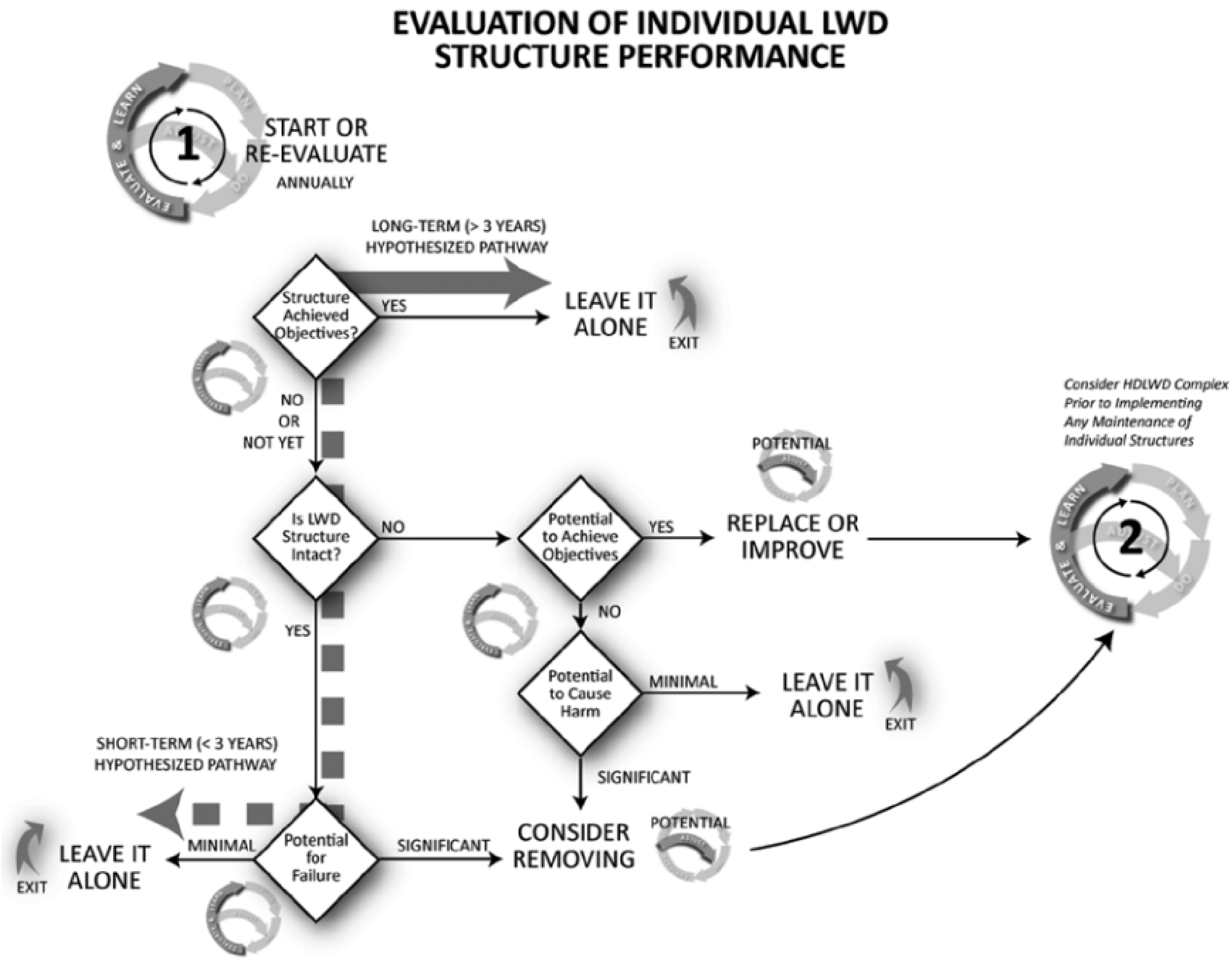

Figure 4: Adaptive management framework (monitoring and maintenance) for evaluation of large woody debris (LWD) structures used as part of the Asotin Creek watershed restoration project (Bouwes et al. 2016).

Within an adaptive management process, monitoring data can be used to adapt project plans, including:

- No action – if project is progressing as expected or is progressing more slowly than expected but will still reach project goals, then no action is needed.
- Maintenance – physical actions, such as repair or replacement, might be needed to keep a project on course to meet goals.
- Adding, abandoning, or decommissioning – Certain project plan elements may need to be added or removed if information suggests that project goals will not be met.
- Modification of restoration goals – Monitoring data may indicate that the project goals will not be met if the project is maintained as-is or even if other elements are added or removed. Project partners may decide that the project will result in other desirable properties or functions and may choose to modify restoration goals rather than modifying the project itself.

4. Steps for Effective Monitoring

Determining the effectiveness of various restoration techniques is required to inform adaptive management and inform planning of future restoration efforts (Roni 2005b). As mentioned above, restoration monitoring is most useful if monitoring objectives are developed concurrently with restoration objectives and the connection between them is explicit. A restoration monitoring plan should capture the core goals, objectives, design, and metrics of monitoring and relate them back to project goals and objectives. Although it might seem idealistic or unapproachable to create a full-blown monitoring plan, even a one- to several-page document will increase the success of the effort, in part by forcing clarity and structure in your thinking. With that in mind, there are several useful steps to follow when developing a restoration monitoring plan (Kershner et al. 1997; Roni et al. 2013):

Step 1. Identify restoration goals and objectives

Because the purpose for restoration can vary from one restoration project to another, the first step towards designing an effective monitoring program is to define or revisit project-specific goals and objectives (Wheaton 2005; Skidmore et al. 2013). Project goals should address limiting factors and define success—that is, the desired hydrological, physical, or biological endpoints. If limiting factors, i.e. the habitat or biological characteristics that are directly and negatively impacting trout, are not addressed by your project, then you may fail to observe a response. Objectives should define timely and measurable steps towards attaining project goals. Reference conditions—that is, regional examples of pristine or pre-disturbance conditions—can provide objective targets for restoration. Some examples of clear goals and objectives include the following:

*Project Example 1***.** A riparian exclosure was constructed to improve spawning habitat and reduce late-summer stream temperatures to benefit a Cutthroat Trout population.

<u>Project Goal</u>: Increase abundance of Cutthroat Trout to reference conditions.

<u>Key Limiting Factors</u>: Elevated late-summer stream temperature, decreased macroinvertebrate production, and embeddedness of spawning gravels (i.e., excess fine sediment).

<u>Project Objectives</u>: (1) increase canopy cover to at least 50% in 5 years, (2) decrease maximum summer stream temperature by 2° C in 5 years, (3) reduce fine sediment by 50% in 5 years, and (4) increase abundance of Cutthroat Trout to 1,000 fish per mile in 10 years.

*Project Example 2***.** Addition of gravel to a stream to increase availability of spawning beds and numbers of Brook Trout.

> Project Goal: Increase abundance of Brook Trout.
>
> Key Limiting Factor: Lack of suitable spawning gravel, poor trout recruitment.
>
> Project Objectives: (1) increase the area of spawning gravels within the restoration site by 50% within 2 years, and (2) increase Brook Trout nest density to 20 redds per stream kilometer within 5 years.

Recommended reading[3]:

Skidmore, P., T. Beechie, G. Pess, J. Castro, B. Cluer, C. Thorne, C. Shea, and R. Chen. 2013. Developing, designing, and implementing restoration projects. P. Roni, and T. Beechie, editors. Stream and watershed restoration: a guide to restoring riverine processes and habitats. Wiley & Sons, Oxford.

Step 2. Identify monitoring goals and objectives

Once the goals and objectives of restoration have been defined, the goals and objectives of monitoring can be articulated. As noted above, ideally the two sets of goals and objectives should be developed concurrently[4]. After reading the monitoring objectives, a person should know what will be measured, know what data will be generated, and have a general understanding of the bounds of monitoring (e.g., study area, timeline, species, habitat features measured).

Project Example 1, continued. Monitoring riparian exclosure.

> Monitoring Goal: Evaluate whether fence construction increased abundance of Cutthroat Trout to reference conditions.
>
> Monitoring Objectives: Determine (1) if riparian canopy increased to at least 50% cover in 5 years, (2) if maximum summer stream temperature decreased by 2°C in 5 years, (3) if fine sediment was reduced by 50%, and (4) if cutthroat trout abundance increased to 1,000 fish per mile in 10 years.

[3] Suggested readings may be in Trout Unlimited's Zotero library. Contact Matt Barney: matt.barney@tu.org
[4] Monitoring objectives can sometimes be decoupled from restoration objectives—for example, when a project partner implements their own supplemental monitoring protocol to answer a question related to the project that is of specific interest to their agency or organization.

Project Example 2, continued. Monitoring addition of spawning gravel.

<u>Monitoring Goal</u>: Evaluate whether gravel augmentation increased Brook Trout spawning.

<u>Monitoring Objectives</u>: Determine (1) if the area of available spawning gravels increased by 50% in 2 years and (2) if Brook Trout nest density is greater than or equal to 20 redds per stream km in 5 years.

Note that while the restoration goals were very similar in Example 1 and Example 2, the monitoring goals differed. In Example 1, the monitoring goal was to validate whether restoration increased fish production to a level typically observed in desired habitat conditions (i.e., reference conditions), whereas in Example 2 the monitoring goal was to evaluate whether restoration improved factors indirectly (spawning habitat) and directly (spawning activity) related to fish production.

Recommended reading:

Kershner, J. L. 1997. Monitoring and adaptive management. Pages 116-131 in J.E. Williams, C.A. Wood, and M. P. Dombeck, editors. Watershed restoration: principles and practices. American Fisheries Society, Bethesda, Maryland.

Roni, P., M. Liermann, S. Muhar, and S. Schmutz. 2013. Monitoring and evaluation of restoration actions. P. Roni, and T. Beechie, editors. Stream and watershed restoration: a guide to restoring riverine processes and habitats. John Wiley & Sons, Oxford.

Step 3. Determine scope of inference and appropriate scales of monitoring

The scope of inference defines the general bounds in which inferences (generalizations) can be made and is related to at least three primary factors: spatial scale, temporal scale, and ecological scale.

Spatial scale.—The spatial scope of monitoring should match the desired spatial scale of response. If, for example, the monitoring goal is to evaluate whether restoration produced a watershed-scale change, then monitoring should be conducted at the watershed scale (Pierce et al. 2013). It would generally be inappropriate to extrapolate data from one or several sites to the watershed scale. However, a single gage site might appropriately be used to measure conditions that integrate factors across an entire watershed (e.g., water quality, discharge; Figure 5). A site-scale design should be appropriate for a site-scale project.

Temporal scale.—The temporal scope of monitoring should match the expected response time of monitoring parameters (aka, metrics). If the parameter of interest is, for example, one that changes at the rate of years or decades (e.g., long-lived fishes), then the monitoring timeline should correspond to that period (e.g., monitor every so often for decades). A short-term study would be insufficient to detect long-term change, though short-term responses might provide helpful indicators of progress toward a long-term goal. For instance, observation of redds in a previously unoccupied habitat might indicate that trout are on their way to reestablishing a self-sustaining population. Meanwhile, a short-term study could be appropriate when, for example, measuring the immediate impact of large wood additions or determining whether a fishway restored fish passage (e.g., Case Study #1: Fish passage restoration and effectiveness monitoring)

Figure 5. A DIY Mayfly water quality monitoring station deployed by Trout Unlimited.

Ecological scale.—The ecological scope of monitoring should match the biological attributes (e.g., species and habitats) of interest. If the monitoring goal is, for example, to evaluate whether restoration led to increased fish biomass, all qualifying species should be monitored; it would be misleading to use a single species as an indicator of change to an entire fish assemblage (Lake et al. 2007).

Step 4. Identify an appropriate monitoring study design

An oft-neglected aspect of monitoring is the explicit definition of a study design. An ideal study design should be deliberate in what, where, how much, and how often you're monitoring. An ideal study design will match the spatial, temporal, and ecological scales of a project and allow you to efficiently answer the question: was our restoration project effective (i.e., did we reach our goals)?

As described in more detail below, study designs vary in their sampling characteristics (spatial and temporal replication) and in their inclusion/omission of pre-project data, control sites, and reference sites. A control site is a nearby location or reach that closely resembles a restoration site but that will not be restored or altered. Because control sites are subject to the same external factors (e.g., climate, flow) as restoration or treatments sites, comparison between them can help us tease apart restoration effects from environmental variation. While not as effective for teasing apart environmental variation, reference sites (benchmarks of desired physical or biological characteristics) may be more tractable to use in certain situations (Hughes et al. 1986). Reference data might be available in an agency report or as part of a formal agency monitoring program.

The study design stage is when it can be quite beneficial to consult someone with training and experience designing monitoring programs (e.g., statistician or research scientist, including TU scientists). Common study designs are discussed below, ordered from weakest to strongest in terms of the ability to infer influences of a given restoration action (Roni et al. 2013):

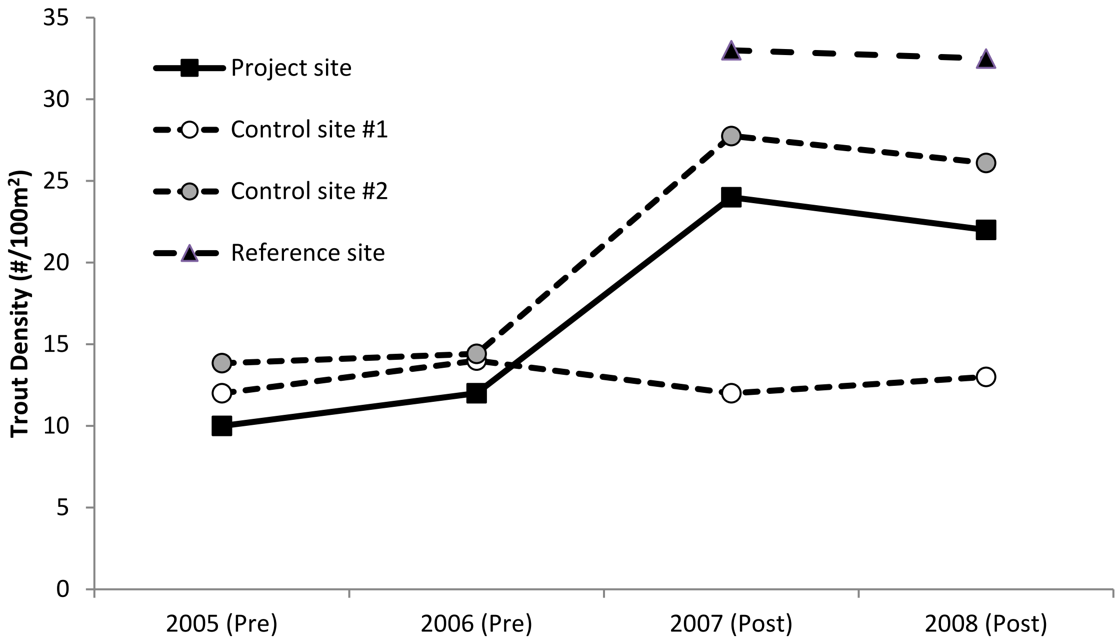

Figure 6. Example of trout abundance data collected at a project site, control site, and reference site.

Post-treatment.—With a post-treatment, or retrospective design, monitoring is performed only after a restoration project is implemented. This design may be appropriate for answering certain questions where pre-restoration data are not needed or available. If a minimum flow right has been negotiated, post-project streamflow monitoring may be all that is needed to ensure those minimum flow levels are met. Where pre-project data may have been desirable but do not exist, post-treatment monitoring can generate data for comparison to a reference condition. As Figure 6 illustrates, you could compare post-project trout abundance between a project site and reference site. However, the absence of pre-restoration data precludes you from determining whether abundance was already at or near reference levels before restoration; other information can inform this assumption, such as the pre-restoration existence of water quality conditions known to be lethal to fish. For example, Rummel and Wolfe (2019) monitored macroinvertebrates in response to acid mine drainage treatment in Pennsylvania. They were able to show, using only post-treatment data, that macroinvertebrate assemblages (Index of Biotic Integrity) were now meeting Aquatic Life Usage Attainment levels, which are benchmarks for Clean Water Act reporting typically developed from reference stream conditions.

Before-After.—With a before-after study design data are collected from the project site both before and after restoration (Figure 7). Before-after data are then compared to determine if change occurred. With this design your data might show trout density increased from ~11 fish / 100 m^2 before restoration to ~23 / 100 m^2 after restoration – a 109% increase (Figure 6). Unfortunately, without a control site you cannot definitively disentangle restoration effects from natural variability. For instance, precipitation and streamflow, rather than the restoration work itself, may have increased spawning success that led to the observed increase in trout density. In this case, environmental change is a “confounding factor” that can not necessarily be accounted for in the before-after design. It would be appropriate to conclude there was increased trout densities after restoration, but only with the caveat that densities may also have been affected (confounded) by other factors that were unmeasured. As with the post-treatment design, reference conditions might provide important context, a benchmark, in which to interpret your results; See Case Study #3 on acid mine drainage reclamation on eastern Brook Trout for a great example.

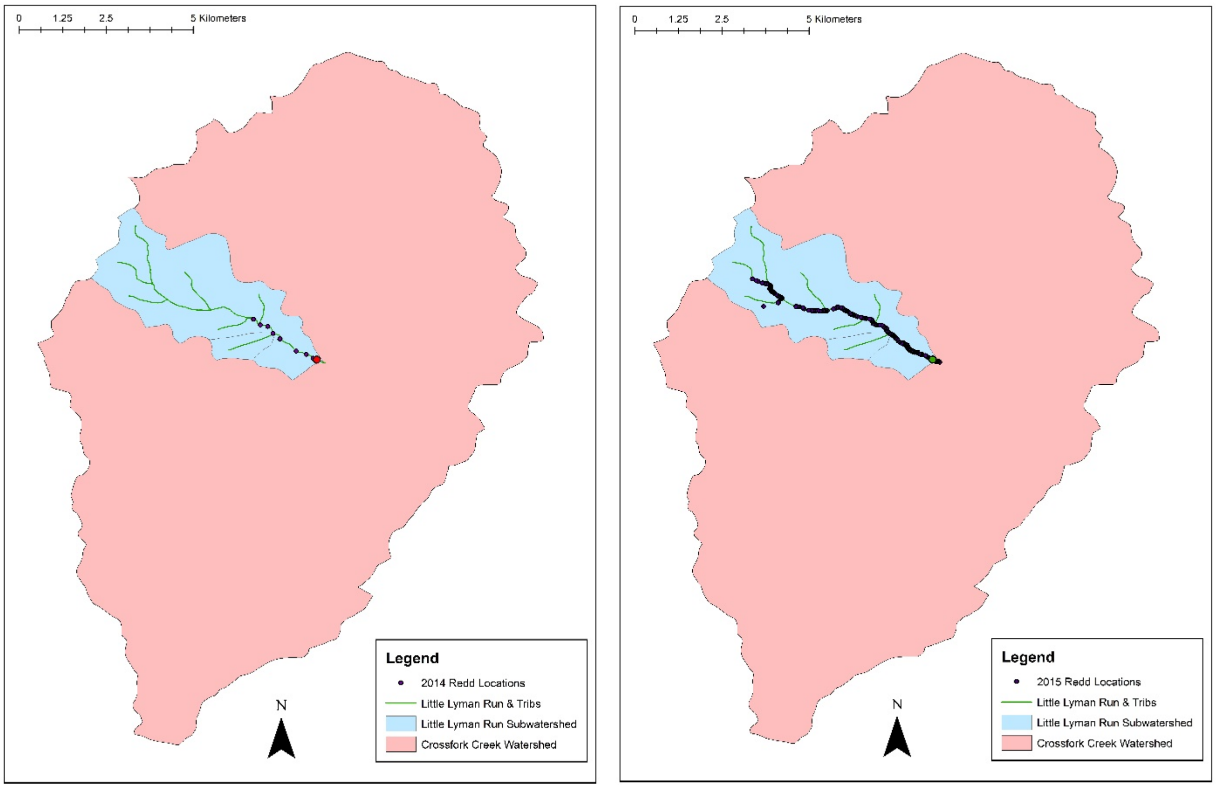

Figure 7. Redd survey data before (2014; left) and after (2015; right) culvert replacement on Little Lyman Run, Pennsylvania. While expert judgement suggests the increase in redds was due to culvert replacement, a control stream would confirm that the increase is from the culvert replacement and not interannual variation in spawning prevalence (due to flow conditions, etc). Professional judgement, and explicit assumptions, thus play a role in interpretation of these data.

Before-After, Control-Impact (BACI).—Under a before-after, control-impact (BACI) - the most robust of study designs - data are collected both before and after restoration from both impact (i.e., restored) and control (unaffected) sites. As mentioned earlier, the latter are used to distinguish restoration-based effects from natural variability. Looking again at Figure 6, we see that trout density was fairly constant over time at Control Site #1 but increased over time at your project site – supporting a conclusion that the effect is attributable to restoration. However, if your control site was Control Site #2 in Figure 6 above, the fact that abundance at this control site increased at a similar rate to the project site would suggest that some outside factor (e.g., climate) influenced abundance across *both* sites. Unfortunately, these results lack evidence that your project increased trout abundance, at least in the first two years of monitoring. Putting your data into context is important and is why BACI designs are so valued (see Case Study #2:

Improving riparian health and satellite-based effectiveness monitoring). Yes, they are more work to implement, but the work is usually worth it because of the clear conclusions they allow you to draw about the effects of restoration.

Table 2. Summary of study designs commonly used to evaluate watershed restoration projects. See text for description.

	Design				
	Before and After			Post-treatment	
Attribute	Intensive	Extensive	BACI	Intensive	Extensive
Includes pre-restoration data[a]	yes	yes	yes	no	no
Includes controls[b]	no	no	yes	yes	yes
Captures inter-annual variation	yes	yes	yes	yes	no
Detects short-term response	yes	yes	yes	no	yes
Detects long-term response	yes	no	yes	yes	yes
Appropriate scale (1 = watershed, 2 = reach)	1, 2	1, 2	1, 2	1	1, 2
Application of results	limited	broad	limited	limited	broad
Results influenced by climate	yes	yes	yes	yes	no
Years to detect fish response	10+	1 -3	10+	5+	1 - 3
Relative cost	low	low	high	moderate	moderate

Source: Modified from Hicks et al. (1991) and Roni (2005b).
[a]Pre-restoration data allow for evaluation of how parameters differed before and after restoration.
[b]Controls allow for discrimination between restoration effects and natural variability.

Each of the three study designs discussed above can take on different forms. Generally speaking, the designs can be enhanced by: 1) increasing the number of replicates in space (i.e., sites) and/or replicates in time (i.e., sampling periods); and 2) including control sites (Table 2). Replication in space and time helps distinguish signal from noise and provides the foundation for making strong inferences (generalizations) from data; it is hard to conclude much from only one observation, but consistent patterns from repeated observations make it easier to draw strong conclusions. Monitoring where data are collected intensively at one or several sites (or site pairs) over numerous years is often called *intensive monitoring*, and monitoring at an extensive number of sites (e.g., 10 – 30) over the course of 1 – 3 years is often called *extensive monitoring* (Table 2). Some monitoring designs (e.g., staircase design, asymmetrical BACI) expand on the designs above by combining intensive and extensive data collection routines (Walters et al. 1988; Loughin et al. 2021). Others have advocated pulsed monitoring, whereby there is an intense monitoring period after project completion that is then followed up with periodic monitoring over longer time periods (Bryant 1994). Any study design should be based on the spatial, temporal, and ecological scales of interest and will need to balance being spatially and/or temporally extensive while considering time constraints and costs. In all instances it is important ensure your inferences on effectiveness are appropriate for your monitoring design.

Recommended reading:

Noble, R. L., D. J. Austen, and M. A. Pegg. 2007. Fisheries management study design considerations. Pages 31-49 *in* C. S. Guy, and M. L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Roni, P., M. C., Liermann, C. Jordan, and E. A. Steel. 2005. Steps for designing a monitoring and evaluation program for aquatic restoration. Pages 13 – 34 in P. Roni, editor. Monitoring stream and watershed restoration. American Fisheries Society, Bethesda, Maryland.

Step 5. Select monitoring parameters

The goals and objectives of a monitoring plan will help to define appropriate monitoring parameters (a.k.a. metrics) - the things you want to measure to evaluate goal attainment (Table 3). Ideal parameters will:

1. *Be relevant to the question(s) asked*—such that answers match questions
2. *Be clearly associated with restoration actions*—so they will reveal effects of restoration
3. *Be well studied*—so comparisons can be made to other studies
4. *Exhibit low spatial and temporal variability*—to increase the probability of detecting a restoration effect amidst variability (or noise) in the environment
5. *Respond predictably to natural and anthropogenic change*—so inferences can be made about causes for change
6. *Be quantifiable*—so that measurements can be consistently replicated and compared over the monitoring timeframe

Table 3. Common stream monitoring parameters.

Category	Monitoring Parameters
Physicochemical	
Bank stability	Bank erosion, slope angle, vegetative cover
Channel dimension	Channel cross-sectional shape
Channel pattern	Planform changes in meander geometry using areal maps and imagery
Channel profile	Longitudinal bedform elevation profile
Substrate composition	Pebbles counts, sediment cores
Hydrological	Discharge, velocity, flow complexity
Large wood	Density (# pieces per unit length)
Sediment	Embeddedness, percent fines, aggradation/degradation
Temperature	Daily mean and maximum, 30-day mean, 7-day maximum
Dissolved oxygen	Daily minimum or diel fluctuation
pH	Point sample or diel fluctuation
Biological	
Macroinvertebrates	Abundance, feeder groups, taxa richness (diversity), presence in fish diet
Fish	Abundance, density, biomass, condition, distribution, presence-absence, size and/or age structure
Vegetation	Canopy cover (% of sky obscured by vegetation), density (% of ground covered), stubble height

A conceptual diagram of expected responses to restoration can help to identify appropriate types of monitoring parameters. Consider the earlier example of a riparian fencing project (Project Example 1), the goal of which is to increase abundance of Cutthroat Trout to reference conditions. Outlining expected mechanisms of change reveals at least nine potential monitoring parameters (Figure 8). Of the nine or more potential parameters in Figure 8, trout abundance may be the single-most effective metric for evaluating project success because (1) success (i.e., goal attainment) is measured by an increase, or lack thereof, in trout abundance and (2) fish populations integrate, and therefore respond to, a suite of influences (e.g., food abundance, habitat quality, water temperature). However, of the available parameters, trout abundance is arguably the most difficult and intensive to monitor because data collection requires special equipment, permits, and expertise. Also, trout populations exhibit a high degree of variability due to a variety of factors, which makes it difficult to measure change (i.e., signal is often masked by noise). Finally, trout abundance provides little or no feedback about influences of restoration on limiting factors. If trout abundance remains unchanged, for example, it will be unclear from that result alone whether temperature, sediment, and/or another factor limited trout production (e.g., Stewart et al. 2009).

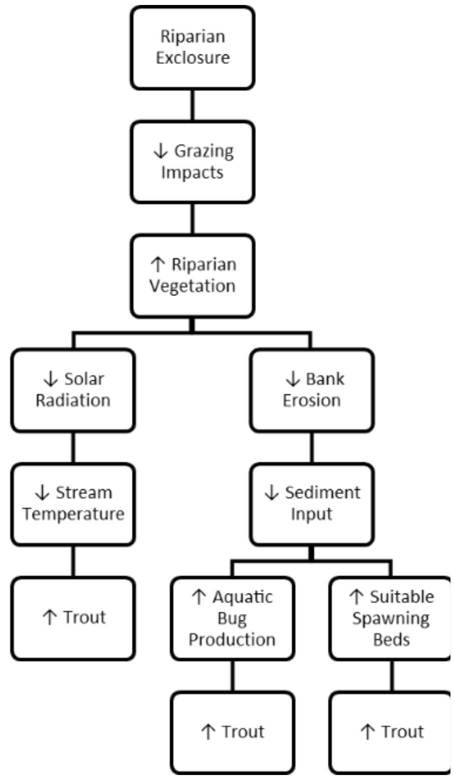

Figure 8. A conceptual diagram showing expected responses of a riparian exclosure project. A positive sign (↑) denotes an increase or positive feedback; a negative sign (↓) denotes a decrease or negative feedback.

Because a plethora of options exist with respect to monitoring metrics some general guidance is warranted. Monitoring one or more physical parameters and evaluating if the project effected the intended change to habitat is typically straightforward. Physical habitat parameters are usually easy to measure, and monitoring can commence soon after a project is completed. Much research has been done to determine which elements of physical stream habitat can be accurately and precisely measured over time by different field crews, another important consideration. For example, Roper et al. (2002) found that the stream habitat attributes Percent Pools and Bank Stability were inconsistently measured between different field crew members (adding noise, in this case from measurement error, that reduces your ability to capture a true response signal), whereas attributes Stream Gradient and D_{50} (the median diameter of streambed substrate) were consistently measured. If measurable changes were found in physical habitat, then it may follow that the biota also exhibited a measurable response. At TU we are typically concerned with the response of fish, though it can take many years to detect change and one needs to assess whether time and resources (grant funding, or agency partner availability) are available for long-term biological monitoring.

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Step 6. Select sampling scheme

A sampling scheme dictates the location, spacing, and frequency of data collection. If properly executed, a good sampling scheme will result in collection of data that is representative of a study site and matches the desired spatial, temporal, and ecological scopes of inference. Collecting data from only the most pristine or degraded sites, sites that are clumped or restricted to only one type of habitat, or from only the most accessible sites, can lead to sample bias and result in poor inference. Moreover, these sites may not represent the broader domain to which you wish to generalize. Sites near road-stream crossings, for example, may be more likely to be degraded or have non-native trout, which will confound your ability to draw conclusions about the effectiveness of restoration (Balkenbush and Fisher 1999).

Several sampling schemes exist to guide random or systematic collection of representative data (Table 4). Sometimes the parameters selected for monitoring will influence the choice of sampling scheme. For example, if you are conducting redd counts and can hike the entire project area for the duration of the spawning season, you might consider a complete census (census in time and space). Conversely, if you are measuring bankfull stream widths, you might use a systematic sampling scheme whereby you measure bankfull width at transects spaced every 10-m through your project reach.

Table 4. Summary of common sampling designs.

Type of Sampling	Description
Census	All units are sampled.
Simple random	A subset of randomly selected units is selected; each unit has an equal chance of being selected.
Systematic	A first unit is chosen randomly and every *i*th unit thereafter is sampled.
Stratified Random	Units are first categorized (e.g., by stream type); units are randomly selected within categories.
Line transect	Data are collected along a predetermined line or transect.

*Modified from Roni (2005).

Recommended reading:

Hansen, M. J., T. D. Beard Jr., and D. B. Hayes. 2007. Sampling and experimental design. Pages 51 - 120 *in* C. S. Guy, and M. L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

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5. Challenges of Evaluating Restoration Effectiveness

No effect, or unexpected results

Restoration monitoring is prone to many challenges. It is okay for monitoring to show that your restoration project was not successful based on your carefully thought out restoration goals. The reason to monitor is to learn and adapt as we go. Of course, there should be a clear analysis of your data, and a thorough and comprehensive interpretation that includes comparison to similar monitoring efforts completed elsewhere. Did an unexpected complication arise during monitoring, such as an extreme environmental event (e.g., flood)? Did your sampling design prohibit you from drawing strong conclusions? Did restoration address limiting factors, or might conditions still not be suitable for fish for reasons other than what your restoration addressed (e.g. water quality may still be inhospitable in the targeted habitat even though your culvert remediation provided access)? These questions emphasize why thinking through your project goals and associated monitoring goals, parameters and design *before* you implement the restoration work can be so helpful, as you may be able to head off some avoidable issues with your restoration project just by clarifying your monitoring needs. Use logic, your expertise, and the results of others to assess whether your results are real – that your project really was not effective – before drawing this important conclusion that will cause you to take further action. Action could entail changing the restoration approach in a similar situation in the future (i.e., you and your partners adapt). Do your due diligence and write it up so you can share what you learned with others.

A common goal of restoration is to improve habitat and increase fish production, often to the benefit of anglers. However, as noted above detecting a population response to restoration is challenging for a number of reasons. First, fish populations are subject to natural variations in environment at various spatial and temporal scales. Consider, for example, that marine survival of anadromous salmonids can, depending on ocean conditions, range by orders of magnitude. Accordingly, the number of adult spawners can vary widely year-to-year irrespective of restoration of freshwater habitat. Second, fish move—sometimes out of intact reaches and into restored reaches. To distinguish a true increase in fish production from a localized increase in fish density requires that a monitoring program is of sufficient spatial scale to evaluate whether fish are actually produced within a project site, reflecting an overall population benefit, or simply move into a project site from outside areas – the 'fish attractor' or 'magnet' dilemma (Polivka and Claeson 2020). Third, relative to other aquatic organisms (e.g., macroinvertebrates), fish populations can take a long time to respond to changes in environment. Research suggests that because of the long generation (i.e., population replacement) times of some fishes, at least 10 years of data are required to detect changes in salmonid abundance and distribution. The requisite long-term investment is one reason people elect to monitor factors *related* to fish populations rather than the fish populations themselves. Monitoring plans are often a compromise between ideal study design and monitoring parameters versus feasible options given available or projected resources. In some cases, monitoring may not be worthwhile or even recommended if you cannot monitor in a way that is desirable. For example, you might undertake a limited monitoring effort because of limited funding. That limited effort may be insufficient to detect a positive response that actually occurred, which then means you might conclude 'no benefit' or 'inconclusive' because of low sample size or poor monitoring design. However, creatively engaging existing or new project partners may help you increase your monitoring capacity, the next topic.

Monitoring complexity

Sometimes the size and scope of a restoration project may necessitate a monitoring effort that is complex. You may need to account for confounding factors, for example. Or, you might be monitoring multiple projects sites as part of a watershed-scale effort. For example, in Case Study #2 multiple riparian exclosures were evaluated for their effect on riparian vegetation, and the effect of exclosures was estimated by analyzing data from multiple treatment and control sites. Case Study #4 is another example that illustrates the effects of habitat reconnection on Lahontan Cutthroat Trout demographics. A statistical model was used to evaluate the removal of partial and complete passage barriers while also accounting for the important environmental effects of wildfire and flow regime. Variation from these factors needed to be accounted for to reveal the true effect of fish passage on trout abundances. If these needs prove beyond your abilities or scope, never hesitate to ask for help. Help may be needed in the design of a monitoring program, use of passive integrated transponder (PIT) tag arrays or satellite imagery as monitoring metrics, or in the analysis of data yielded from a complex monitoring design. Help can come within TU or from outside partners.

Monitoring capacity

Monitoring is critical to determining restoration success, but it can also be expensive and time consuming. Monitoring can be implemented in a number of ways, and you may need to be creative when finding time and resources to make it happen. Oftentimes monitoring is written into the narrative of the original grant proposal for a restoration project. Other times, new grant opportunities or volunteer peoplepower may be available for monitoring as a match element to project implementation grants. Trout Unlimited staff and volunteers, community scientists (Figure 9), agency partners, and universities all could play a role in restoration monitoring (Williams et al. 2016) and they all have different levels of capacity and expertise.

As with development of restoration projects themselves, project monitoring may best be accomplished through a collaborative partnership approach. A mix of partners and funding will often be needed to complete monitoring of both short-term and long-term goals. A monitoring plan then serves as the organizational framework that describes each partner's role in monitoring project effectiveness. It becomes a critical communication vehicle and creates institutional memory despite staff and partner turnover.

Figure 9. TU staff, Jake Lemon, demonstrating to TU Volunteers how to collect water quality data with a mobile application.

6. Conclusions

Monitoring plays an important role in the science-based field of restoration. Moreover, monitoring is how we evaluate whether our restoration goals are being met and whether we need to adapt to meet those goals in the future. However, it is neither necessary nor advisable to monitor every project. Monitoring should focus on learning about a novel technique, new landscape, or different focal species. Monitoring should be conducted only when resources are likely to be available to do it well. A monitoring plan, even if only one or several pages in length, can organize monitoring efforts, link monitoring goals and objectives to restoration goals and objectives, lay out the monitoring (study) design, and define what, when, where, and how things will be measured. A plan will serve to create a clear and consistent thought process across partners and staff. Never hesitate to seek help, from other TU staff or outside partners, in constructing a monitoring plan or reporting out your monitoring results. Continued sharing of these restoration successes and failures through monitoring is what will move the science-based field of stream and river restoration forward.

7. Acknowledgments

We would like to thank Anonymous #1 for reviewing this document and for providing several good case studies. Much of this document was based on papers, books, and book chapters developed by Phil Roni, Cramer Fish Sciences (formerly of NOAA).

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Appendix A. Restoration Monitoring Case Studies

Case Study #1: Fish passage restoration and effectiveness monitoring

Project summary: In 2014 Trout Unlimited and the U.S. Forest Service retrofitted a concrete box culvert with a fishway to restore passage of Colorado River Cutthroat Trout to historical headwater habitats. A multi-year study was conducted from 2012-2016 to evaluate restoration effectiveness.

Restoration goal: To restore passage of adult Colorado River Cutthroat Trout through an impassable culvert.

Monitoring goal: To evaluate the biological effectiveness of the fishway for restoring passage of Colorado River Cutthroat Trout.

Monitoring objectives: To evaluate 1) fishway efficacy (whether or not the project met its fundamental goal), 2) approach efficiency (the probability that a fish approached the fishway), 3) attraction efficiency (the probability that a fish approaching the fishway entered it), and 4) passage efficiency (the probability that a fish entering the fishway also passed through it).

Methods

Capture, tagging, and antenna construction.—In 2012-2015, approximately 550 Colorado River Cutthroat Trout were captured in a 1.6 km-segment of stream immediately below the box culvert and each was injected with a passive integrated transponder (i.e., PIT tag). Stationary PIT antennas that detect tagged fish that pass over or through them were constructed in and around the fishway following its construction in 2014—namely, at locations immediately downstream of the fishway, at the downstream entrance to the fishway, at the upstream exit of the fishway, and in the downstream-only bypass to the fishway (Figure 10). Antennas were operated in two consecutive years post restoration: from May to November of 2015 and from April to October of 2016.

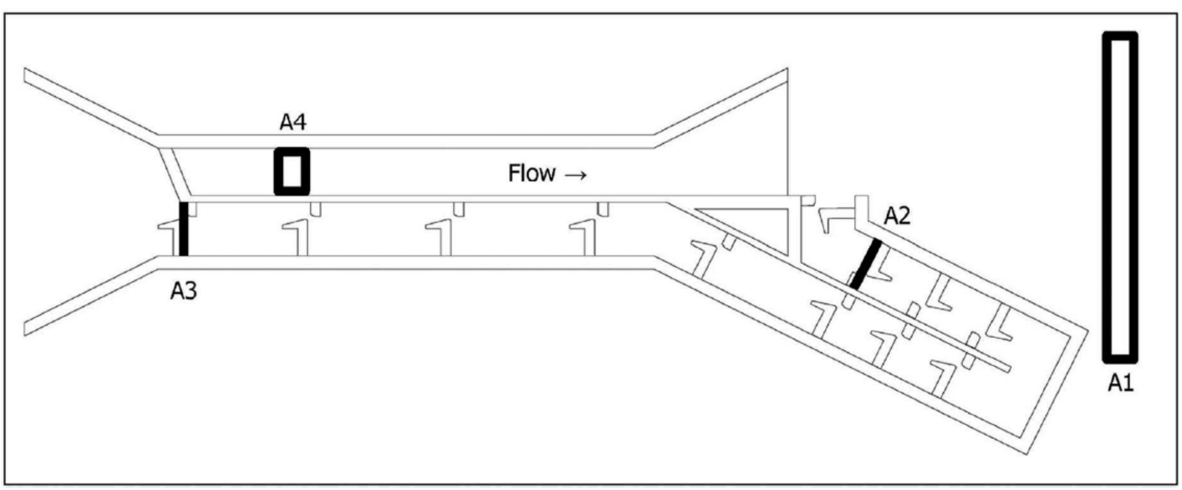

Figure 10. Antenna locations in and around the fishway (A1-A4).

Data analysis.—Metrics of success were calculated from antenna detections. Moreover, an encounter history, or record of detections at antennas, was constructed for each PIT-tagged trout (Figure 11). All encounter histories were used to fit a model, and model parameters then used to calculate approach efficiency, attraction efficiency, and passage efficiency.

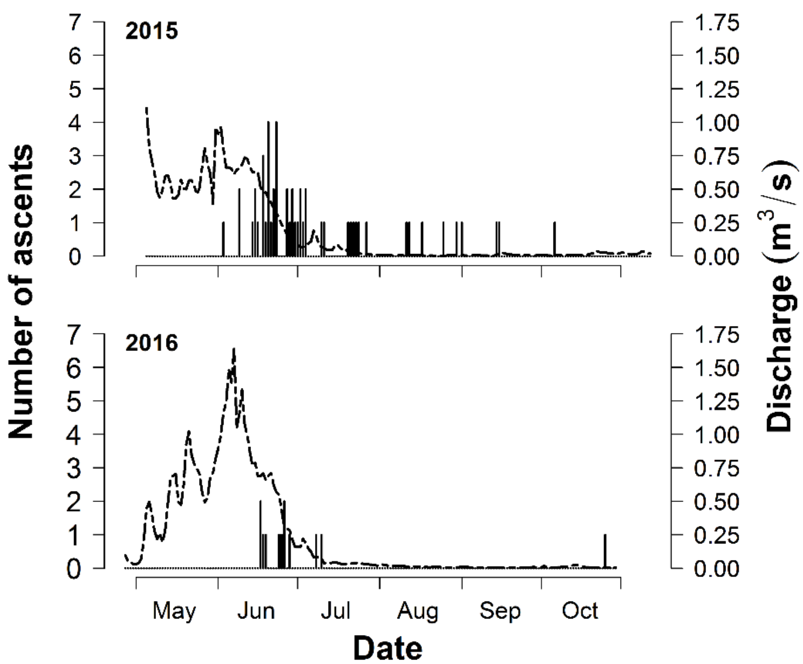

Figure 11. Number of fishway passes (bars; fishway efficiency) relative to stream discharge (dashed line).

Discussion

The spatial and temporal scope of 1.6 km and two years were selected on the front end to strike a balance between effort (and cost) and rigor. A shorter reach and/or shorter time frame would have translated to smaller sample sizes (i.e., smaller numbers of tagged fish and detections) and thus yielded less robust efficiency estimates. In hindsight, larger sample sizes and additional years of monitoring were not required to confirm the efficacy of the project. Monitoring for a third year, for example, would have added more insight regarding interannual variability but had no effect on the desired outcome (successful fish passage) of Years 1-2. Had we failed to detect fish in Year 1 and Year 2, however, we might have adapted and run antennas for a third year. Unlike simple proportion-based efficiency estimates, which can underestimate true numbers of successes and/or attempts, our model-derived estimates accounted for the probability of detecting an attempt or success.

Conclusion: Monitoring allowed TU and its partners to validate the effectiveness of the restoration project. Further, it provided a basis for future use of fishways in inland waters

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Case Study #2: Improving riparian health and satellite-based effectiveness monitoring

Project summary: From 1982 to 2005, the Bureau of Land Management installed fencing to prohibit livestock access to certain riparian areas, amongst other actions (grazing intensity and duration; off-stream watering), to improve riparian health in the Goose Creek Allotment (Cassia County, Idaho). Trout Unlimited used remote sensing to assess responses in riparian condition due to exclosures for the BLM.

Restoration goal: Improve riparian function of streams in the Goose Creek Allotment.

Monitoring goal: Evaluate woody riparian vegetation response to livestock exclusion.

Monitoring objectives: Quantify changes in woody riparian vegetation before and after livestock exclusion (1982 to 2015) using NDVI, a remotely-sensed measure of vegetation vigor.

Metric: *Normalized Difference Vegetation Index (NDVI).*—The Landsat satellite system has collected 30-m multispectral data for every point on earth every 16 days since 1982. From the multispectral data (Blue, Green, Red, and Infrared bands), a Normalized Difference Vegetation Index (NDVI) can be computed as a measure of vegetation greenness (and vigor) for every satellite image collected. To evaluate the response of riparian vegetation due to exclosures, the peak growing season NDVI (maximum NDVI from spring-summer) for each year was summarized in a 25-m buffer of the riparian area at four sites inside (impacted, or project sites) and four sites outside (control sites) each of the seven riparian exclosures in the allotment (exclosures ranged from 180 to 7,530-m in length). Each exclosure, except one, was constructed after 1982, when the Landsat system began collecting 30-m data; this meant there was before-after data for each exclosure as well as the control sites, therefore yielding a Before-After, Control-Impact (BACI) design with replication (multiple sites inside and outside of exclosures).

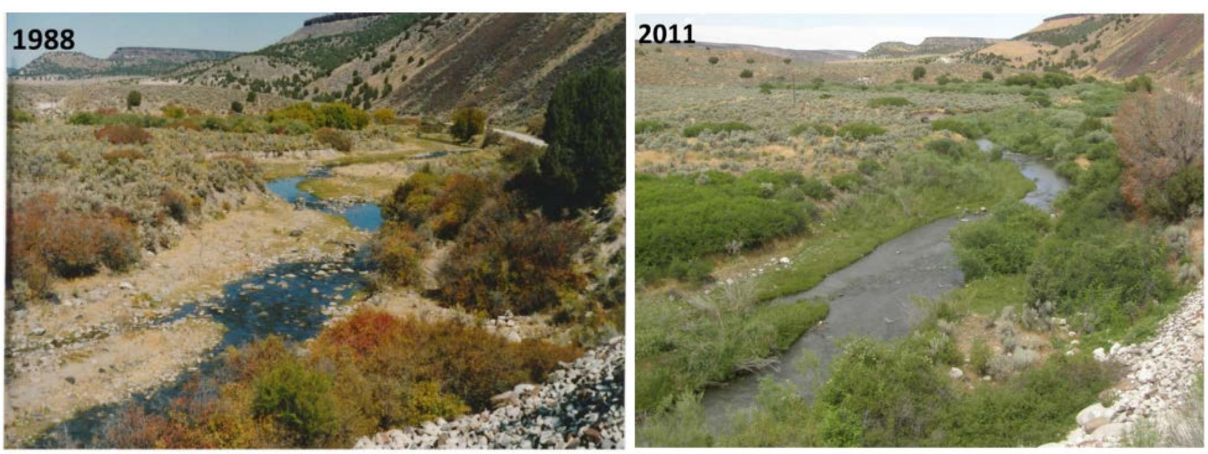

Figure 12. Photos from before (1988) and after (2011) installation of a riparian exclosure on the Goose Creek mainstem, Cassia County, Idaho.

Design: *BACI.*—1988 and 2011 before-after photo points provide a visual of vegetation changes in the Goose Creek mainstem exclosure (GOCR; Figure 12). Average NDVI across the four sites inside and outside of each exclosure was plotted over time (Figure 13). Though not always necessary (see Discussion), a statistical model was used to evaluate how NDVI was influenced by site location (inside, outside) and timeframe (before, after) according to the BACI study design. As is typical of a BACI design, a statistically significant interaction between location (control-impact) and timeframe (before-after) signifies the desired response; that is, that NDVI was higher at sites inside the exclosures than outside but only after livestock were excluded.

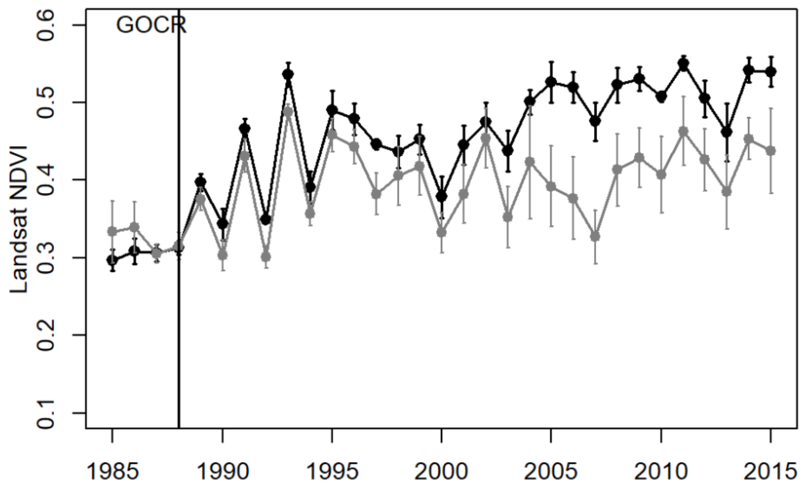

Figure 13. Mean (±1 SE) Landsat NDVI over time for the Goose Creek exclosure (black=inside; gray=outside). Vertical line indicates when exclosure was constructed. Note there is significant interannual variation of NDVI both inside and outside the exclosures, in part driven by annual variation in precipitation. Despite this variation the exclosure effect can be seen as the clear separation of lines after the exclosure was constructed.

Discussion: The availability of 30 years of satellite data allowed a retrospective BACI design to be used to evaluate riparian vegetation response to livestock exclusion. While one would expect woody riparian vegetation to grow and become more dense when livestock are excluded, the BACI design with control sites outside of the exclosure allowed the effect of exclosures to be teased apart from natural spatial and temporal variation in riparian vegetation and, thus, NDVI. While the statistical model allowed the exclosure effect on NDVI to be estimated formally (estimated effect size with confidence intervals), simply plotting the data for each exclosure showed the positive effect of livestock exclusion on riparian vegetation for most, but not all, of the exclosures in the study.

Conclusion: Monitoring allowed TU and the BLM to document the expected benefit of exclosures on riparian vegetation, but it also allowed a close look at which exclosures may have been more effective and which may need maintenance (data not shown). Although it does require specific expertise (which luckily TU has), the use of satellite imagery allowed retrospective analysis of NDVI and thus implementation of a BACI design from a desktop computer – a very cost and time efficient monitoring tool and one of the satellite archives' tremendous benefits.

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Case Study #3: Brook trout recovery from abandoned mine drainage pollution

Project summary: From 2007-2013, Trout Unlimited and project partners constructed several passive treatment systems (Figure 14) to mitigate acidic abandoned mine drainage (AMD) pollution that had eliminated Brook Trout populations from approximately 10 km of streams in a northcentral PA watershed. Brook Trout had been isolated to the headwaters (upstream of AMD pollution) in three tributaries. Water quality monitoring was initiated prior to the construction of all treatment systems. Long-term monitoring of brook trout populations began in 2009 to evaluate the effectiveness of the treatment systems and to document the recovery of Brook Trout in the impaired stream reaches. One to three years of data were collected prior to the activation of each treatment system, with the exception of one site that was activated prior to the 2009 fishery surveys.

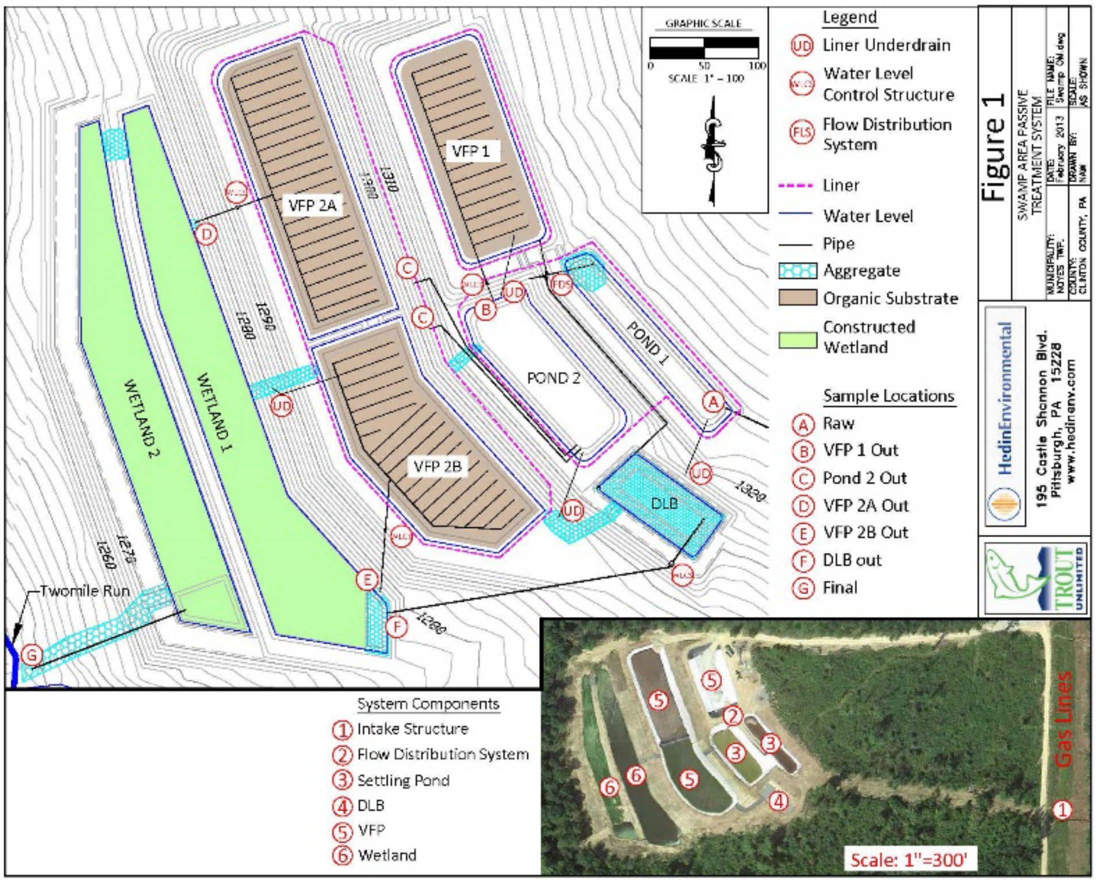

Figure 14. Schematic and overhead view of one of the passive treatment systems installed. Monitoring locations throughout the system are depicted in the schematic. Raw mine drainage water enters the system at point A and is discharged to the mainstem at point G.

Restoration goal: Restore water quality in stream reaches impaired by abandoned mine drainage (AMD) pollution to levels that support Brook Trout populations.

Monitoring goals: 1) To evaluate the effectiveness of AMD restoration on water quality and 2) document the natural recovery of Brook Trout populations in previously impaired stream reaches.

Monitoring objectives: 1) To monitor treatment system water quality for effectiveness and maintenance needs, 2) Brook Trout population dynamics throughout watershed before/after treatment.

Methods

Water quality – A standard suite of water chemistry parameters (pH, alkalinity, metal concentrations, etc.) and stream flows are monitored on a quarterly basis both in-stream and throughout the passive treatment systems.

Brook Trout populations – Multiple pass electrofishing is completed at eight sites throughout the watershed in September each year. Survey sites include one site upstream of each passive treatment site that serves as a reference condition and several sites downstream of treatment. In the field, all fish species captured are identified and assigned a relative abundance. Brook Trout that are captured are weighed and measured (total length) in the field. Metrics calculated for each site include population estimates, biomass, density, and size class distribution. Using sites upstream of the historic pollution as controls, a BACI study design can be used to compare Brook Trout population metrics. Time-series analyses of population trends, water quality, and other environmental metrics have also been used.

Discussion: Water quality data from key points in the passive treatment system (influent to each treatment phase, effluent to stream, etc.) are used to determine the effectiveness of the treatment system. Overall, the treatment systems are generally treating water with an average pH of 3.8-4.0 to an effluent pH of 6.0 with low metal concentrations. These data are also used to detect when the treatment system is in decline (not effectively treating water) and maintenance is required. This is essential to not offset the progress of biological recovery in the previously polluted stream segments.

In stream water quality downstream of the treatment systems has improved to levels suitable for Brook Trout. Brook trout populations have been documented in the newly available habitat in stream reaches downstream of treatment systems that were absent of brook trout prior to treatment (confirmed by annual electrofishing fishery surveys). Brook trout populations have increased over the years since treatment and are similar to or exceeding populations in the reference sites upstream of historic AMD pollution with multiple size classes present, indicating successful reproduction (Figure 15).

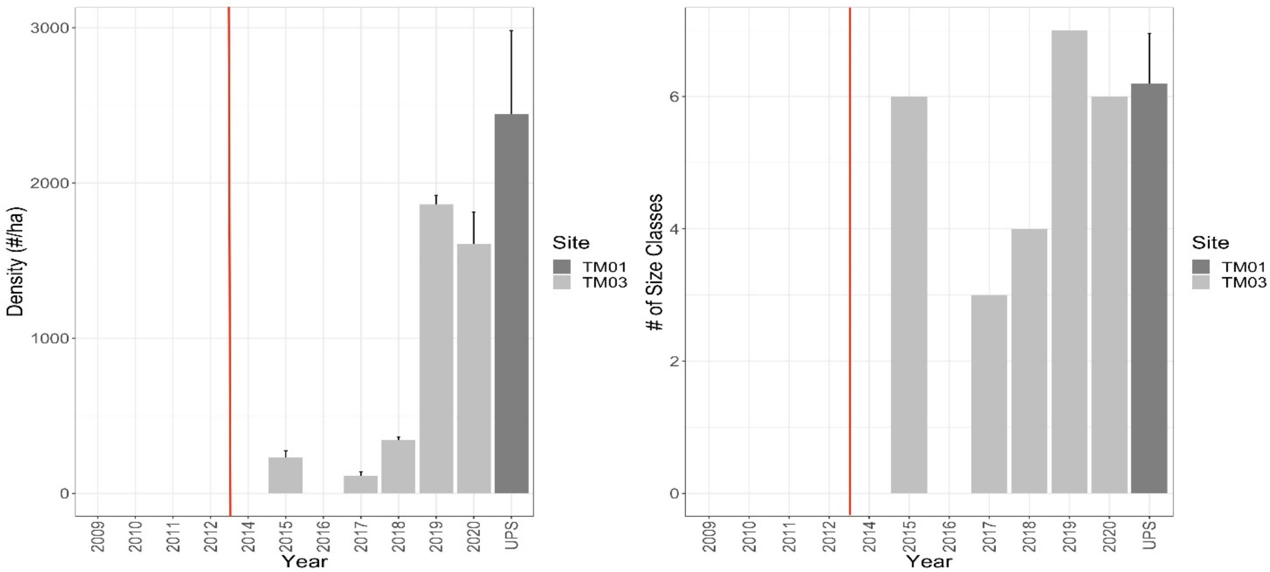

Figure 15. Brook Trout density and size classes over time at a sample site downstream of all passive treatment systems (light grey bars) and the mean density and size classes at the reference site (UPS; upstream of treatment). The red vertical line indicates when all treatment systems upstream of the sample point were functioning. Data were not collected in 2013 and 2016 due to high stream flows. No trout were present in the 2009-2012 surveys.

Conclusion: Monitoring has validated the effectiveness of treatment, informed TU on when treatment system maintenance was needed, and documented the recovery of Brook Trout populations throughout the watershed.

Case Study #4: Demographic and genetic responses of Lahontan Cutthroat Trout to stream reconnection

Project summary: In the fall of 2005 various partners replaced largely impassible road culverts on three tributaries and an irrigation diversion in the mainstem river to increase habitat connectivity in Maggie Creek basin. This work was part of a larger restoration effort beginning in the 1990s to offset mining impacts and benefit Lahontan Cutthroat Trout recovery.

Restoration goal: Reconnect Maggie Creek tributaries to the mainstem to allow for Lahontan Cutthroat Trout movement among tributaries and increase life history expression (fluvial behavior), genetic diversity, and abundance, while improving size structure (including large individuals), especially in the most isolated tributary, Beaver Creek.

Monitoring goal: In response to habitat reconnection, document movement among tributaries, and its benefits, using genetic assignment, increased genetic diversity and abundance, and the presence of large, assumedly migratory individuals.

Monitoring objectives and metrics: Quantify individual movement among tributaries using genetic assignment of individuals, and quantify genetic diversity, age-1+ abundance, and size structure from pre to post reconnection for seven years after restoring connectivity.

Metrics: Genetic assignment; genetic variation (Theta and F_{ST}); age-1 and older abundance (No./100-m); size distribution (length frequency histograms).

Design: *Pre-Post.*—TU implemented a pre-post design to document genetic and demographic changes in response to habitat reconnection. Although technically a pre-post design, this study did include a soft-control in terms of the assumed differing degree of isolation caused by the original culverts (partial versus complete barrier to passage) and, therefore, expected different responses by Cutthroat Trout within each tributary. Forty-four 100-m sites were established systematically across the three Maggie Creek tributaries (Figure 16); they were sampled by backpack electrofishing for Lahontan Cutthroat Trout annually from 2001–2007 and again in 2009 and 2012 (with some exceptions). Tissue samples were collected during sampling for genetic analysis, which was done by the University of Nevada – Reno (laboratory analyses to provide genotypes) and TU (data analysis of genotypes). Wildfires and highly variable streamflows, common to the Great Basin landscape, occurred during the 12-years monitoring period, and monitoring data showed that the abundances and their trends varied among tributaries both before and after habitat reconnect in response to multiple environmental factor (Figure 17). As a result, a statistical model was used quantify the effect of habitat reconnection while accounting for the uncontrollable (confounding) impacts of fire and large flow events that are also known to affect recruitment. The model showed that after accounting for these environmental effects, abundances in Beaver Creek, the most isolated tributary previously, increased three-fold in response to removal of the complete barrier. Size distributions also improved, especially in Beaver Creek, with indication of consistent reproduction (presence of young of year) and the increased presence of larger, migratory-sized individuals (Figure 18). Genetic-based individual assignment showed clear increases in mixing among tributaries after culvert removal: individuals captured in Beaver Creek were genetically assigned to the other two tributaries, particularly in two suitable-flow years, demonstrating they had moved into Beaver

Creek (Figure 19). Population-level genetic responses (metrics of genetic diversity and structure such as heterozygosity, allelic richness and differentiation), however, were complicated and did not change consistently as predicted. Details in Neville et al. (2016).

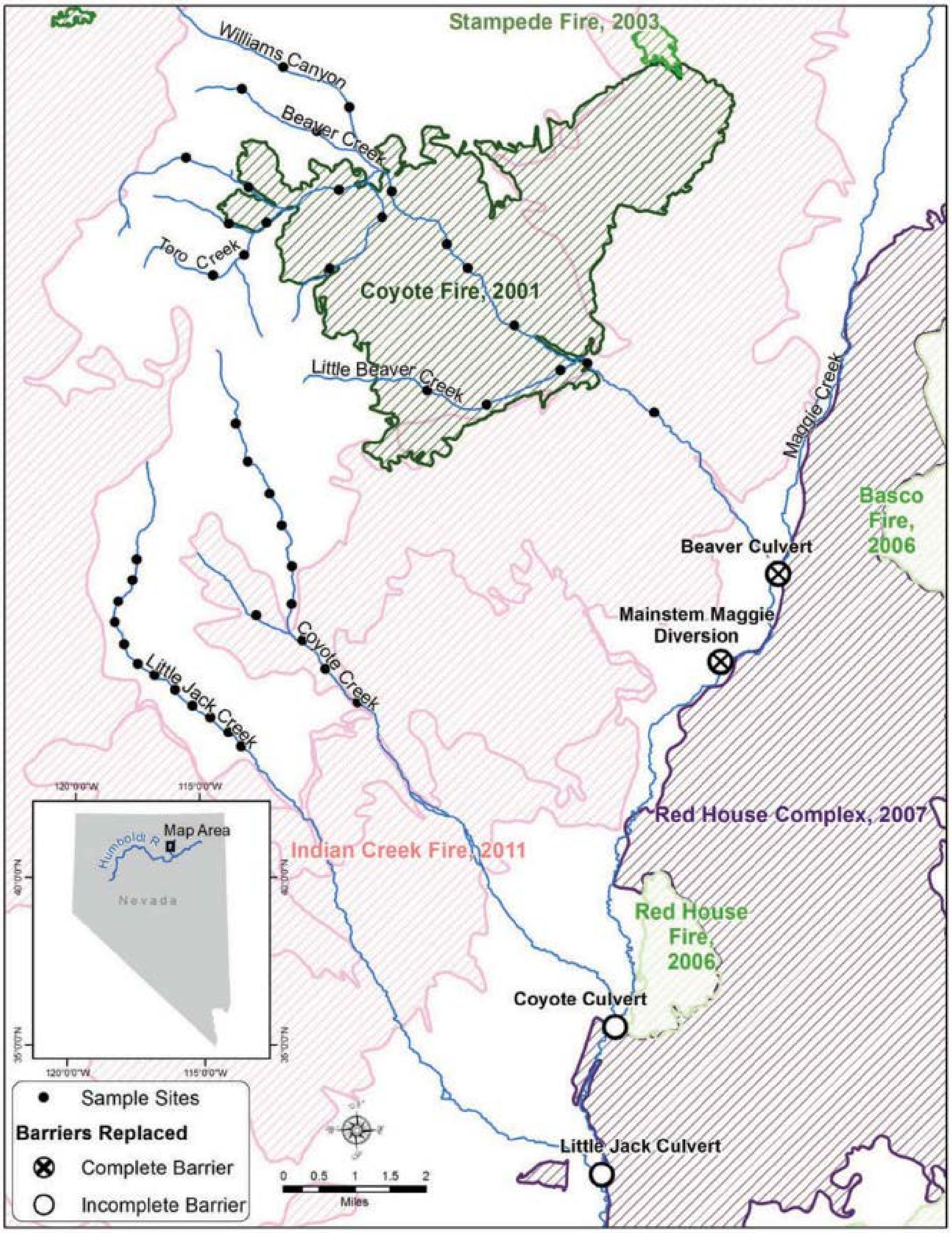

Figure 16. Lahontan Cutthroat Trout sample sites in Maggie Creek, northern Nevada. Lahontan Cutthroat Trout occupy three primary tributaries outlined in blue: Little Jack, Coyote, and Beaver (including Toro Creek and Williams Canyon) creeks. Culverts in Little Jack and Coyote creeks were assumed seasonally passable (shown as open circles), while the culvert and diversion at the base of Beaver Creek and in the main-stem Maggie Creek (shown as open circles marked with an ×) were thought to be complete fish barriers except possibly in the highest flows; all four were replaced in 2005 with structures designed to allow fish passage. Black dots show locations of 100-m fish sampling sites, and the different hatched perimeters outline fires which occurred during the study.

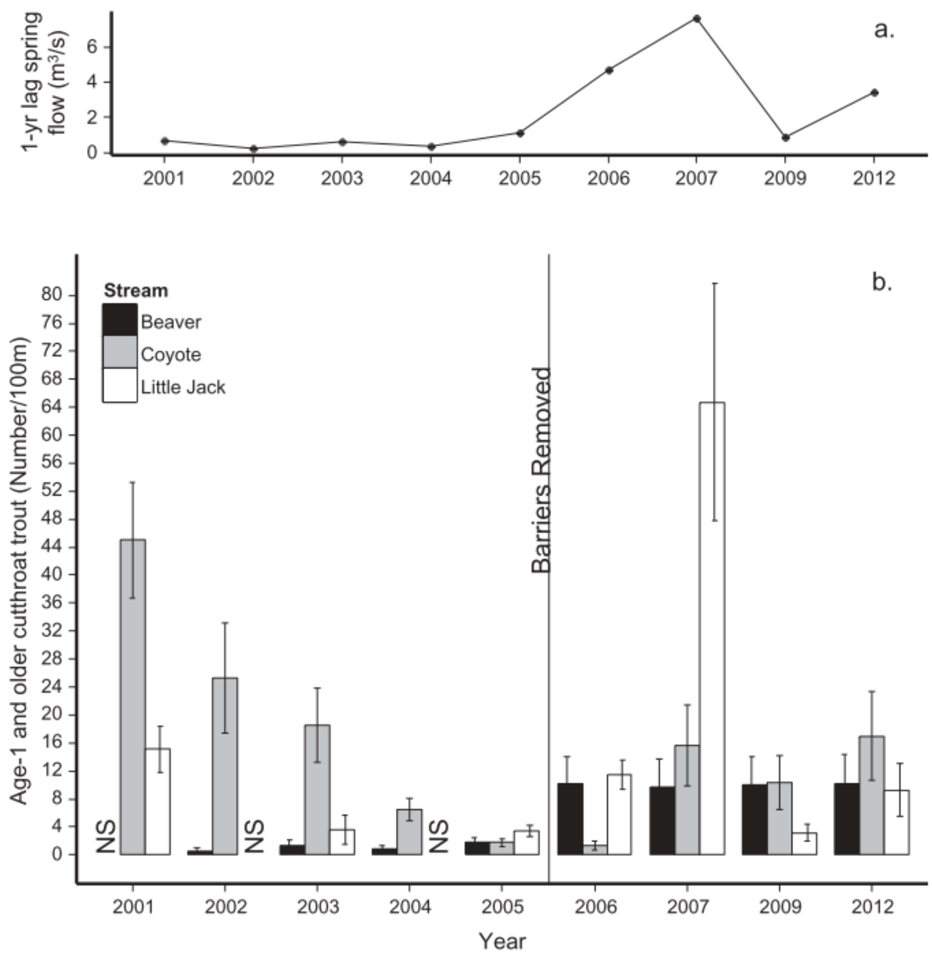

Figure 17. (a) One-year lag of mean spring streamflows (m^3/s; March through June) and (b) mean density of age-1 and older LCT (number/100 m; ±SE) in three tributaries to Maggie Creek, Nevada, from 2001 to 2012. Connectivity among the tributaries was restored after fish sampling in 2005 when three culverts and an irrigation diversion were replaced with passable structures (black line). NS = not sampled: Beaver Creek was not sampled in 2001 due to a fire, and Little Jack Creek was not sampled in 2002 or 2004.

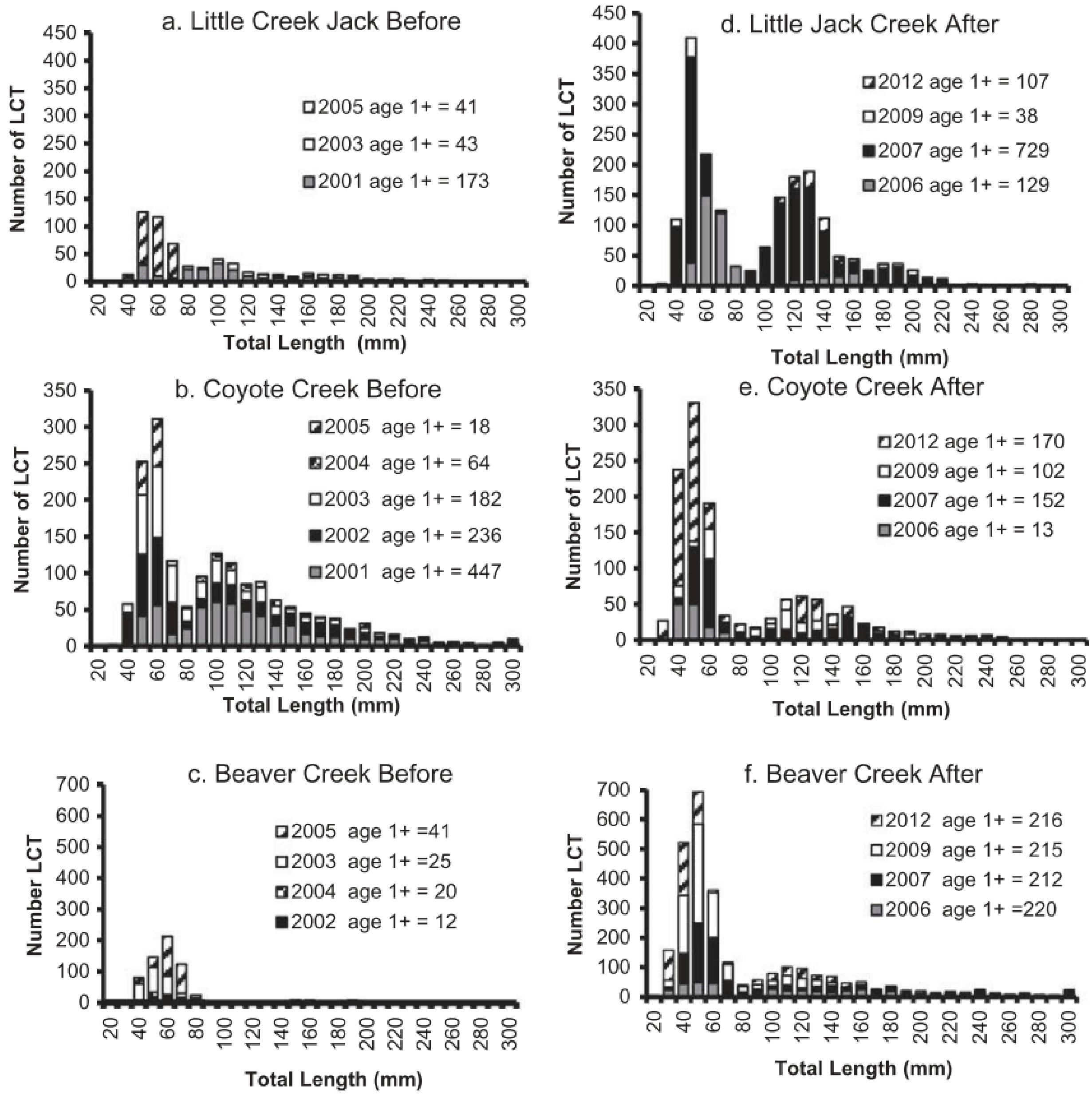

Figure 18. Length frequency distributions of LCT in Little Jack Creek, Coyote Creek, and Beaver Creek for years (a–c) before and (d–f) after culverts were replaced with structures allowing passage. Note the different y-axes and that individuals <80 mm are displayed in the histogram but are not included in the “age 1+ = N” summary for each year.

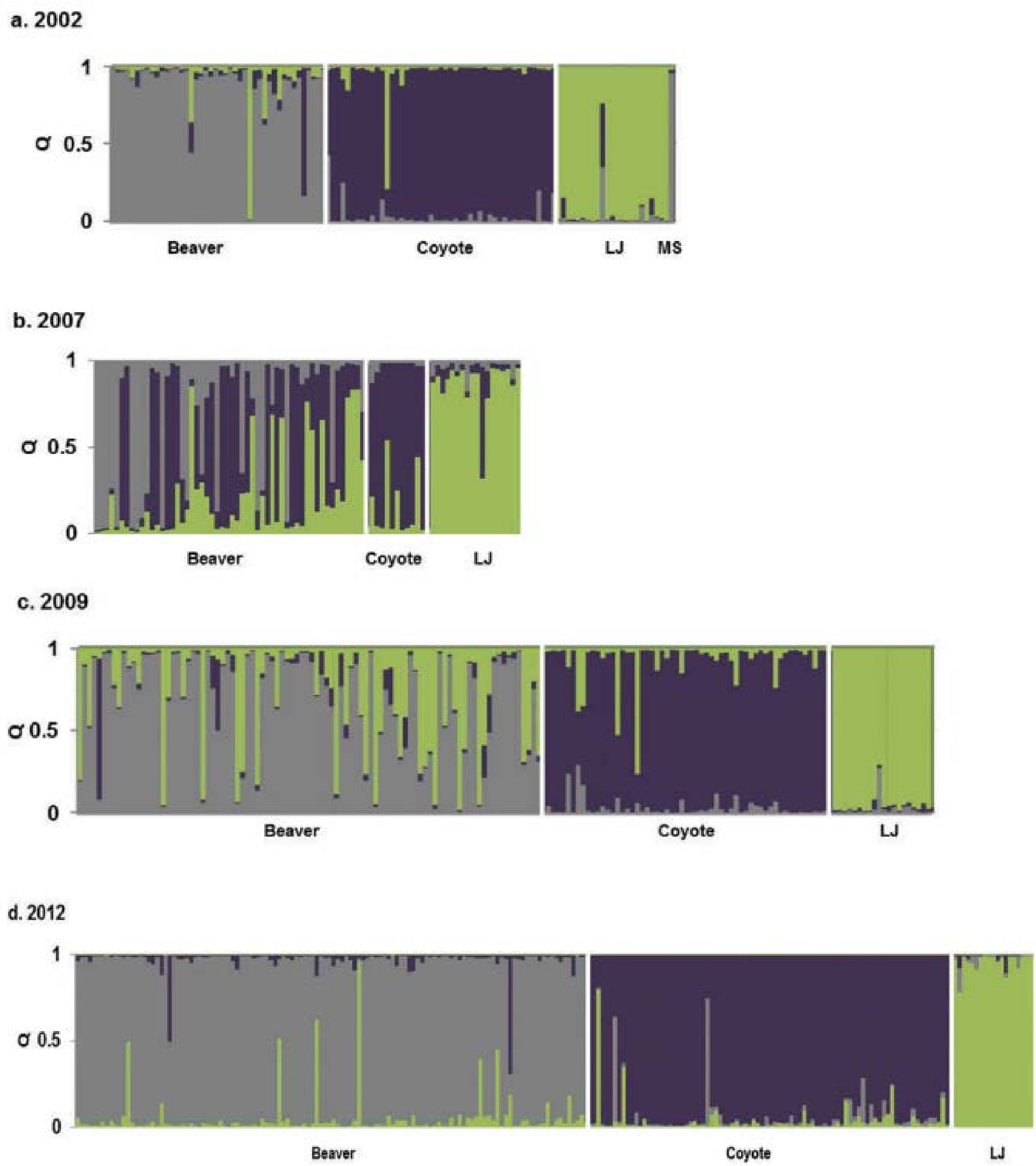

Figure 19. Results of STRUCTURE simulations from 2002 to 2012. Each vertical bar represents an individual fish, with the three different colors representing genetic clusters defined by STRUCTURE (with Beaver, Coyote and Little Jack characterized by the grey, purple and green clusters respectively). Each fish is organized by its capture location but is colored according to its assigned proportional ancestry (Q, from 0 to 1 on the vertical axis) in the different clusters. In 2007 and 2009 there is clear evidence of movement into Beaver Creek - from both Little Jack and Coyote (individuals captured in Beaver Creek that are mostly green and purple) in 2007 and mostly just Little Jack (green individuals) in 2009.

Discussion:. This monitoring example emphasizes the value of a long-term, watershed-scale monitoring program to document the complex responses of fish populations to habitat reconnection and other unexpected events or influences that can occur over a decade of monitoring (e.g., wildfire). Our monitoring work was cost and time intensive (with an estimated total of US$150,000 for 8 years of field sampling and 4 years of genetic laboratory work, excluding time for professional expertise for subsequent demographic and genetic analyses), but it was still only a fraction of the cost of the culvert removals (which was approximately $540,000). The data showed clear evidence of temporally variable movement of fish and a demographic boost, especially to the most isolated population (Beaver Creek), following habitat reconnection, thus verifying success in terms of the two major goals of this restoration effort. It is uncertain what the trajectory of each of these populations would have been if fish could not move in response to fires and variable streamflows as no true control was used, as even small levels of immigration into populations have been shown to have large effects on the persistence of trout populations. The results verify the benefit of reconnecting this watershed, aligning with the broadly held expectation that restoring large, networked populations to foster life history diversity and provide access to disturbance refugia will be essential for ensuring the persistence of native trout in an increasingly disturbance-prone environment – which is highly valuable in recovery planning for ESA-listed species. This emphasizes the need for clearly defined biological response goals which incorporate the situational complexities of dynamic populations living in harsh, dynamic landscapes.

Conclusion: Monitoring allowed TU to work with partners to document the impact of habitat reconnection the Maggie Creek basin. Increased abundances, size structure, and movement among tributary systems will increase the resiliency of this population, a population important to species recovery, amidst harsh Great Basin environmental conditions (fires, variable streamflows).

Further reading: Neville, H., D. Dauwalter, and M. Peacock. 2016. Monitoring demographic and genetic responses of a threatened inland trout to habitat reconnection. Transactions of the American Fisheries Society 145(3):610–626.