THE EFFICACY OF BEAVER MIMICRY RESTORATION TECHNIQUES ON RIPARIAN VEGETATION VIGOR IN CENTRAL OREGON

by

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DEDICATION

I would like to thank my family for their steadfast support in my pursuit of graduate school, a career change, and in my endless curiosity for the natural world. To my parents, thank you for modeling fortitude and work ethic. To my sisters, Carrie, and Devon, thank you for your living examples of resilience and strength. You are two of my biggest heroes.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Anthropogenic disturbances have adversely affected riparian habitat and accelerated stream incision across rangeland systems of the Western United States. There has been mounting interest in mitigation efforts to accelerate ecosystem recovery, including the development of beaver mimicry structures known as beaver dam analogs (BDAs). I examined a time-series analysis of five sites of stream-adjacent riparian vegetation using remote sensing techniques, imagery from the National Agricultural Imagery Program (NAIP), and the Normalized Difference Vegetation Index (NDVI) over an eight-year period before and after beaver dam analog construction along a segment of the Crooked River in Central Oregon. I hypothesized that post-restoration NDVI values would be higher than pre-restoration NDVI values in areas upstream of BDA complexes due to increased water impoundment generated by BDA structures and, thus, increased water accessible to adjacent riparian vegetation. Results from this study, however, revealed variable trends in NDVI values pre- and post- construction of BDA complexes compared with NDVI values from control locations absent of BDA development. For each complex, there was a consistent increase in NDVI values observed after the initial construction. However, in subsequent years, NDVI values declined for complexes 1 and 2 by 51% and 26% respectively between 2016-2020, were unchanged for complex 3, decreased by 50% in 2020 and increased by 120% in 2022 for complex 4, and consistently increased for complex 5 by 45% from 2016-2022. Possible explanations for variability in results include individual BDA structural failure resulting from high flows throughout the course of my study period. Recommendations for future studies include the use of higher resolution imagery from unoccupied aerial vehicles (UAVs) to monitor fine-scale nuances in riparian vegetation productivity, incorporating supplementary vegetation indices, and applying spatial covariates to strengthen statistical analyses and improve understanding of outcomes.

INTRODUCTION

Beavers (*Castor canadensis)* are a keystone species across North America's natural landscapes playing an integral role in preserving and diversifying stream and riparian habitats. Throughout the 19^{th} century, beaver populations declined as European colonization and exploitation increased. As the largest rodents in North America, beavers were targeted primarily for oil and fur and extirpated in certain areas for agricultural land purposes. Throughout the last century, proper wildlife management, combined with the reintroduction of beaver by land managers, has initiated a rebound of populations currently estimated at 15 million in North America (MacDonald et al., 1995).

Reduced populations of North American beaver in the 19^{th} century had important implications for stream geomorphology and both aquatic and terrestrial species (Orr et al., 2020). Given their role in dam building and vegetation foraging, beavers alter stream and riparian spatial distribution by impounding flows, increasing the water table, and maintaining water for longer residence times for both surface and groundwater levels (Pollock et al., 2007). As a result, beavers impact the spatial distribution of riparian surface area and, consequently, generate habitat for aquatic invertebrates, waterfowl, birds, mammals, amphibians, and terrestrial plants.

Reintroducing beavers to landscapes where they were absent has transformed intermittent streams into perennial ones and facilitated reconnections to floodplains. Dams and ponds created by beaver habitat contribute to peak attenuation during floods, dissipates stream energy, and traps sediment (Green and Westbrook, 2009). On a southeastern Alaskan island, a single pond created by a beaver dam was estimated to reduce peak flows by greater than 5% (Beedle, 1991). Hence, it is expected that streams with multiple beaver dams have a larger cumulative effect in reducing peak flows (Pollock et al., 2007).

Beaver habitat modifications, such as the construction of natural beaver dams, contributes to lower stream velocities, water impoundment, and flow resistance (Castro 2017). As a result, expanded water availability in riparian areas facilitates the growth of emergent vegetation, thus dominating pre-existing upland shrubs and trees. Furthermore, surface water flow into floodplains promotes the development of successional wetland communities. Micro- and macro-invertebrates benefit from boosted productivity in ponds and wetlands (Francis et al., 1985). In arid ecosystems, a narrow corridor of vegetation productivity occurs along streams (Figure 1) and supports a wide array of biodiversity and habitats (Fesenmyer et al., 2018).

Figure 1. Drone aerial showing a narrow corridor of vegetation productivity along Hay Creek, an upper reach of the John Day River in Eastern Oregon. Photo by Allison Law.

There has been increased awareness and support among land managers opting for beaver coexistence versus eradication (Jordan and Fairfax, 2022) and beaver-related restoration techniques to recover incised streams across America's western rangelands. Restoration approaches include the construction of anthropogenic structures known as beaver dam analogs (BDAs), which offer a relatively inexpensive and "process-based" (Orr et al., 2020) method aiming to facilitate natural processes, using semi-porous wooden post structures traversing the stream channel to mimic a natural beaver dam (Figure 2.)


Figure 2. Typical BDA restoration design. Photo by Allison Law.

Castro et al. (2017) describe general recommendations for building BDA complexes comprised of a primary dam with additional structures downstream to decrease stress on the main dam to reduce the likelihood of failure in the event of peak flows. BDA complex structure is generally determined by stream gradient and geomorphology as dam failure is commonly associated with steeper gradients (Wheaton et al., 2019). Published protocols emphasize using willow branches, depending on availability, woven in between vertical wooden posts driven into the ground far enough to reduce the risk of structural failure. Additionally, fill material consisting of mud and vegetation is placed upstream and in between posts to facilitate water retention.

Other purposes for BDAs include the reinforcement of an existing natural beaver dam. BDAs may also attract incoming resident beavers, which assume the role of short- and long-term management, demonstrating a complementary dynamic between human and natural processes.

The legal process for approving BDA construction is complex and varies by state. Water laws, land use, and fish and wildlife habitat must be considered during permit application from the U.S. Army Corps of Engineers (Davee et al., 2019). If endangered species are present, the National Oceanic and Atmospheric Administration (NOAA) or the U.S. Fish and Wildlife Service (USFWS) must evaluate. State and federal agencies often require an archeological assessment. Surveying for cultural artifacts may also be conducted by Native American tribes. In the state of Oregon, regulatory approaches are intended to streamline and expedite the permitting process and approve projects designed specifically to promote ecological function and mimic natural habitats (ODFW).

The roles that natural beaver dams and beaver dam analogs play in water retention and subsequent impacts on stream-adjacent riparian plant productivity in arid and semi-arid regions has not been well studied to date (Fairfax and Small, 2018). To holistically assess and monitor vegetation vigor across these ecosystems, both field-based observations and remote sensing techniques have proven to be effective methodologies. However, in situ observations are costly and have limitations across broader spatial and temporal scales due to their restrictions to smaller regions of interest (Lausch et al.,2018). Remote sensing observations offer a cost-effective, timely, and repeatable assessment of stream and vegetation monitoring at both local and global scales by measuring electromagnetic radiation remotely from satellite, aerial, and unoccupied aerial systems (UAS).

Given the trends observed with the presence of natural beaver dams facilitating water surface area expansion, and thus, the emergence of riparian vegetation (Pollock et al., 2017), my study objective was to use remote sensing and the Normalized Difference Vegetation Index (NDVI) to assess time series riparian vegetation productivity in areas upstream of the construction of beaver dam analogs. Among 100 vegetation indices developed from multispectral remotely sensed imagery, the NDVI has become one of the most widespread indices for vegetation assessments (Huang et al., 2020); therefore, I selected this index for this study. The NDVI helps to delineate healthy versus unhealthy vegetation by measuring spectral reflectance in the red and near-infrared regions of the electromagnetic spectrum.

There has been growing interest in examining the benefits of beaver-related restoration practices across western rangelands. However, limited peer reviewed studies exist that focus on investigating both the benefits and failures of such strategies (Bouwes et al., 2016). Monitoring successes and shortcomings is crucial to determine the efficacy of beaver-based restoration projects. More than half of the projects in the western United States have occurred in Oregon, Idaho, and Washington. Bridge Creek near Mitchell, Oregon is one of very few monitored BDA systems in the scientific literature to date (Orr et al., 2020). Given the diverse nature of vegetation, stream gradients, disturbance, and geology in riparian systems, improved monitoring across a variety of temporal and spatial scales is vital to determine BDA effectiveness in reference to restoration goals.

My study, using both NDVI metrics and qualitative assessments, aims to answer the following questions regarding the impacts of BDA development on riparian-adjacent vegetation vigor: 1) Are higher NDVI values observed in upstream vegetation post-BDA versus pre-BDA construction? 2) How does vegetation vigor compare in areas upstream of BDA construction

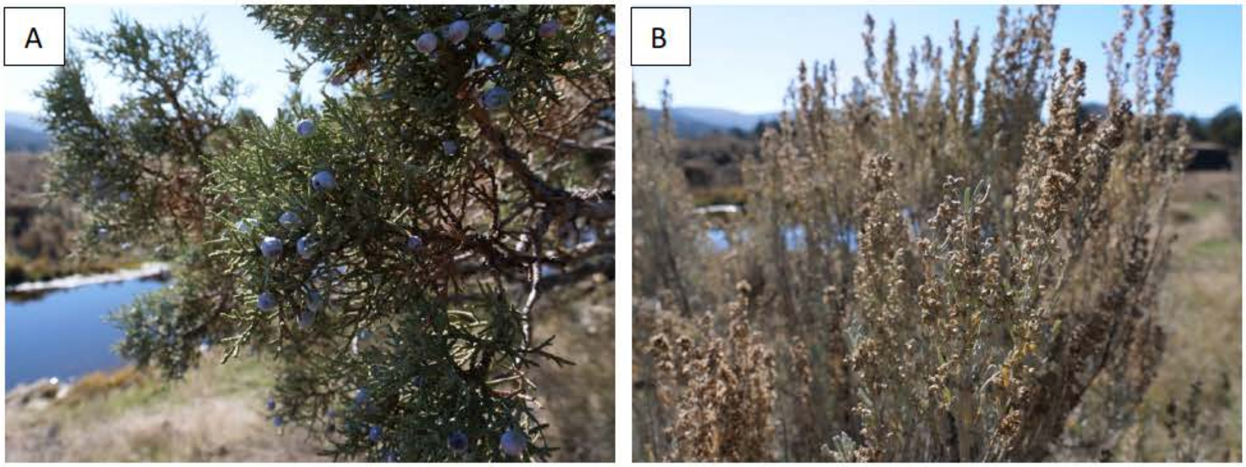

Figure 3. Riparian vegetation A) Western Juniper (*Juniperus occidentalis*) and B) Sagebrush steppe. Photo by Allison Law.

Figure 4. South Fork tributary of the Crooked River near Paulina, Oregon. Photo by Allison Law.

SITE SELECTION

I chose sampling locations based on Orr et al. (2020) where pre-existing BDA restoration projects have occurred. This area of approximately 4,856,228 sq. meters in central Oregon (Figure 4) was purchased by a private landowner in 2003 with the intent of removing grazing and prioritizing conservation. Five BDAs were installed by Orr et al. (2020) and monitored during a one – to two-year period for sediment transportation, streambed aggradation, BDA structural integrity, water temperatures, and the response of restoration plantings in areas lacking woody vegetation.

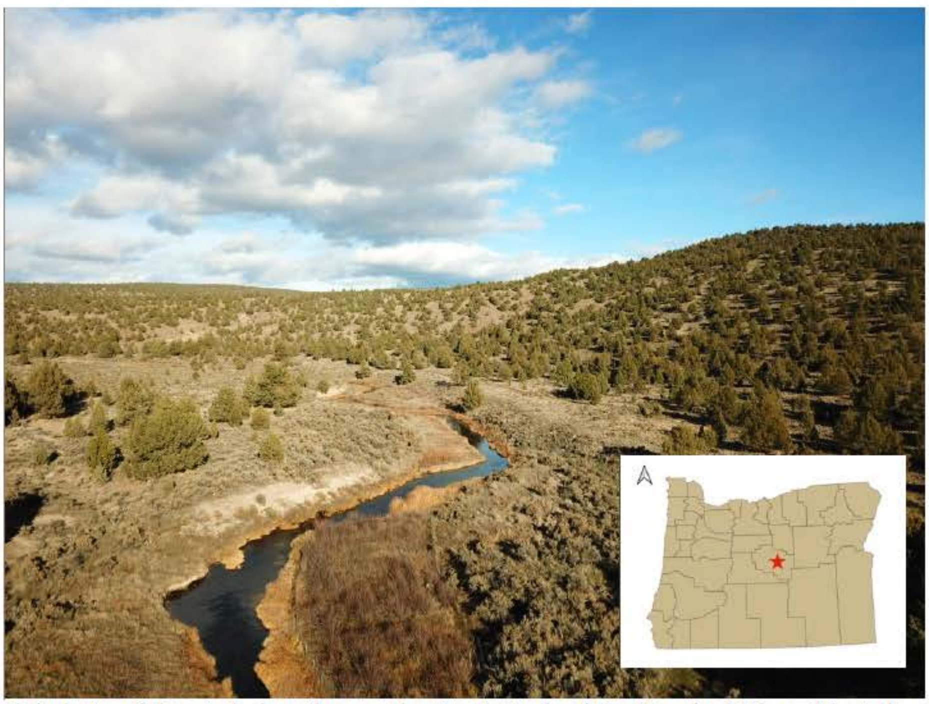

Figure 5. Aerial photo of the study location on the South Fork of the Crooked River. Photo by Allison Law.

Due to the remote geography and under-development of this landscape, remote sensing via aerial imagery using historical archival imagery has logistical advantages for monitoring riparian vegetation productivity versus field observations. I downloaded National Agricultural Imagery Dataset (NAIP) imagery from the United States Geological Survey (USGS) website for the study area for the month of June to capture active vegetation green-up for the years 2014, 2016, 2020, and 2022. Recent NAIP collections have a spatial resolution of 60 cm. Images were transformed (Figure 6) in MultiSpec© (Universal 64-bit version; Purdue Research Foundation, 2020) using band 1 and band 4 (Table 1) to calculate NDVI (Equation 1) (Perry and Lautenschlager, 1984) where red and near infrared (NIR) are spectral radiance measurements recorded by a sensor in the visible (red) and near infrared (non-visible) regions:

$$\mathbf{NDVI} = \boldsymbol{NIR - \ Red \,/\, NIR + Red} \qquad \textbf{(1)}$$

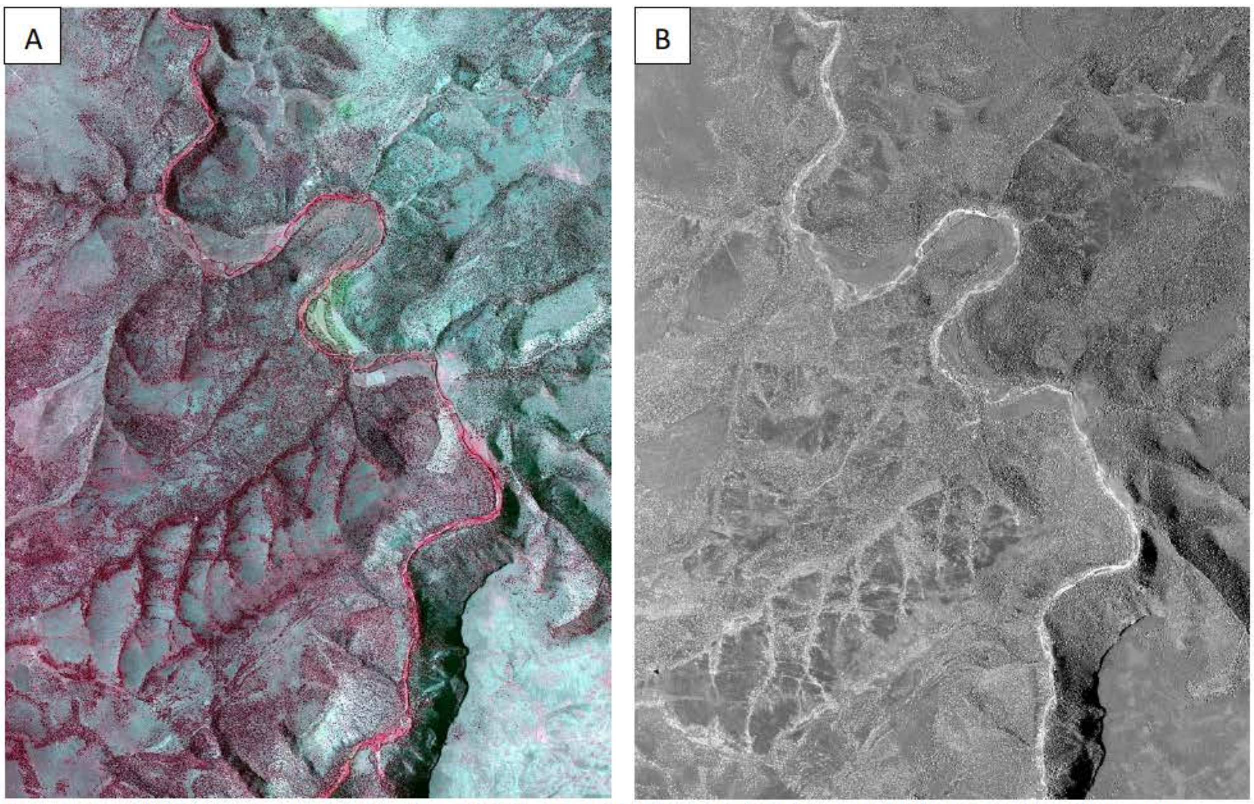

Figure 6. NAIP imagery processing from 2014 using MultiSpec A) 3-Channel Color (4, 3, 2) with healthy vegetation reflected by bright red hues B) Single band NDVI transformation.

Table 1. Band numbers and names for NAIP. Source: National Agricultural Imagery Program.

Band Number	**Band Name**
1	Red
2	Green
3	Blue
4	NIR

After NDVI was calculated, I rendered images in QGIS© Geographic Information System (Version 3.23.3 – Lima) overlaid with vector polygon layers for each BDA and control site per year. BDA polygons were designated upstream of each complex based on qualitative observations of active photosynthesis (Figure 7) using Google Earth Pro© (Version 7. 3. 6. 9345 64-bit, 2022). I hypothesized there would be an increase in availability of groundwater to support the growth of upstream adjacent riparian vegetation. Control polygons were designated in locations interspersed between BDA sites (Figure 8).

RESULTS

SITE EVALUATIONS

Control vs BDA 1

For the control and BDA 1, NDVI means were plotted for 2014, 2016, 2020, and 2022 (Figure 9). Installed in 2016, BDA 1 endured high flows, and required minor repairs from 2016 through summer of 2021. There was an increase in NDVI means for BDA 1 after the initial construction inn 2016. Between years 2016 to 2020, there was a decrease in mean NDVI of 51% with a subsequent increase of 20% between 2020 to 2022 (Figure 9). Beaver dam analog 1 NDVI means are higher compared with the control average between years 2014 to approximately 2018. Control means increased compared to BDA 1 by 21% in 2020 and 4% in 2022. Higher stream flows were recorded in 2019, which necessitated repairs due to structural damage, scouring, and removal of sediment resulting in altered stream flows and reduced functionality of BDA 1.

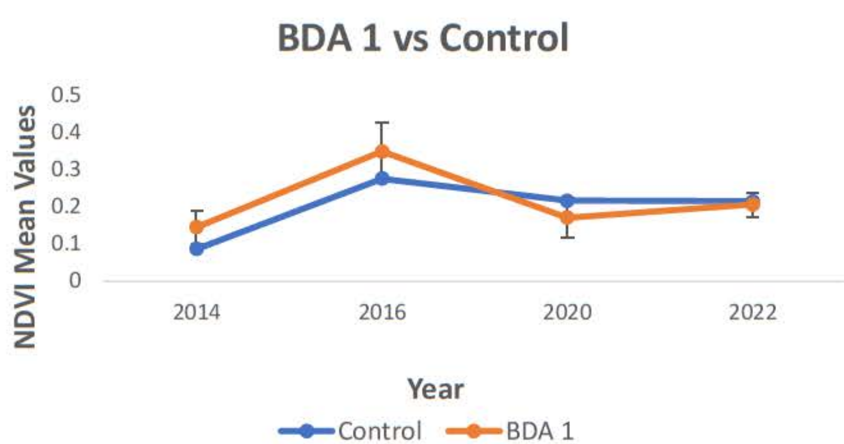

Figure 9. Comparison of NDVI means of BDA 1 with standard deviation and the control average.

Control vs BDA 2

Installed in 2016, BDA 2 washed out in 2017 due to high flows. In July of 2017, BDA 2 was rebuilt approximately 20 m downstream of its original location and required minimal maintenance from 2017 through 2021. There was an increase in both BDA 2 and control means between 2014 to 2016 (Figure 10). In succeeding years, a gradual decrease of 26% was observed in 2020 and 28% in 2022. Control means were higher compared with BDA 2 means during consecutive years after installation.

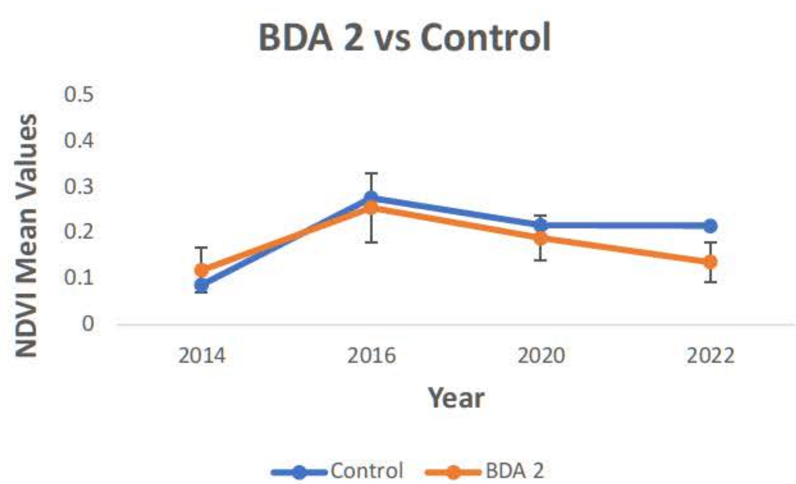

Figure 10. Comparison of NDVI means of BDA 2 with standard deviation and the control average.

Control vs BDA 3

Beaver dam analog 3 was installed in August 2016. Maintenance required was minimal from 2016 until 2019 when seven posts were replaced, and stream-adjacent willows were planted. No additional maintenance was performed from 2019 to 2022. The control NDVI means were consistently higher throughout subsequent years (Figure 11). The greatest percent difference between BDA and control NDVI means occurred during the initial year of installation. Results from BDA 3 means showed a large increase in NDVI in 2016 after installation and remained consistent during subsequent years.

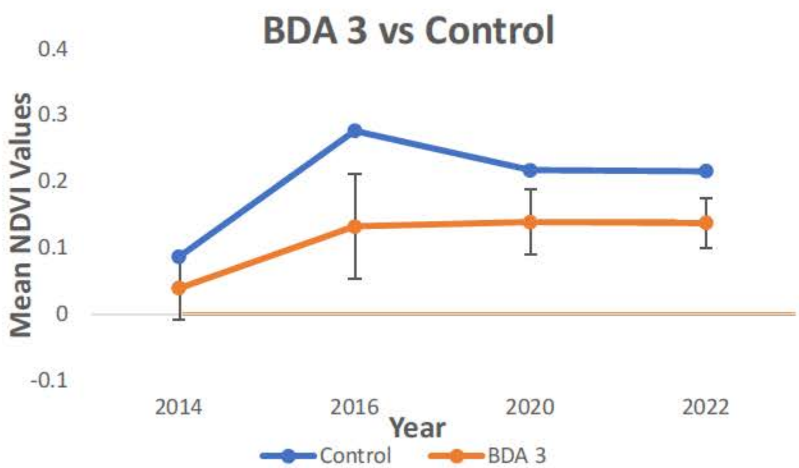

Figure 11. Comparison of NDVI means of BDA 3 with standard deviation and the control average.

Control vs BDA 4

Beaver dam analog 4 was installed one year later in spring of 2017. Additional maintenance was required by September 2017 due to high summer flows. Supplementary maintenance was minimal until summer of 2020 when beavers assumed management responsibilities using adjacent riparian vegetation to rebuild. Overall, control means were higher compared with NDVI means for BDA 4 for each year with the largest percent difference of 53% occurring during the summer of 2020 (Figure 12). Between 2020 and 2022, there was a marked increase in BDA means compared to the control, which declined by 5%.

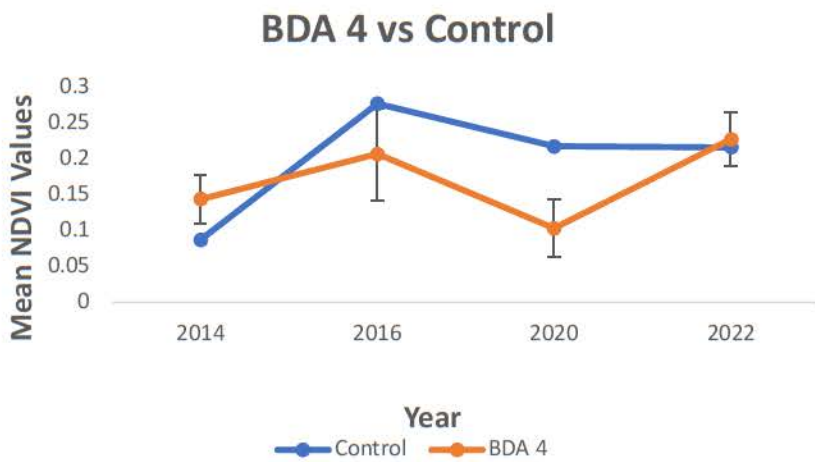

Figure 12. Comparison of NDVI means of BDA 4 with standard deviation and the control average.

Control vs BDA 5

After installation of BDA 5 in 2016, a blowout occurred in spring of 2017 due to high flows. In July 2017, BDA 5 was rebuilt 5 m upstream of the original site. Replacement of structural vegetation was required by August of 2017 due to undercutting from flows. Marginal maintenance occurred in 2018 with later replacement of vegetation completed in 2019. In July of 2020, extensive maintenance was required due to structural failure on the right side of the BDA. BDA 5 was holding water without intervention and did not require further maintenance after 2020.

Control NDVI means were higher compared to BDA means from 2014 through 2022. Both control and BDA means were higher during the initial year of BDA 5 construction (Figure 13). However, means were 70% higher for the control compared to BDA 5. While control values tapered off by 2022, BDA values showed a consistent increase from 2016 through 2022.

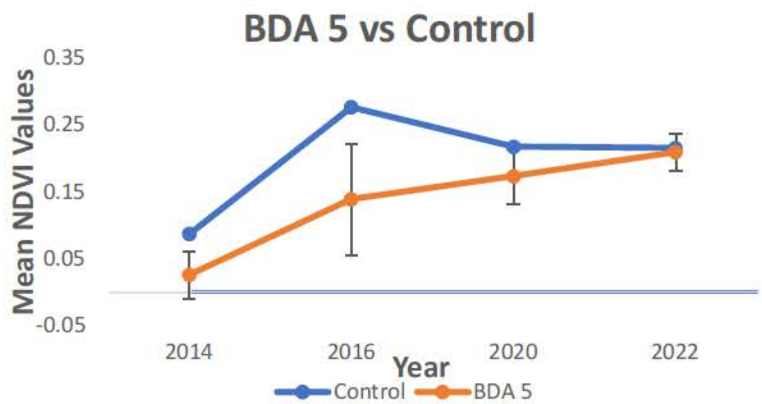

Figure 13. Comparison of NDVI means of BDA 5 with standard deviation and the control average.

DISCUSSION

Streams across the American West have historically faced degradation in areas where beaver had been extirpated. Throughout the early 20th century, awareness grew among land managers concerning the vast range of ecosystem services offered by the presence of beavers. Thus, restoration efforts began focusing on beaver-related stream projects. This involved both the reintroduction of beaver and the development of process-based beaver dam analogs to mimic natural processes.

Beaver dam analogs offer a cost-effective approach to restoration yielding ecosystem services comparable to natural beaver dams. However, to date, there have been limited studies elucidating whether BDAs successfully increase riparian vegetation productivity upstream of BDA development as a result of impounded water made available to adjacent vegetation. The aim of this study was to assess whether quantitative and qualitative differences were present in stream-adjacent riparian vegetation pre- and post- beaver mimicry development using time series aerial imagery and NDVI.

My results indicated an initial increase in NDVI means observed in adjacent riparian vegetation upstream of each BDA complex after original construction compared to NDVI means pre-BDA construction in 2014. During subsequent years, however, I observed variations in NDVI means within each individual BDA complex and across sites.

Decreasing trends were observed in NDVI means for BDAs 1 and 4 from 2017 - 2020 and increases between 2020 – 2022. An increase in NDVI means was observed in BDA 2 after construction in 2016 yet showed incremental declines each succeeding year from 2016-2022. Conversely, BDA 3 showed a steady increase in means after initial construction in 2016 through 2021 and a slight reduction in NDVI means in 2022. Results from BDA 5 demonstrated a consistent increase in NDVI means from 2016 through 2022. After construction, each BDA endured structural malfunctions and scour at varying times throughout the assessment period resulting in three out of five BDAs requiring reconstruction. Of note, BDAs 2, 4, and 5 washed out entirely in 2017 due to high flows and structural failure. During summer of 2017, BDAs 2 and 5 were rebuilt after flooding; BDA 4 was rebuilt below BDA 3 rather than at its original site.

Structural failure of BDAs reduces the utility of impounding water available to adjacent vegetation upstream where NDVI was measured. Maintenance of BDA 4 was assumed by beavers through herbivory of nearby riparian vegetation used for dam structural resources, which may have impacted vegetation productivity and hence NDVI values.

In addition to BDA structural failure, another contributing factor accounting for variations in NDVI values is precipitation. Fesenmyer et al. (2018) distinguished a link between vegetation productivity, growth, and annual precipitation impacting soil water moisture content and groundwater elevations. For this study area, the greatest amount of precipitation for April, May, and June occurred in 2022, 2020, and 2022, respectively (Figure 14). Also notable, the winter after BDAs 1, 2, 3, and 5 were constructed, the primary segment of the Crooked River experienced its second to highest flows since 2000 (ORWD 2019).

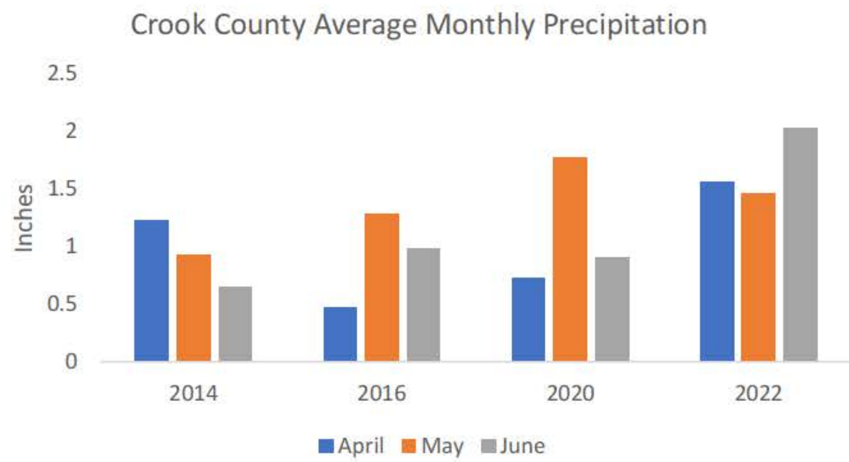

Figure 14. Average annual precipitation during vegetation green up months of April – June for the study area from years 2014 – 2022.

Shortcomings also exist with using NDVI, which may impact my study results. These include atmospheric effects as a result of Rayleigh scattering resulting in higher radiance in the red region compared to the near infrared region (Huang et al., 2020). Unfavorable atmospheric conditions can also hinder the signal with noise arising from clouds, ozone, aerosols, and off-nadir viewing with low sun angles can decrease infrared reflectance (Hird and McDermid, 2009).

Another limitation associated with NDVI includes saturation and an insensitivity to environmental and biomass conditions. For measuring finer scale nuances in phenological variability, Berra et al. (2019) found NDVI datasets from UAVs more effective compared to data captured by satellite imagery.

Overall, results from my study using these methods did not elucidate consistent trends of higher NDVI means in areas upstream of BDA complexes compared to control areas. I did, however, observe qualitative changes with greater vegetation vigor in riparian adjacent areas upstream post- BDA construction. Factors contributing to variable trends within individual BDA complexes and across multiple complexes include, but are not limited to, seasonal precipitation variability, BDA structural integrity, discrepancies in NDVI values, and sensor type.

RECOMMENDATIONS

In future studies, I recommend long-term monitoring of a larger sample of BDA structures using small unoccupied aerial vehicles (UAVs) with high resolution multispectral imagery to assess fine scale variations in vegetation productivity. Using a variety of UAV sensors is advantageous by minimizing radiometric errors and, therefore, improving the reliability of reflectance data. It is important to note that despite the advantages of higher resolution imagery offered by UAV sensors, the quality of the data varies greatly. I advise systematic calibrations to improve multispectral imagery to reduce the risk of geometric and radiometric errors associated with high spatial resolution imagery from UAV multispectral sensors.

To date, there is limited availability of time series historical UAV data compared to coarse resolution satellite data products. Furthermore, Norman et al. (2014) recommends in-situ assessments, for both vegetation abundance and groundwater levels, to supplement analyses using remote sensing technologies.

Orr et al. (2020) recommend evaluating the effects of BDA construction on stream incision and vegetation productivity across a variety of stream gradients and watersheds. The area of interest for this study was based on a stream where BDAs were situated between a steep slope on one side and a floodplain on the other. Ideally, this terrain should alleviate stress on BDA structures during high flows by funneling over the main channel and, therefore, reducing the risk for structural scouring, as recommended in Pollock et al. (2011).

The spectral responses of vegetated areas vary depending on soil moisture and brightness, vegetation type, shadows, and other environmental effects. Therefore, using additional vegetation indices that are tailored to specific applications and platforms, such as the Enhanced Vegetation Index (EVI) is optimal for its utility in correcting for distorted light reflections such as Rayleigh scattering (Askam et al., 2022).

To bolster statistical analyses and corroborate findings using remote sensing products, I recommend selecting spatial covariates to predict riparian vegetation productivity such as the continuous measurement of total water year precipitation, elevation, stream size, stream slope, and grazing. Finally, long-term monitoring is a critical aspect of successful stream restoration projects to account for environmental fluctuations associated with natural, dynamic processes.

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