

TECHNICAL ARTICLE

Low-tech riparian and wet meadow restoration increases vegetation productivity and resilience across semiarid rangelands

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Restoration of riparian and wet meadow ecosystems in semiarid rangelands of the western United States is a high priority given their ecological and hydrological importance in the region. However, traditional restoration approaches are often intensive and costly, limiting the extent over which they can be applied. Practitioners are increasingly trying new restoration techniques that are more cost-effective, less intensive, and can more practically scale up to the scope of degradation. Unfortunately, practitioners typically lack resources to undertake outcome-based evaluations necessary to judge the efficacy of these techniques. In this study, we use freely available, satellite remote sensing to explore changes in vegetation productivity (normalized difference vegetation index) of three distinct, low-tech, riparian and wet meadow restoration projects. Case studies are presented that range in geographic location (Colorado, Oregon, and Nevada), restoration practice (Zeedyk structures, beaver dam analogs, and grazing management), and time since implementation. Restoration practices resulted in increased vegetation productivity of up to 25% and increased annual persistence of productive vegetation. Improvements in productivity with time since restoration suggest that elevated resilience may further enhance wildlife habitat and increase forage production. Long-term, documented outcomes of conservation are rare; we hope our findings empower practitioners to further monitor and explore the use of low-tech methods for restoration of ecohydrologic processes at meaningful spatial scales.

Key words: hydrology, rangelands, remote sensing, resiliency, riparian, wet meadow

Implications for Practice

- Riparian and wet meadow restoration techniques do not need to be expensive to be effective, but they do need to be scalable to the scope of degradation.
- Increasing hydrologic connectivity (laterally and vertically) can lead to increases in mesic vegetation resilience to climatic variability.
- Simple satellite-based analyses of systems can be effectively leveraged to capture ecosystem responses to low-tech restoration projects that cover broad extents.
- Robust methods for monitoring riparian and wet meadow restoration reported here can be implemented freely and simply with web-based tools.

Introduction

In semiarid landscapes, such as the rangelands of the western United States, riparian and wet meadow ecosystems occupy a small portion of the broader landscape, yet have a disproportionately important influence on wildlife, vegetation, and water resources (Naiman et al. 2010; Donnelly et al. 2016). Hydrologic resources in water-scarce regions are highly sensitive to land management and climatic variability (Schlesinger et al. 1990). Varied anthropogenic impacts have contributed to

riparian and meadow degradation (Goodwin et al. 1997) and contraction such that over 44% of riparian areas in xeric ecoregions of the United States have high riparian disturbance and over 49% have poor or fair riparian vegetative cover (U.S. EPA 2006). In many watersheds, impacts have induced channel incision following high-flow events thereby impairing hydrologic function by disconnecting floodplains, lowering water tables

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and groundwater discharge, and reducing soil water storage capacity (Chambers & Miller 2004). Because of the sensitivity of vegetation to groundwater availability, the net effect has been a decrease in the extent of riparian and meadow areas, changes in plant community composition and structure, and reduction in resilience to drought (Chambers & Miller 2004).

Traditional approaches to stabilize or restore incised channels often involve highly engineered and costly treatments, such as wire gabions, channel reconfiguration using heavy equipment and earthwork, and revegetation. One popular restoration method known as natural channel design can cost \$165,000/km in small rangeland streams (Nagle 2007). Given the scale of degradation, practitioners are increasingly turning to restoration techniques that are more cost-effective, less intensive, and more practical for landowners and managers to implement on their own. These low-tech restoration approaches, such as simple rock and wood structures (Zeedyk & Clothier 2014), management with beaver (*Castor canadensis*) (Pollock et al. 2014), and time-controlled grazing management (Swanson et al. 2015) rely primarily on human labor and natural materials to foster hydrologic, ecologic, and geomorphic processes that are intended to accelerate recovery of incised channels. Average costs for these alternative approaches vary but can be an order of magnitude cheaper than traditional methods (e.g. approximately \$11,000/km for beaver-assisted restoration; Bouwes et al. 2016).

In rangeland systems of the Intermountain West, benefits of proper grazing management have been reported (Oles et al. 2017), but in general, implementation of low-tech restoration has outpaced evaluations of efficacy (Pilliod et al. 2018). One common fundamental outcome necessary for success of many restorations is enhanced soil water storage capacity to promote riparian and wetland vegetation (Hammersmark et al. 2008). Increasingly accessible remote sensing data and cloud computing now make evaluations of vegetation response to near-surface groundwater possible at broad spatial and temporal scales (Huntington et al. 2016).

The lack of monitoring and documented outcomes in riparian restoration has been widely recognized (Bernhardt et al. 2005, 2007). Practitioners often report insufficient funding to support monitoring and evaluation whereas scientists often struggle to find detectable responses in the restoration projects they do monitor (Wheaton et al. 2006). Designing projects to improve degraded systems at a larger, more encompassing spatial extent allows for the use of freely available satellite imagery as a monitoring tool; solving both the practitioner's financial challenge and the scientist's detectability issues. New online tools, such as the Sage Grouse Initiative's (SGI) Mesic Resources map (<https://map.sagegrouseinitiative.com>) and The Desert Research Institute and The University of Idaho's Climate Engine (<https://app.climateengine.org/>), enable nonremote sensing experts free access to satellite imagery that can be used to monitor restoration efforts dating back to the mid-1980s.

In this study, we use satellite remote sensing to explore changes in the normalized difference vegetation index (NDVI) of three riparian and wet meadow, low-tech restoration projects

(Fig. 1). Projects range in primary restoration technique applied (Zeedyk structures, beaver dam analogs [BDAs], and time-controlled grazing management), geography (Colorado, Oregon, and Nevada), and time since implementation. For two projects, we evaluate changes in NDVI before and after restoration, compare those to control reaches, and use aerial extent of greenness to identify annually when higher NDVI is most apparent. For the third project, we compare NDVI before and after restoration, and at early-, mid-, and long-term stages along a 22-year restoration continuum. Using these long-term data, we explore changes in vegetation sensitivity to precipitation as a metric of ecohydrologic resiliency to climatic variability.

Methods

Site Background

Gunnison, Colorado. We evaluated a large-scale project underway to restore riparian and wet meadow areas and build climate resiliency across the Upper Gunnison Basin, Colorado (Table 1; TNC & GCWG 2017). Riparian and wet meadow areas within the sagebrush (*Artemisia* spp.) landscape support habitat for imperiled Gunnison sage-grouse (*Centrocercus minimus*) and other wildlife along with domestic livestock. Since 2012, over 1,000 small and mostly hand-built rock and wood structures have been installed to improve hydrologic function of wet meadows and intermittent/ephemeral streams. These structures (hereafter Zeedyk structures) were installed using Zeedyk restoration methodology (Zeedyk & Clothier 2014) and were designed to slow and disperse water, dissipate energy, capture sediment, increase soil moisture, and promote mesic and wetland plant species expansion.

Bridge Creek, Oregon. Bridge Creek restoration project was initiated to create Steelhead (*Oncorhynchus mykiss*) habitat through increased instream complexity, floodplain connectivity, geomorphic stability, and water quality (Bouwes et al. 2016; Weber et al. 2017). Restoration activities commenced in 2009 through installation of BDAs throughout the lower 32 km of stream before it flows into John Day River. BDAs are built to mimic the function of natural beaver dams with on-site building materials (wood, turf, mud, cobble), and can be reinforced with wooden posts. Along with providing similar benefits to natural beaver dams, BDAs encourage natural beaver activity (Bouwes et al. 2016; Weber et al. 2017). In Bridge Creek, the number of natural beaver dams increased 4-fold after BDAs were installed. By 2012, there were 236 total beaver dams in the lower reach of Bridge Creek; only 121 of them were installed BDAs. This combination of constructed and natural beaver dams can create widespread benefits at relative low-cost per area restored (Gibson & Olden 2014).

Maggie Creek, Nevada. We also examined a watershed-scale project to improve riparian function and condition through time-controlled grazing management improvements in Maggie Creek, Nevada. Up until the early 1990s, most of Maggie Creek

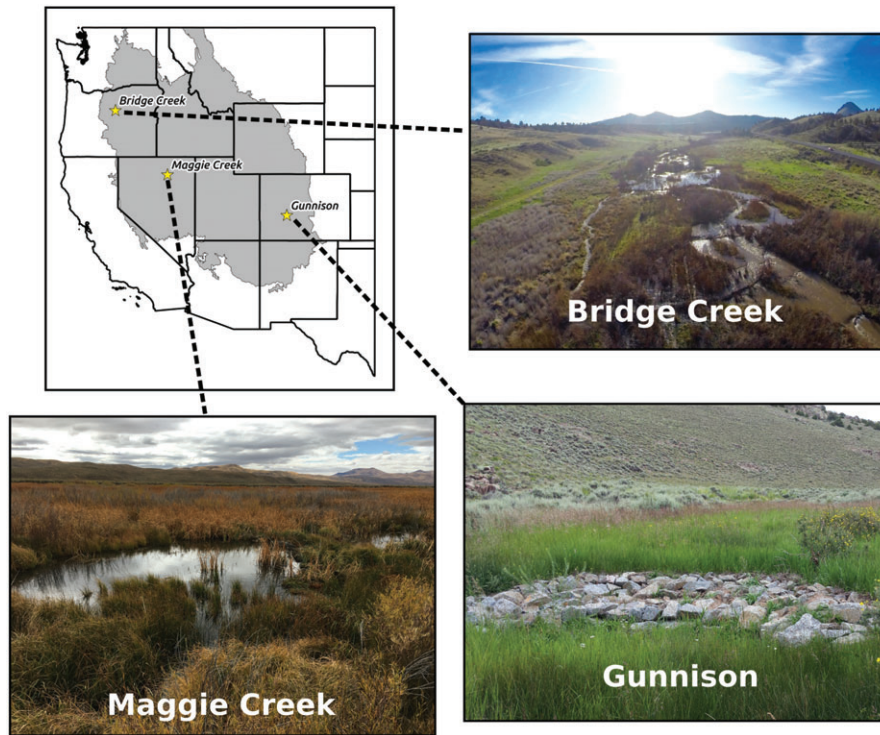


Figure 1. Locations of the three restoration projects with associated representative ground images of postrestoration conditions. The gray area in the map represents the general extent of the Intermountain West, United States.

Table 1. Study site characteristics.

Study Area	Elevation Approximately (m)	Upstream Basin Size (km ²)	Hydrology	Primary Restoration Technique
Gunnison, CO	2,350	N/A	Intermittent and ephemeral streams, wet meadows	Zeedyk structures
Bridge Creek, OR	600	710	Perennial stream	Beaver dam analogs
Maggie Creek, NV	1,600	890	Perennial stream	Time-controlled grazing management

had been grazed heavily by livestock throughout the growing season, resulting in a nonfunctional watershed (Kozlowski et al. 2016). Much of Maggie Creek watershed is managed by the Elko Land & Livestock Company, a subsidiary of Newmont Mining Corporation.

In 1994, Newmont and Elko District of Bureau of Land Management developed the Maggie Creek Watershed Restoration Project (Evans & Snyder 2012), with a primary goal of restoring the watershed through improved grazing management. Grazing management improvements included changes in season of use, installation of watering points away from the riparian zone, and grazing exclusion of sensitive areas. By the late 1990s willow (*Salix* spp.) began to reestablish within the riparian zone and soon after natural beaver recolonization occurred. Overall, the project has enhanced 82 miles of stream, 2,000 acres of riparian habitat, and 40,000 acres of rangeland (Kozlowski et al. 2016).

Vegetation Productivity

For each restoration project, we assessed changes in vegetation productivity using the NDVI calculated from the Landsat surface reflectance archive. NDVI is calculated from the visible red and near-infrared reflectance at 30-m resolution and ranges from -1 to $+1$. We used NDVI as a proxy for vegetation productivity and vigor; higher values generally reflecting increased water uptake, photosynthesis, and improved plant condition (Yoder & Waring 1994). Hereafter, we use the terms “NDVI” and “productivity” interchangeably. We adjusted for inconsistencies between sensors when merging images from different Landsat missions (5, 7, and 8) using methods described in Roy et al. (2016). Areas within the Landsat images containing data anomalies (i.e. cloud, cloud shadow, and snow) were filtered and removed using the Landsat CFMask band (Foga et al. 2017). We averaged NDVI between 15 July and 30 September annually, a time of water scarcity through the Intermountain West, and

compared values before and after restoration (see the Site Analyses section). To explore temporal changes in NDVI, we calculated the length a restoration site stayed above the NDVI threshold of 0.3—indicative of higher primary productivity in sagebrush ecosystems (Donnelly et al. 2016). We used a Welch's *t* test to calculate statistical significance. To minimize the effects of autocorrelation for Gunnison and Bridge Creek we sampled the prerestoration years based on aggregate mean precipitation and for Maggie Creek we compared two different time periods. Annual precipitation, used to establish controls and to account for climate effects, was calculated using the water year (1 October to 30 September) and the University of Idaho Gridded Surface Meteorological Data (METDATA) product (Abatzoglou 2013). All analyses were performed using Google Earth Engine (Gorelick et al. 2017).

Site Analysis

Gunnison, Colorado. We evaluated restoration sites within four different sub-basins where Zeedyk structures were installed. Due to having minimal postrestoration data we compared “treated” gridcells with “control” gridcells. Because the width of many streams was less than 10 m, and Landsat spatial resolution is 30 m, we evaluated gridcells where at least one restoration site was fully contained. We used a threshold of NDVI greater than 0.4 on our data to ensure the gridcell was adequately capturing the riparian and/or wet meadow landscape rather than adjacent upland areas. It is inevitable that in spite of this threshold, we are still sampling some uplands that are not hydrologically connected to the restoration sites. For this reason, our results may be conservative in terms of the actual magnitude of change on the ground. After applying these criteria, there were 156 treated gridcells to evaluate.

To develop control sites we eliminated any gridcells that were outside of the stream floodplain. We roughly delineated the floodplain using a cost distance algorithm based on the flowlines from the National Hydrography Dataset (U.S. Geological Survey 2013) and a 10-m digital elevation model (U.S. Geological Survey 2017). These methods are based on those established in Nagel et al. (2014). We also eliminated any gridcell that fell within a restoration reach. Finally, we imposed a lower (0.435) and upper (0.447) limit to NDVI values. This forced the NDVI distribution of control gridcells ($n = 173$) to more accurately match the NDVI distribution of treated gridcells.

To account for climate effects when making direct comparisons between before and after restoration, we used four prerestoration years that provided the most similar average water-year precipitation to the 4 years postrestoration. Selected prerestoration years (2004, 2005, 2008, and 2009) had an average precipitation of $1.33 (\pm 0.13)$ mm/day, matching postrestoration precipitation ($1.33 [\pm 0.05]$ mm/day) almost identically.

Bridge Creek, Oregon. To evaluate the riparian corridor of Bridge Creek, we used the same upstream and downstream boundaries of treatment and control reaches defined in Bouwes et al. (2016). Due to having minimal postrestoration data we compared “treated” gridcells with “control” gridcells. We

narrowed lateral boundaries manually to match the extent of the riparian vegetation within the stream corridor. This adjustment allowed us to focus primarily on areas that are more regularly inundated rather than the 2-year (or longer) timescale that the larger, floodplain width would provide. After this adjustment, the treatment and control areas were 3.8 and 4.2 acres, respectively. To account for climate effects when making direct comparisons before and after restoration, we used prerestoration years that provided the most similar average annual precipitation to years postrestoration. Selected prerestoration years (1997, 1998, 1999, 2001, 2005, 2006, and 2008) had an average precipitation of $1.24 (\pm 0.25)$ mm/day, matching almost identically our postrestoration measurements ($1.24 [\pm 0.16]$ mm/day).

Maggie Creek, Nevada. Established in 1994, the Maggie Creek Watershed Restoration Project allows for evaluation of over 20 years of postrestoration conditions. The stream reach used for evaluation begins at the confluence with Beaver Creek and flows approximately 30 km downstream to Soap Creek. We used a 60-m buffer on either side of the creek as lateral boundaries when examining vegetation productivity. Due to the longer period of analysis and broader extent we did not use a control watershed for comparison, but rather compared trends in NDVI directly with precipitation. We used the postrestoration years 1994–2016 for trend comparison and the years 1985–1993 as prerestoration conditions.

The extended time since restoration enabled us to evaluate sensitivity of changes in NDVI to changes in precipitation over time. We used a rolling linear regression with a 5-year window to examine the relationship between NDVI and precipitation. We normalized precipitation so that values were between -1 and 1 , matching the range of NDVI. By normalizing precipitation values we can interpret slope of the linear regression as unit change in NDVI per unit change in water-year precipitation (i.e. sensitivity) during the specified 5-year window. A value of one represents 100% sensitivity, meaning that any change in precipitation is expressed similarly in NDVI and a value of zero represents 0% sensitivity, meaning that any change in precipitation is not expressed in NDVI. We hypothesized that a reduction in sensitivity through time could be a signal of increased resiliency against impacts of drought and climate variability. To test this idea, we fit data as a nonlinear least squares model using an exponential decay function:

$$Y = Y_0 (e^{-kt}),$$

where Y is estimated sensitivity, Y_0 is the initial sensitivity value, k is the steepness of the curve, and t is the independent variable represented as number of years since restoration.

Results

Productivity increased following restoration in all three projects (Figs. 2–4). Productivity increased by 24% at Gunnison (before: 0.41 ± 0.05 NDVI, after: 0.51 ± 0.02 NDVI; Fig. 5A),

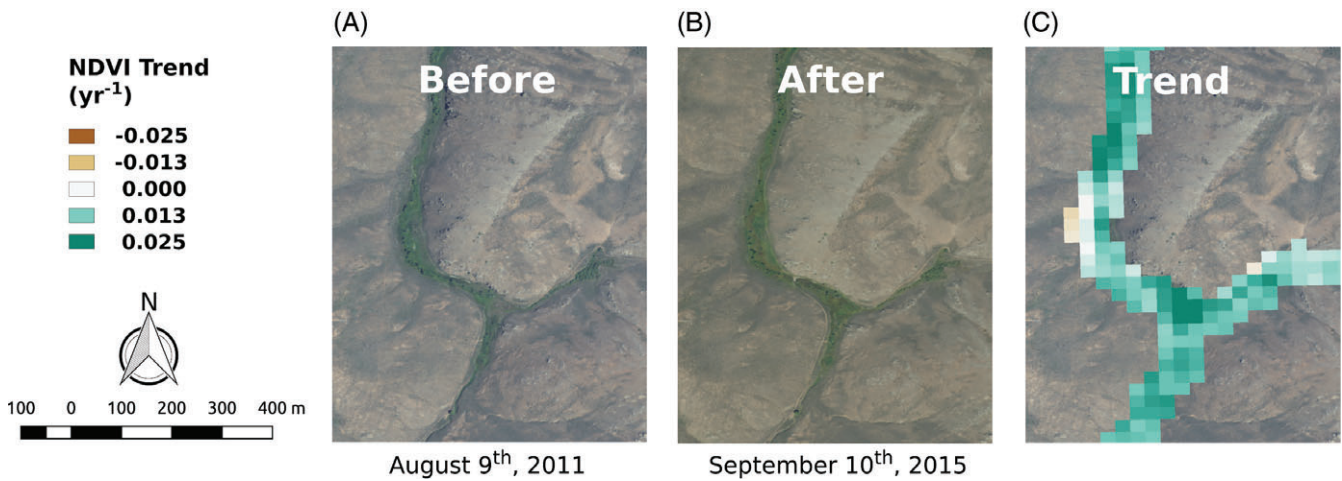


Figure 2. Aerial images of a Gunnison restoration reach where over 40 structures were originally installed. The image is from (A) before and (B) after restoration. (C) The linear trend in NDVI (calculated from Landsat satellite imagery) since restoration, representing increased vegetation productivity.

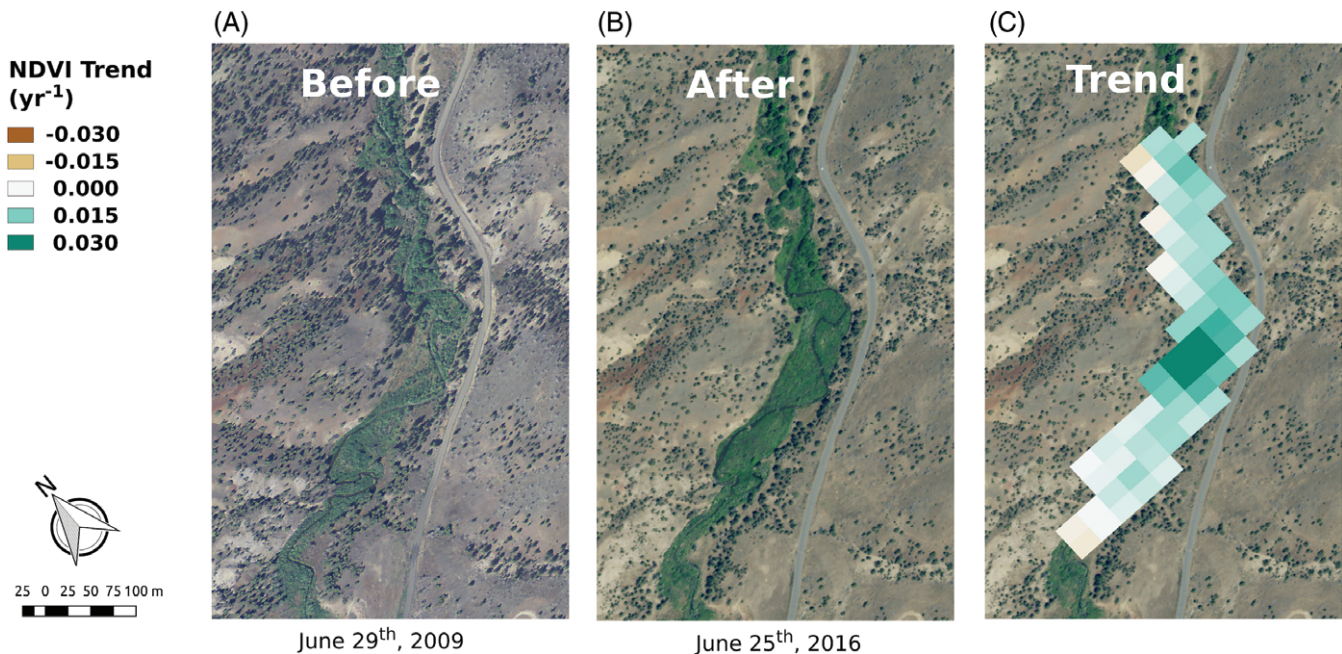


Figure 3. Aerial images of a Bridge Creek restoration site from (A) before and (B) after restoration over a 600-m stretch of the total 4 km treated reaches. (C) The linear trend in NDVI (calculated from Landsat satellite imagery) since restoration, representing increased vegetation productivity.

and by 20% at Bridge Creek (before: 0.38 ± 0.03 NDVI, after: 0.45 ± 0.03 NDVI; Fig. 5B). Treated sites showed immediate improvements over the control sites in productivity after restoration and consistently maintained higher levels (Fig. 5A & 5B). Furthermore, improvements between the treated and control sites, pre- and postrestoration, were statistically significant at the $p < 0.005$ level for both Gunnison and Bridge Creek. Interannual variability of productivity in the control and treated sites align well with the variability in the water-year precipitation. At the long-term site, Maggie Creek productivity increased by 22% in the first 11 years postrestoration (before: 0.34 ± 0.03 NDVI, after: 0.41 ± 0.03 NDVI) compared to the

decade prerestoration, and by 31% in the most recent 11 years (before: 0.34 ± 0.03 NDVI, after: 0.44 ± 0.03 NDVI). The linear trend in NDVI indicated that productivity continued to increase postrestoration (slope = 0.002, $p = 0.04$) with no change in precipitation over time (slope = -0.001 , $p = 0.89$).

At all sites, restoration not only increased the overall vegetation productivity but extended such productivity longer into the growing season (Figure 6). At Gunnison, the proportion of productive mesic area (NDVI > 0.3 threshold) within treated reaches increased the most during October (83%) and November (721%) (Fig. 6A). At Bridge Creek, large increases in productive mesic areas are present in winter, spring, and fall, with

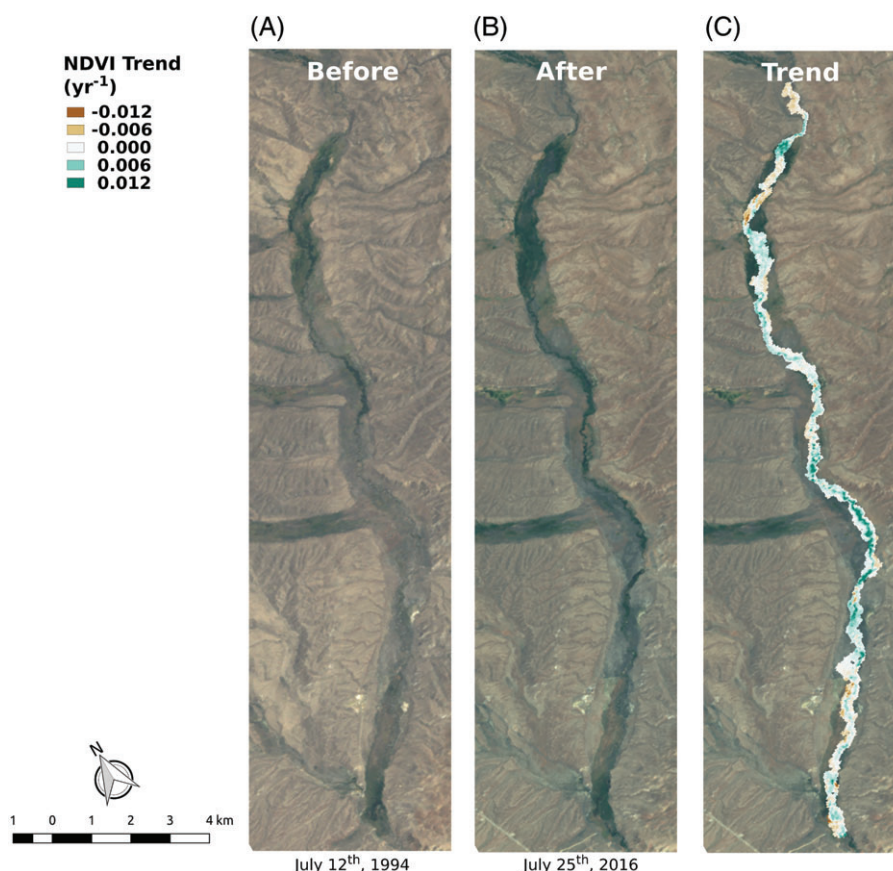


Figure 4. Aerial images of the Maggie Creek reach used in the evaluation from (A) before and (B) after restoration. (C) The linear trend in NDVI (calculated from Landsat satellite imagery) since restoration, representing increased vegetation productivity.

the largest increase occurring in November (276%) (Fig. 6B). At Maggie Creek, we delineated three separate time periods to evaluate percent productive mesic area of the treated reach through time (Fig. 6C). All months had increases in productive mesic area in the first 11 years after restoration. All months except July showed further increases in productive mesic area during the subsequent 11 years. The largest increases occurred during the first decade after restoration in the summer and fall months. All months except January, February, and May had increases that were statistically significant at the $p < 0.1$ level.

At Maggie Creek, sensitivity to precipitation decreases rapidly from 0.22 to around 0.03 over the first 10 years postrestoration and then levels off ($Y_0 = 0.188$ and $k = 0.273$; Fig. 7). Most improvements in sensitivity are made in this first decade after restoration. After which, a new equilibrium appears to be reached where productivity fluctuates very little with changes in precipitation, thus suggesting greater resiliency against the impacts of drought and climate variability.

Discussion

Our results show that low-tech restoration methods applied to riparian and wet meadow systems effectively increased productivity of vegetation in magnitude and duration. These

results were obtained using freely available and relatively coarse remote sensing monitoring methods, suggesting that the magnitude of increased productivity presented here is likely conservative compared to actual on-the-ground results. These increases suggest enhanced soil water storage and the potential for basin-wide ecohydrologic improvements. Furthermore, restoration efforts have reduced ecosystem sensitivity to climatic drivers, creating resilience, which is particularly important in regions where drought is expected to increase in intensity, frequency, and/or duration. Enhanced soil water storage lessens dependence of vegetation productivity on precipitation, allowing water resources and overall ecosystem function to remain intact during periods of low precipitation.

Our results at each of these water-limited sites further suggest that restoration projects are making the same amount of annual water more available for vegetation. The critical relationship between vegetation productivity and soil moisture in treated riparian and wet meadow landscapes is well known (Loheide & Gorelick 2007; Hammersmark et al. 2010). Above- and below-ground vegetation structure will adapt in various ways and over multiple timescales to optimize soil moisture to vegetation type and structure (Eagleson 1982). This relationship leads to a positive correlation between plant productivity and soil moisture (Rodríguez-Iturbe et al. 1999), inferring relative changes

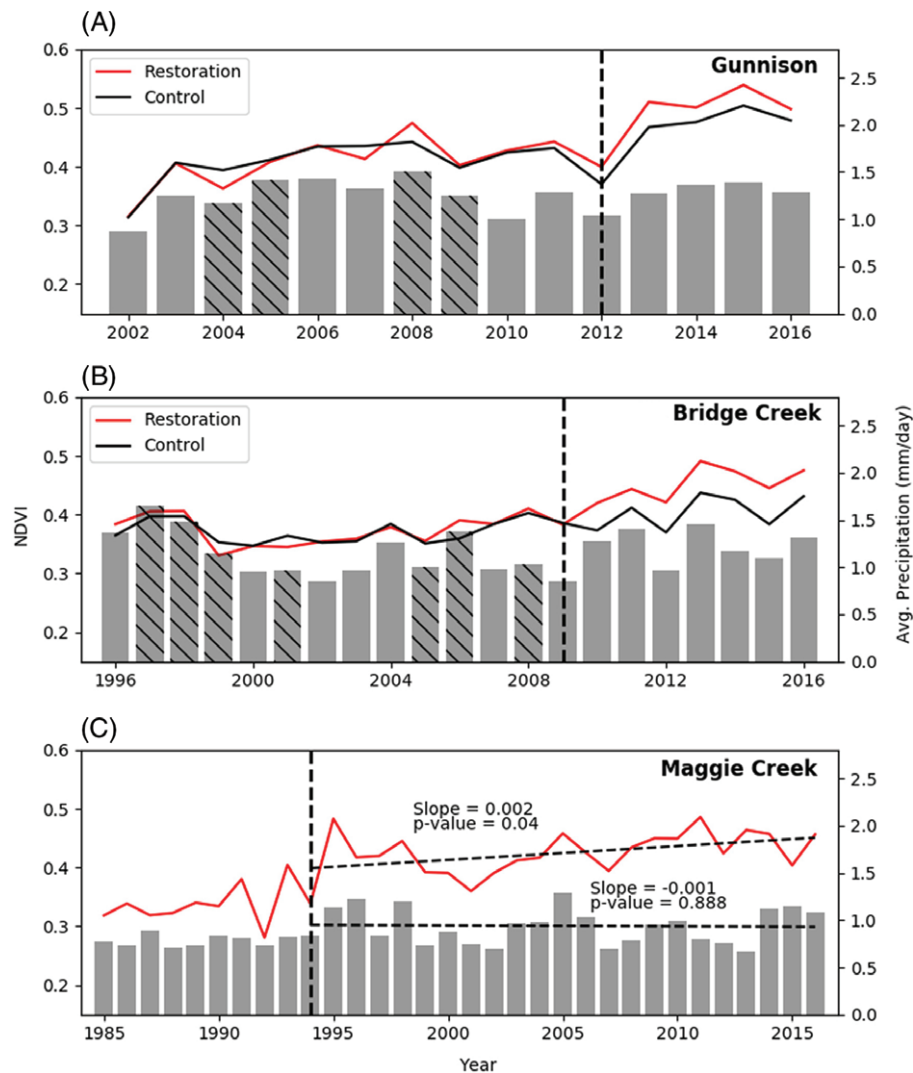


Figure 5. Annual late season (15 July to 30 September) mean NDVI for (A) Gunnison, CO, (B) Bridge Creek, OR, and (C) Maggie Creek, NV restoration sites. Where applicable, the red line represents the mean NDVI of the treated sites and the black line represents the mean NDVI of the control sites. The bar chart shows average annual daily precipitation for the region over the same time period. The hatched bars mark the years used to represent prerestoration conditions at Gunnison and Bridge Creek. The vertical dashed line represents the year that restoration activities commenced. For Maggie Creek, NDVI and precipitation trends are illustrated with a dashed line.

in soil moisture through changes in aboveground biomass in water-limited environments (i.e. where atmospheric demand is greater than supply).

In the restoration projects where fluvial processes are enhanced directly (i.e. BDAs and Zeedyk structures), depth to water table has likely been reduced, creating more mesic and hydric conditions that reduce rooting depth and increase aboveground carbon allocation (Schenk & Jackson 2002). Additionally, sediment transport is slowed and water is stored behind restoration structures and in reconnected floodplains. For example, previous studies at Bridge Creek quantified a direct rise in the water table and increased base flows, channel widening, and sinuosity after BDA installation, further demonstrating connections between hydrology and riparian vegetation (Bouwes et al. 2016).

Fluvial and hydrologic processes were enhanced indirectly through improved grazing management, fostering increased establishment and productivity of riparian plants. At Maggie Creek, riparian vegetation likely stabilized streambanks and reduced channel cross-sectional area, promoting more frequent and prolonged connections with a channel's floodplain that in turn stores more water in soil. In addition, vegetation provides shading, which reduces hydrologic losses from evaporation at the land surface (Zeedyk & Clothier 2014). Maggie Creek grazing improvements limited livestock access to riparian areas and protected vegetation during critical times (e.g. hot summer growing season). These changes allowed for a productive riparian structure throughout the entire watershed, increasing productivity over a much larger area and longer time period. Grazing changes also fostered substantial natural

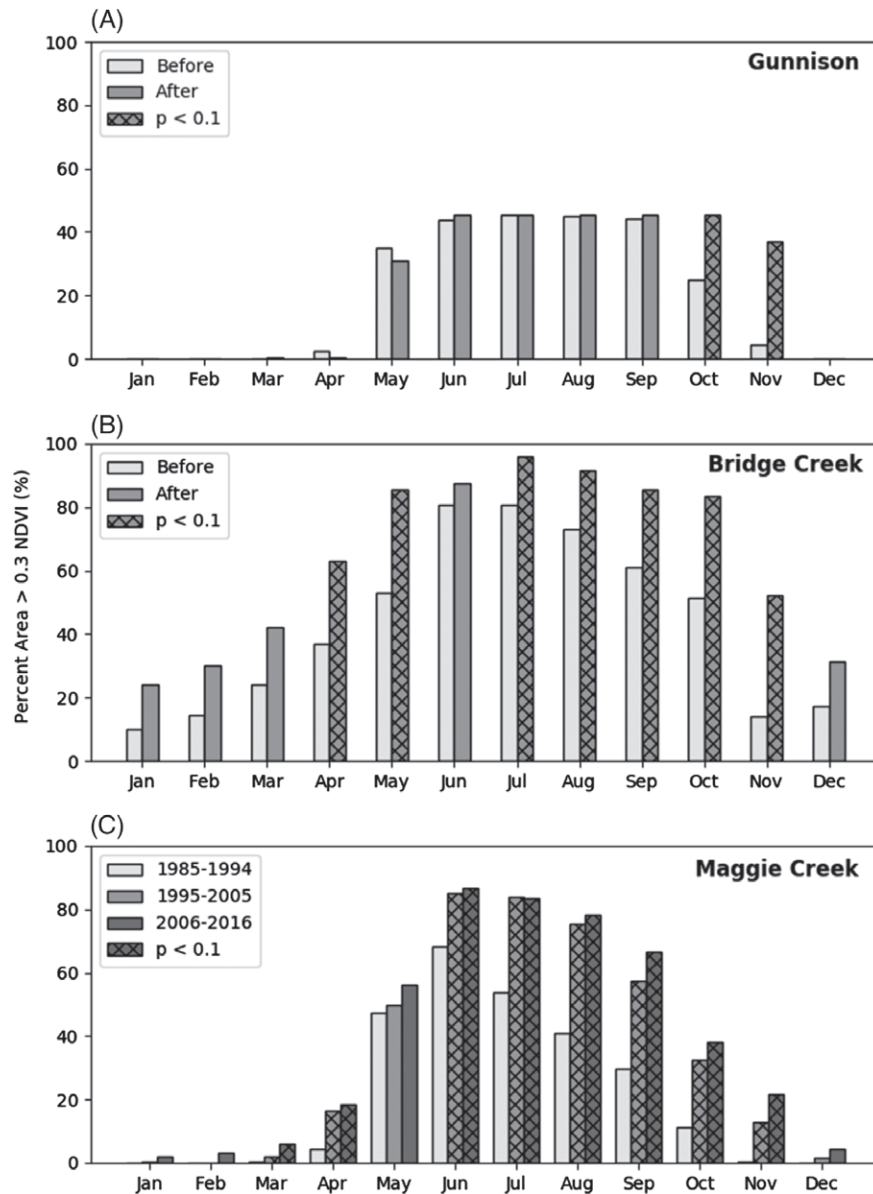


Figure 6. Monthly percent area of productive treated reaches (NDVI > 0.3) in (A) Gunnison, CO, (B) Bridge Creek, OR, and (C) Maggie Creek, NV restoration sites before and after restoration. For Maggie Creek, three different time periods are included: before restoration, first 11 years postrestoration, and second 11 years postrestoration. Hatched bars represent months where the increase in productive area was statistically significant ($p < 0.1$) compared to before restoration.

beaver recolonization, which further enhanced positive feedbacks for recovery of the incised channel (Bouwes et al. 2016; Kozlowski et al. 2016).

Temporal improvements are perhaps more ecologically beneficial than are the resulting spatial shifts. At all study sites, not only is water being made more available for vegetation growth but it is being made available longer. Such extensions can have large benefits to ecosystem function, including wildlife habitat and forage production. Time since restoration plays an important role in longevity of benefits—as projects mature, resulting increases in productivity were apparent for longer durations in the annual cycle. This is best exemplified at Maggie Creek

where the least productive months (i.e. December, January, and February) had the largest productivity increases during the most recent years. These increases suggest a successional pattern to recovery, where vegetation is first restored during the most productive months and then, after broad-scale improvements in ecohydrologic function take place, smaller second-order processes take hold and carry restoration effects into the less productive months.

Two analytical limitations arise from variation in annual water budgets and our inability to distinguish native versus invasive plants from satellite imagery. While we minimized effects of annual water budgets by comparing years with

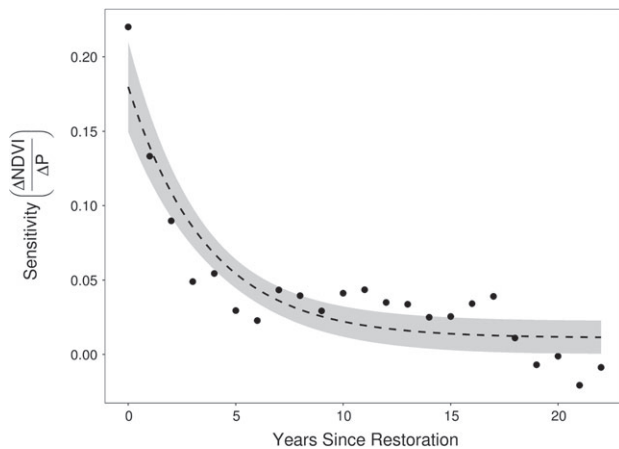


Figure 7. Sensitivity of NDVI to water-year precipitation relative to years since restoration for Maggie Creek. Values are calculated as a moving window linear regression using 5-years as the width of the window. Fitted line represents the best-fit exponential decay curve surrounded by 95% confidence intervals.

similar precipitation, intra-seasonal trends in precipitation and snowmelt timing could affect results. Consistency in results among our sites suggests that these were likely minor. Furthermore, remotely sensed images do not distinguish between productivity gains from native vegetation versus non-native weeds. It is possible that some gains in NDVI could come from shifts in vegetation type and/or increased productivity in non-native plants. Companion ground monitoring studies at all sites suggest that NDVI gains are likely from native vegetation (Bouwes et al. 2016; Kozłowski et al. 2016).

An additional benefit of our analysis is the demonstration of how freely available satellite imagery can be used to track responses to low-tech, low-cost restoration. Typically, monitoring methods are tailored specifically to the restoration project but we show that it might be beneficial to consider designing the restoration project in concert with these coarse, yet robust and economically feasible remote sensing methods. By doing so we solve several issues that are universal among ecological restoration efforts beyond those discussed heretofore. These include developing restoration approaches that are affordable enough to scale to the extent of the ecosystem degradation, creating change that is detectable at landscape scales, and monitoring these changes over a time period to show ecosystem-level response. We use the example of low-tech, low-cost riparian restoration techniques to show that when restoration impact and extent is large enough, they become relatively easy to detect even with moderate resolution satellite imagery (i.e. 30 m). Remote sensing data has been available for decades but its use as a monitoring tool has, until now, required a high degree of expertise. New cloud-based technologies and applications (e.g. SGI interactive web application, Climate Engine, Google Earth Engine, etc.) make monitoring more accessible and economical, allowing society to more efficiently and effectively focus restoration investments and quantify ecological outcomes.

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