Developing and Implementing a UAS-Based Reach-Scale Protocol to Understand and Test Indicators for Monitoring Beaver Dam Analog Effectiveness

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by Charles W. Jones III

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Authorization to Submit Thesis

This thesis of Charles W. Jones III, submitted for the degree of Master of Science with a Major in Natural Resources and titled "**Developing and Implementing a UAS-Based Reach-Scale Protocol to Understand and Test Indicators for Monitoring Beaver Dam Analog Effectiveness**," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Beaver Dam Analogs (BDAs) and other Beaver-Related Restoration (BRR) techniques have increased in use across the western US in response to losses in ecosystem function related to degraded stream systems, head-cuts, entrenched channels, and floodplain and riparian disconnectedness. In hopes of restoring riverscapes and riparian areas and the ecosystem services they provide, managers have implemented these techniques with limited research concerning their effectiveness. Monitoring the effectiveness and the long-term ecological impacts of restoration activities such as BDAs is required to inform managers if objectives have been met and to guide maintenance to ensure effective restoration. I developed and implemented a quantitative monitoring approach that focuses on indicators representing key riparian and stream processes related to reach-scale riverscape changes including: channel length, flow, gradient, BDA structure density, and proportions of riparian vegetation groups, surface water types, and potential riparian/stream area within the valley bottom. Spanning three different ecosystems, I used unmanned aerial systems (UAS) along with in-field measurements to implement the procedure across 31 stream reaches from six BDA projects in Idaho. Univariate and multivariate analyses highlighted possible short-term indicators of treatment effectiveness and the need for more research regarding broader, longer-term impacts. This work supports common short-term expectations such as an increase in percent channel length that is wetted following BDA installation. With a quantitative monitoring approach, effects of riparian and stream restoration can be documented, providing detailed descriptions of the effectiveness of these treatments on different systems and specific functions that managers hope to restore.

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Introduction

Riparian areas account for roughly 1% of land cover by area in the western United States but play an outsized role in the healthy functioning of these landscapes due to the ecosystem services they provide (Chaney et al., 1990). Riparian areas are valued for their ability to provide high quality forage, wildfire breaks, water purification, recreation opportunities, and distinct areas where water resources are available (National Academies, 2002, Silverman et al., 2019). Depending on the functions and services provided by a riparian area, values and uses by humans differ. Across the western United States, riparian systems are primarily used for grazing, human development, recreation, and agriculture (National Academies, 2002). Within Idaho, the variability in system type throughout the state enables riparian areas to vary in their function, condition, and ability to produce services.

Riparian areas also provide vital functions to the watersheds in which they are located. Site specific conditions, seasonal variability, and state of the riparian zone correlate to the quantity and quality of ecosystem functions and services being provided (Boudell et al., 2015). Riparian zones naturally capture sediment (Brooks et al., 2013), uptake pollutants, and cycle nutrients (Dosskey et al. 2010). Wetlands and riparian areas also act like a sponge where they slow runoff, allow sediment in the water column to deposit, and uptake nutrients (National Academies, 2002). These semi-terrestrial and freshwater systems require water at different times of the year to remain ecologically intact and continually provide exchanges of energy, matter, and resources between the terrestrial and aquatic systems (Sabo et al., 2005).

Riparian areas and their vegetation have a dynamic interaction with hydrology, especially local flood events (Gurnell et al. 2016). Riparian plants can be found in areas experiencing both inundated and non-inundated periods annually. Seasonal overbank flow is significant to riparian areas in dispersing flows of water and nutrients laterally across the floodplain (Westbrook et al. 2006). Riparian areas also benefit from disturbances like flooding and natural wildfires through increased structural complexity and niche formation, leading to a broader range and quantity of ecosystem services and goods being provided (Wheaton et al., 2019). Similar to lateral flow, riparian zones have an influence on the greater watershed and the longitudinal flow of energy, resources, and ecosystem services moving up and down the watershed (Burchsted et al., 2010). Services, such as water purification, nutrient cycling, and flood control provided by riparian areas not only affect the site, but extend across the landscape (Ward, 1998).

Studies have shown, however, that riparian areas are degrading from generations of unsustainable land use across entire watersheds (Kauffman et al., 2011). Due to years of overuse and disturbance, natural resource productivity across western US watersheds has become limited (Wheaton et al., 2019). Grazing and mineral removal operations are among the practices that, when operated unsustainably, have resulted in the current degraded condition, such as incised streams, mining scars, low proportions of unstable riparian area in valley bottoms, and altered vegetation composition (Buys et al. 2018). Rivers, floodplains and associated riparian vegetation need spatial and temporal variability similar to natural flow regimes to maintain ecological integrity.

Role and Benefits of Beavers:

Beavers and the dams they create can contribute to functioning riparian areas by amplifying the quantity and quality of ecosystem services produced (Burchstead et al., 2010). Classified as an ecosystem engineer, beavers have significant impacts on the landscape where they dramatically modify, enhance, and maintain riparian and stream function (Orr et al., 2020). As a keystone species, beavers have a disproportionately larger impact on the environment relative to their density and individual biomass (Collen & Gibson, 2000). The benefits of beavers are well supported for areas where they are native, but their individual value depends on how they directly and indirectly impact humans.

Beavers and their dams can change stream flow, alter wetland extent throughout the valley bottom, and affect vegetation succession (Pollock et al., 2017). The presence of beaver is important because they impact sediment layers and sorting as they dig in the channel, while also providing constant maintenance to dams ensuring their longevity and the services the structures provide (Pollock et al., 2017). Beavers can transform the environment above their dams from lotic to lentic. Water exchange with the hyporheic zone can be increased resulting in deeper waters and longer flood periods (Andersen & Shafroth, 2009). Dams provide shelter for beavers, but also indirectly increase the riparian area and diversify forage options for riparian obligates due to lateral flow and increased flooding (Orr et al., 2020). Thus, vegetation composition and structure shifts as a result (Pollock et al., 2017).

As the biophysical structure of the channel and floodplain is changed, the result is an increase in floodplain and channel roughness and the ability to slow flows (Pollock et al., 2014). As water slows and the duration of time that water is moving through the area increases, sediments are deposited, and more nutrients and water can infiltrate through the hyporheic and riparian zones (Pollock et al., 2017). This can affect aquifer recharge, primary productivity, and downstream water quality. With beavers present, riparian and stream systems result in highly complex and productive areas maximizing the utilization of the valley bottom (Buys et al., 2018).

In the past, beaver extirpation and translocation out of stream areas have contributed to the declining health and quality of both stream and riparian systems (Wheaton et al., 2019). As beavers are removed, their dams degrade. Dams can collapse causing erosion and loss of resources downstream (Andersen & Shafroth, 2009). Humans can be impacted by these flash floods through property loss, resource loss, and loss of life (Butler & Malanson, 2005). Without water retention from dams, riparian areas can shrink in size and in some areas disappear altogether as the water table drops (Pilliod et al., 2018). As beavers are removed from riparian areas, vegetation productivity and riparian obligate habitat quality decline, and overall function and stability of riparian areas are limited (Orr et al., 2020). Such areas can experience rapid incision and trench widening processes furthering the system's state from a self-maintaining, dynamic equilibrium state (Cluer & Thorne, 2014).

Riparian and Stream Restoration:

Riparian and stream restoration activities have increased as land managers have recognized the importance of these systems and their declining state and functioning conditions. Some attempts at riparian and stream restoration have consisted of aggressive geomorphic changes, such as channel reconfigurations, to return the site to a functioning condition as quickly as possible, usually involving heavy machinery and high overall project costs (Pilliod et al., 2018). Considering the pros and cons of each restoration technique and the costs of a potential failure, land managers are beginning to consider how natural processes can aid in achieving desired outcomes. Recently, riparian and stream restoration has shifted to low-cost, low-risk procedures utilizing natural processes to aid in the recovery of the system (Boudell et al., 2015, Wheaton et al., 2019).

Beaver-related restoration (BRR) is a group of restoration techniques that aim to improve riparian and stream conditions, attempting to mimic the functions beavers naturally provide and, in some cases, encourage establishment or persistence of beaver activity (Pilliod et al., 2018). With shifting attitudes concerning beavers' impacts on watersheds, BRR has become popular in the western US, especially in arid and semi-arid systems classified as lacking proper functioning conditions (Pilliod et al., 2018). Most BRR projects are low tech and minimize costs by using natural processes to help in the restoration process, specifically the use of beaver for maintenance (Pilliod et al., 2018). A common phrase by some practitioners is to "let the rodents do the work" (Wheaton et al., 2019). Common types of BRR include beaver translocation, vegetation manipulation, and the installation of beaver dam analogs (BDAs) or other types of instream debris structures (Pilliod et al., 2018).

Beaver Dam Analogs:

A BDA is a permeable structure made to mimic natural beaver dams (Wheaton et al., 2019). BDAs are temporary structures that use a combination of locally available woody material, sediment, and fill material (Wheaton et al., 2019). The materials of a BDA consist of those similarly used by beaver to make dams including willow branches, herbaceous vegetation, rocks, mud, and wood posts. Similar restoration techniques that act like BDAs include: Post-Assisted Log Structures (PALS), log steps, Zeedyk structures, gravel dams, meander dams, constriction dams, choke dams, and wood jams (Wheaton et al., 2019). Each technique has their own specific objective and site characteristics where they benefit most. Zeedyk structures, specifically, are rock structures made to stop head cuts and disperse water across the floodplain (Maestas et al., 2018).

Individual BDA structures are typically combined into a complex, and one or more complexes may be arranged in a stream system to meet specific project goals (Figure 1). A complex can span tens to hundreds of meters of a stream segment or reach. The type and design of a BDA, complex, and project depends on many factors. Ultimately, the design of a BDA project should be based on clearly articulated goals resulting from a thorough assessment of site characteristics, stream potential, and management objectives. Project goals provide the guiding vision for finer scale design decisions (e.g., complex and structure designs) (Wheaton et al., 2019). Being a process-based restoration technique, the use of low-tech structures relies on hydrological and ecological processes to aid the site rather than building or creating specific geomorphic landforms (Beechie et al., 2010). BDA project design and development includes predicting impacts from changes made by a structure, complex, and the entire project (Wheaton et al., 2019). Some projects refer to a succession model expressing the rapid incision, trench widening, slow aggradation, and dynamic equilibrium stages of stream channel evolution to help projects justify placement, type, expected changes, and project objectives and goals (Pollock et al., 2014). The succession model is recommended to be used as a broad guide rather than an identification and true justification tool for identifying specific BDA locations and objectives (Pollock et al., 2014).

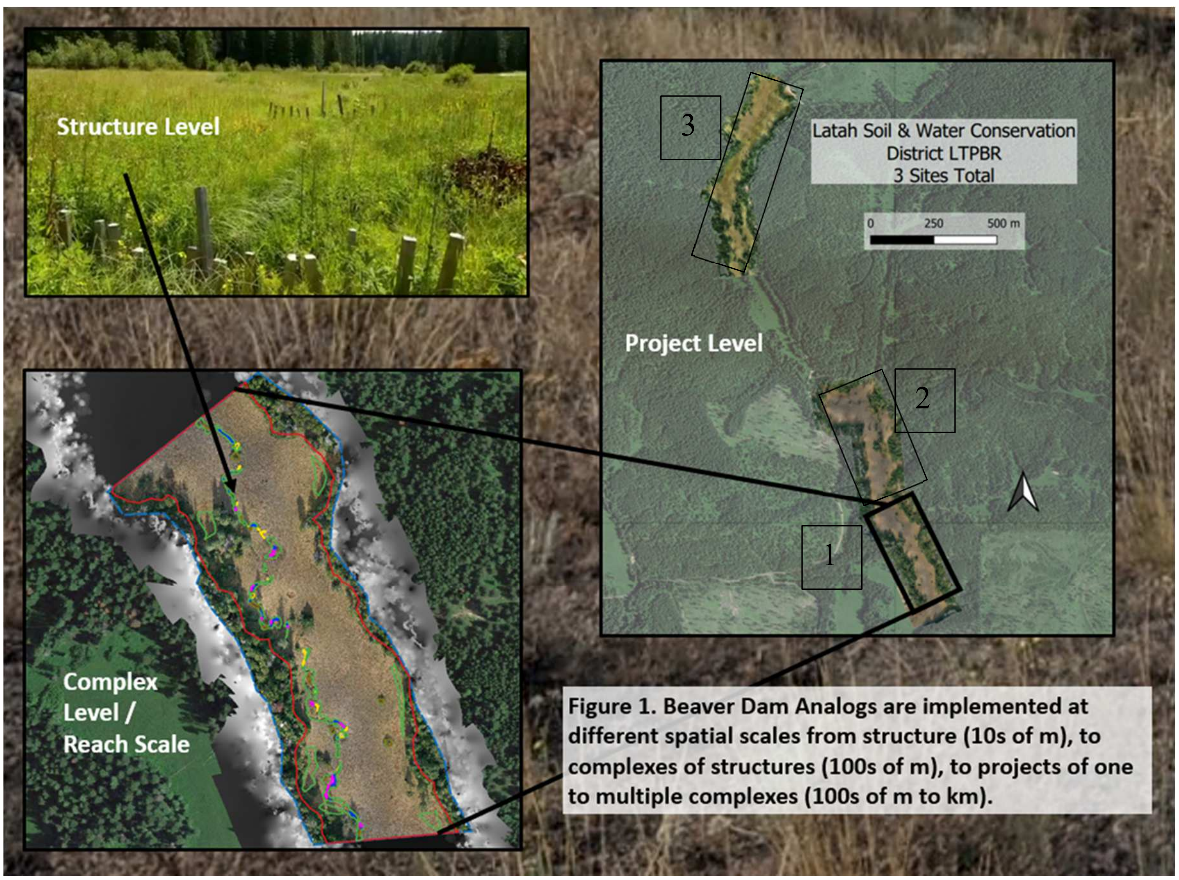

Figure 1. Beaver Dam Analogs are implemented at different spatial scales from the structure, complex, to project scales.

Common BDA Goals:

At the project scale, at least one or more of the following five goals are commonly listed: 1) change hydrologic dynamics, 2) shift sediment dynamics, 3) increase riparian area function, 4) increase habitat provisions for a species of concern, and/or 5) promote beaver colonization (Pilliod et al., 2018). The decision to use BDAs coincides with a shift towards valuing the presence of beaver or beaver related ecosystem services in a watershed. Common broader project goals include increasing: system resilience, species abundance, species diversity, riparian expansion, temporary water storage, and flood attenuation. Some project goals are the complex goals when the project consists of only one complex (Figure 2). Common complex goals include increasing lateral and vertical connectivity, incision recovery within a specific reach, habitat complexity, and increasing beaver presence and number of natural dams. Individual structure goals include: diversifying hydraulics, structurally-forcing geomorphic processes, and forcing overbank flow (Wheaton et al., 2019). Managers are using BDAs for a variety of reasons depending on the scales to which goals correspond and the broader restoration goals themselves, such as increasing flood control, increasing water resources, increasing cattle forage, reversing riparian and stream degradation, promoting late season flow, and increasing the habitat for greater sage-grouse (*Centrocercus urophasianus*), aquatic species, and other riparian species (Pilliod et al., 2018).

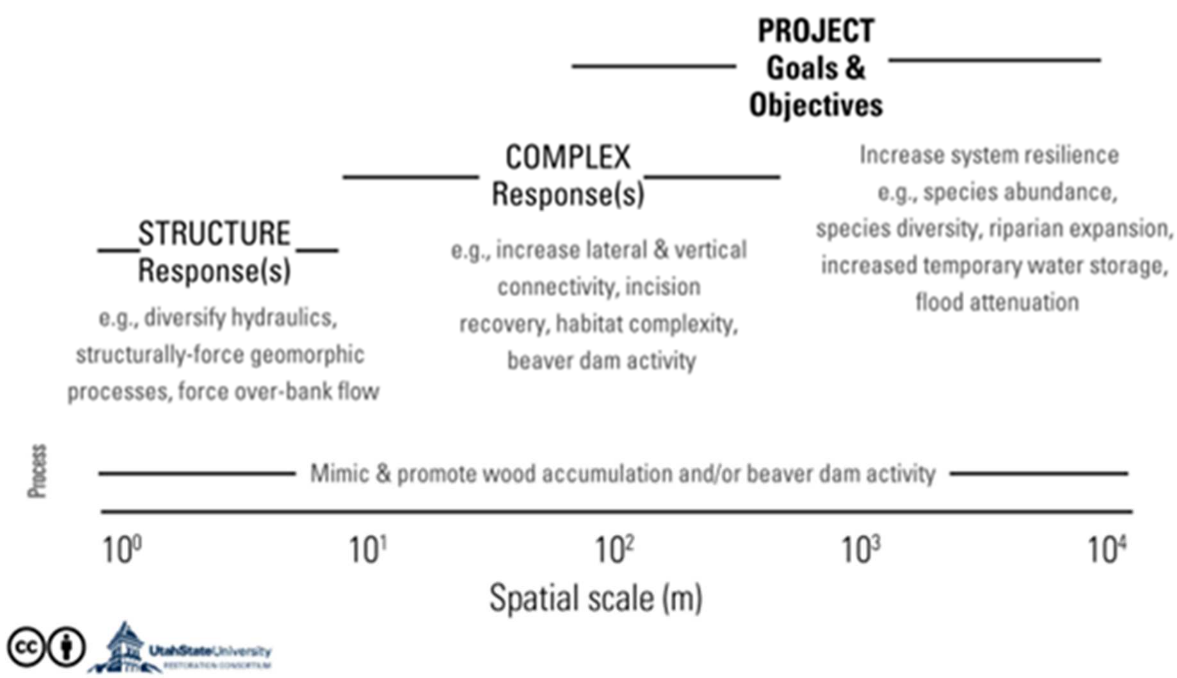

Figure 2. BDA projects objectives are typically structured into three levels: Project, Complex, and Structure. Figure from Wheaton et al., (2019).

Reach Scale BDA Expected Effects & Impacts:

BDAs have expected direct and indirect effects on riparian areas and stream systems based on knowledge about how natural beaver dams impact ecosystems. However, being a relatively new technique, there is little data supporting or refuting expected changes of BDAs across ecosystems and timeframes (Pilliod et al., 2018).

Complex scale (e.g. reach-scale) direct effects are linked largely to hydrogeomorphic processes and changes to the hydrologic and sediment regimes impacted at the structure level (Gurnell et al., 2016). As BDA structures are installed, flow velocity through the reach is expected to decrease due to an increase in overall roughness within the channel (Pollock et al., 2014). This increases sedimentation, while flow is forced laterally along the channel cross-section (Pollock et al., 2014). BDAs are also expected to influence many different parts of the sediment regime, from geomorphic complexity, laterally and longitudinally throughout the valley bottom, to bed grain size and material composition and distribution (Pollock et al., 2014).

Lateral movement of water across the valley bottom is expected to result in an increase in area of inundation throughout the floodplain (Schweiger et al., 2016). As water depth increases, there is more exchange with the hyporheic zones (Hafen, 2017), with the largest impact being the exchange rate of water with the hyporheic and deep groundwater zones. By directly increasing the duration of time water sits in the reach, it may promote more opportunities for infiltration and/or exchange of water with the deep groundwater reservoirs (Chen & Chen, 2003).

Indirect effects of BDAs correspond largely to expected impacts on riparian area and stream function, and output of ecosystem goods and services at the complex and project scale. As water moves laterally and has more time to move in and out of the floodplain, riparian vegetation is expected to experience greater late season growth, water resource availability, and overall extent across the valley bottom, if maximum potential is not already met (Nash, 2018). Lateral water movement is also expected to impact the planform and increase sinuosity (Bierman & Montgomery, 2013). Slower water velocity decreases the erosive power of the stream on the streambanks (Pollock et al., 2014). Increased flooding across the floodplain is also expected to result in a structurally diverse and productive riparian zone (Pollock et al., 2014).

Higher productivity levels and increased overall extent of riparian areas within a valley bottom would increase the ability of a reach to uptake pollutants and cycle nutrients (Dosskey et al., 2010). As a riparian buffer grows and geomorphology changes, the system could experience improved conditions for aquatic life in the form of reducing stream temperatures and increasing geomorphic complexity within the channel, which can benefit various species of trout and other fish (Bouwes et al., 2016). Increased structural diversity and extent of riparian areas may also increase habitat for riparian obligate species (Buys et al., 2018). These indirect effects are expected to favor native species and result in a dynamic equilibrium riparian-stream state (Schweiger et al., 2016). Indirectly, BDAs may also increase resiliency and resistance to disturbances and improve ecological integrity of the areas to maintain function (Schweiger et al., 2016).

Evaluating and Monitoring BDA Effectiveness:

In the context of evaluating BDAs, effectiveness is a cumulative measure of a structure's or group of structures': 1) ability to achieve specific, stated objectives, and 2) impact on a site's ecological integrity and resiliency. Ecological integrity is the ability of a system to sustain ecological processes needed to maintain a system's function, while resilience is the capability of a system to recover functions after disturbance (Wheaton et al., 2019). The ultimate impact of BDAs is constrained by land potential, which is the maximum possible extent to which the restoration effort can impact the system due to abiotic and biotic constraints (Richardson et al., 2007). Similar to the factors that shape the design of BDA projects, the influential factors determining riparian area potential include the geomorphic, hydrologic, and ecological dynamics present at the site considering human maintenance. Also, climate and future changes in climate patterns like precipitation have an external influence on BDA impacts (Brooks et al., 2013). Aside from this, long term success of any wetland project is ultimately dependent on headwater conditions and sustainable management of the entire watershed.

Monitoring is a critical step in adaptive management (Walters & Holling, 1990), and monitoring the effectiveness of BDAs is recommended in most project descriptions and design manuals. Current BDA monitoring protocols involve qualitative assessments of the success of single structures and complexes in meeting stated project objectives (e.g., Wheaton et al., 2019) or field surveys detailing dam attributes, direct hydraulic response to dams, and mapping of geomorphic units (e.g., Weber et al., 2020). At the project level, assessments include delineating valley bottom characteristics using satellite or unmanned aerial systems (UAS) imagery, including channel lengths, and areas associated to the channel, floodplain, and riparian vegetation (e.g., Weber et al., 2020).

Other, more general riparian and lotic monitoring protocols may also be useful for assessing BDA impacts. The proper functioning condition assessment (PFC) for lotic areas (Dickard et al., 2015) is a standardized approach for representing hydrologic, vegetative, and geomorphic attributes and processes to assess the condition of riparian areas at a specific point in time. The Multiple Indicator Monitoring (MIM) of stream channels and streamside vegetation by Burton et al. (2011) is used by state and federal agencies throughout the US and is intended to focus monitoring efforts on the impacts of land uses such as livestock grazing on riparian systems. The BLM's Lotic Assessment, Inventory, and Monitoring (AIM) strategy standardizes aquatic core indicators, field sampling methodologies, electronic data capture, and sampling designs for wadeable streams and rivers (Bureau of Land Management, 2017).

Remote sensing technologies including satellite imagery and UAS have become more popular for managers to use in monitoring ecosystem changes across the landscape. These tools are effective at accurately and efficiently monitoring certain characteristics of the landscape. However, understanding the scale at which indicators can be represented is key to effectively using these technologies in monitoring changes in natural resources.

UASs are an attractive technology for monitoring BDA effectiveness because of their ability to easily collect very-high resolution imagery at multiple points in time. Using structure-from-motion photogrammetry, sets of overlapping aerial images can be processed into orthomosaics, digital elevation models, and 3-dimensional (3D) point clouds (Westoby et al., 2012). Previous studies have demonstrated the effectiveness of very-high-resolution image products in estimating vegetation indicators such as cover and composition (Booth et al., 2006; Cagney et al., 2011; Duniway et al., 2011; Karl et al., 2014), bare ground (Karl et al., 2012; Gillan et al., 2020), density (Booth & Cox, 2008), and vegetation height and structure (Cunliffe et al., 2016; Karl et al., 2020). UAS-collected imagery has also been used to monitor changes in site topography (Genchi et al., 2015; Gillan et al., 2016; Gillan et al., 2017; d'Oleire-Oltmanns et al., 2012) and changes to streams as a result of beaver activity (Puttock et al., 2015). Collecting monitoring data via UAS can also be faster and more cost-effective than field measurements of similar indicators (Laliberte et al., 2010; Karl et al., 2020).

Objectives:

With the lack of data demonstrating their effectiveness in different situations and across landscapes, BDA projects do not have a consistent framework for understanding broader ecosystem impacts and influencing factors that may impact their effectiveness across different scales and ecosystems (Pilliod et al., 2018). There is a need for techniques to quantify effects and changes BDAs have on riparian areas after installation. This project attempts to understand the broader impacts of using BDAs and propose and test a protocol to quantify reach-scale indicators of importance that correlate with key drivers of BDA complex scale expected changes to riparian and stream systems. Specifically, I propose a protocol to quantify key indicators of stream and riparian change and test that protocol at various riparian sites across Idaho. This work will begin to bridge the gap between the planning and monitoring of BDAs at structure, complex, and project levels within the community of BDA researchers and practitioners. My specific objectives were to:

1. Develop a reach-scale (i.e., roughly 300 m in stream length) BDA effectiveness monitoring protocol to better understand impacts of BDA installation and to begin quantifying effectiveness.
    a. The proposed protocol will measure indicators related to stream and riparian ecosystem processes at the reach scale.
    b. Indicators will be measured and calculated from UAS-collected imagery processed using structure-from-motion photogrammetry and field-based data.
2. Implement the protocol on a set of BDA complexes of various ages or streams to have BDAs installed in various ecosystems of Idaho to determine suitability of methods at detecting change, analyze indicators considering system specific characteristics, and begin quantifying reach-scale impacts of current BDA complexes.

Developing UAS-based BDA Monitoring Protocol

The protocol described here focuses mainly on monitoring the reach-scale impacts of BDAs and related BRR techniques and the success of restoration objectives. The protocol design enables a flexible monitoring approach and analysis aimed to quantify indicators correlated to the common BDA goals and expected effects. An advantage to broadly defining a suite of monitoring indicators is that it enables the collection of data not associated with specific project objectives that can give insight as to why and how important indicators are changing (Karl et al., 2017).

For this protocol, a site consists of a small stream segment between approximately 100 m and 1000 m in length where roughly one complex of BDAs having similar objectives are installed or plan to be installed (Gurnell et al., 2016). The length of the site is not as important as whether the group of structures have a similar objective and were built at the same time. Those details are typically outlined in project design plans. Monitoring at the reach scale as opposed to broader watershed or landscape scales has advantages including easier site visits to gain an in-person perspective and record indicators related to the structures within the site. Another advantage includes the ability to relate reach-scale indicators to project-level objectives which may be monitored by broader-scale methods (Figure 2).

Considering the capabilities of current technology and use of UASs in ecological monitoring, the protocol described below uses a combination of UAS imagery and in-field methods of data collection (Table 1). With common UAS and available photogrammetry software, a 300 m site can be efficiently documented with a combination of imagery products at cm-level resolutions and in-field measurements.

Table 1. Indicators corresponding to key processes of ecosystem change at the reach scale and their general collection-based method. VB stands for Valley Bottom.

Indicators	**Process**	**Methods**
Flow (in vs. out; percentile)	Hydrologic	Field
% Channel Wet/Inundated	Hydrologic	UAS
Inundation (3) Areas (total, pool, free flow) (% of VB)	Hydrologic	UAS
Sinuosity: Valley Bottom, Primary & Non-Primary Channel Lengths (m)	Geomorphic	UAS
Valley Bottom Area (m^2)	Geomorphic	UAS
Avg. Channel & Valley Bottom Widths (m)	Geomorphic	UAS
Bare Channel Area (% of VB)	Geomorphic	UAS
Beaver Density (beaver and sign of beaver)	Ecologic	Field
Dam & Structure Density (noting condition)	Ecologic	Field
Riparian Type (3) Areas (total active, woody, and wet) (% of VB)	Ecologic	UAS
Short Term (<2 treatments ~1-4 years) Potential Area (% of VB)	N/A	UAS
Long Term (>2 treatments ~4+ years) Potential Area (% of VB)	N/A	UAS
Total Potential Area (short + long) (% of VB)	N/A	UAS

Indicators for Monitoring Reach Scale BDA Effectiveness:

Key drivers of riparian and stream reach-scale ecosystem change are channel geomorphology, the current hydrologic regime, riparian functioning and extent across the valley bottom, and human interference (Gurnell et al., 2016). Channel geomorphology includes impacts on geomorphology and sediment dynamics due to changes in channel roughness (*N)*, erosion rates, sedimentation, floodplain connectivity, geomorphic complexity, sinuosity, and planform (Bierman & Montgomery, 2013). Hydrologic regime includes impacts on hydrology and site hydraulics represented by changes in indicators such as area of inundation, soil moisture, floodplain storage capacity, late season plant-available water, and changes in stream flow including velocity, direction, duration, frequency, predictability, and gradient of flow throughout a reach (Brooks et al., 2013). Riparian functioning and extent relate to a site's ecology and biota and can be measured through changes in indicators such as proportion of riparian area to the valley bottom (Dosskey et al., 2010), vegetation structure, composition, distribution (Aguiar et al., 2011), and vigor (Hausner et al., 2018) at the time of specific hydrologic conditions. Ecological indicators also include wildlife and other species present and impacted but depend on resources provided by the vegetation characteristics.

Based on this understanding of expected and potential effects given hydrological and ecological processes and the scales at which BDAs are implemented, indicators were selected to represent effects on three key processes involved with producing a reach's physical and biological characteristics. Hydrologic processes are measured by monitoring area of free flow, pooled area, and total inundation area, along with flow and wetted channel length to represent reach-scale effects. Geomorphologic processes are measured via channel, sinuosity, bare channel area, roughness, channel width, and primary and non-primary channel lengths to represent reach-scale effects. Ecological processes are measured by monitoring woody riparian area, wet riparian area, non-wet herbaceous riparian area, and total riparian area along with recording signs of beaver and their dams to represent reach-scale effects.

Monitoring in consecutive years can account for interannual variability and differences between sites by also recording stream types, flow percentile, valley bottom area, valley bottom width, gradient, structure density and other site-specific measurements. Considering area indicators relative to their proportion of total potential recovery area allows for better comparisons between sites and across projects.

The breadth of indicators measured here is not found in other studies of BDA effectiveness. Studies that have considered similar indicators have mostly used qualitative methods rather than quantifiably monitoring changes in their indicators. Compared to other monitoring protocols that measure whether specific complexes and individual structures have met stated goals or whether maintenance is needed, the indicators above will quantify the broader impacts of BDA projects as well as the success of the project and complex goals. Compared to recent monitoring efforts (e.g., Wheaton et al., 2019), this protocol quantifies indicators related to complex-level objectives and the expected effects at the reach scale specifically. The procedures described below provide quantitative data that can be used to explain and track changes and resulting impacts on the broader ecosystem processes involved with riparian area and stream processes and function.

Protocol Development and Testing

The purpose of this study was to develop and test indicators and methods for monitoring the effectiveness of BDAs, and the statistical methods and study design are specific to that purpose. Application of this protocol in the context of riparian restoration will require specification of monitoring objectives, sampling design, data quality-assurance and quality control procedures, and statistical analyses appropriate to the management goals (McCord et al., 2021).

Methods

For any new monitoring protocol, a test is required to better determine the suitability of the indicators and the performance of methods to measure those indicators. Accordingly, I implemented the protocol below on 31 sites in Idaho to compare how the protocol works in different ecosystems and at different stages of restoration.

Site Selection:

Information on current and pending BDA projects in Idaho was collected from conversations with land managers and by obtaining a list of projects from the Idaho Department of Water Resources (IDWR) in the Fall of 2019. Project descriptions were recorded to gain background information from land managers and applications submitted to IDWR. The compiled list of over 20 projects formed the basis for selecting projects, complexes, and sites for this study (Table 2). To better understand the project areas, landscape characteristics important to reach-scale riparian and stream change were recorded to help with site selection (see Appendix A for full information for each site). This included information on the area's vegetation (Richardson et al., 2007), influential watershed land uses (Buffington & Montgomery, 2013), and average discharge and drainage area from Streamstats (Poff et al., 1997).

With over 20 projects, a ranking was necessary to prioritize them for inclusion in the study based on logistical constraints. Projects were ranked based on the number of complexes present, proximity to other project areas, complex (e.g. reach) age class, and landowner or project-manager permission (Table 2). I prioritized 6 projects including over 50 possible complexes (Table 3, Figure 3).

For each project, multiple reaches were selected to represent different age classes and complex goals. With smaller projects (i.e., less than approximately 0.75 miles of stream), the entire project was measured. Project boundaries were defined in project descriptions. With larger project areas, reaches from the upper and lower most sections of each stream were included, with at least two more sites spatially distributed throughout the project area.

Sampling was conducted in late summer between July-October 2020 to be close to baseflow conditions. The 31 chosen sites ranged in size from 0.3 to 19.3 acres.

Table 2. List of BDA Projects, prioritized for inclusion in the study based on logistical constraints.

Project Name	**Year/s Installed**	**Total BDAs**	**# of Complexes**
Baugh Creek Post-Fire Restoration	2018	17	7
Rinker Rock Creek Ranch Post-Line Weaves	2018	15	4
Rinker Rock Creek Ranch CIG BDA Project	2020	not yet	3
Hawley Creek	2018, 2019, 2020	90	3
IDFG Craig MT 2019	2019	57	1
IDFG Craig MT 2021	2021	not yet	not yet
LSWCD_Wet & Smith Meadows	2019	63	3
Sharps Fire 2020 Restoration Project	2020	not yet	not yet
Crooked Creek Restoration	2020	not yet	not yet
Leadore Restoration	2020	not yet	not yet
Birch Creek Streambed Alteration	2020	20	not yet
Station Creek Restoration	2018	30	7
Post-Line Sheep Creek	2018, 2019	15	2 to 3
PLWW_Unnamed Springs	2019, 2020	not yet	10 to 13
Canyon & Cruikshank Creeks BDA	2018	10	
Benewah Creek Restoration	2017, 2018, 2019	27	6 to 10
Andrus WMA Camp Creek One Rock Dam	2019, 2020	not yet	1
Sulphur Creek BDA project	2019	21	2 to 3
USFS MOU notes- Smokey Creek BDA	2018, 2019	16+	5+
Owyhee	2017, 2018, 2019	60+	
East Fork Fish Creek Restoration	2019	-60	10+
Deary/Anabrach	2020	-15	none

Table 3. List of BDA complexes sampled and location relative to their project.

Project	**Stream**	**Latitude; Longitude**
Rock Creek Post-Line Weaves	Rock Creek	43°25'11.47"N; 114°23'51.83"W
Rock Creek Post-Line Weaves	Rock Creek	43°26'8.68"N; 114°23'33.72"W
Rock Creek Post-Line Weaves	West Fork RC	43°26'11.50"N; 114°23'33.88"W
Rock Creek Post-Line Weaves	West Fork RC	43°26'19.68"N; 114°23'32.03"W
Guy Canyon 2020 Restoration	Guy Canyon	43°23'4.27"N; 114°24'27.27"W
Guy Canyon 2020 Restoration	Guy Canyon	43°23'25.30"N; 114°24'32.92"W
Guy Canyon 2020 Restoration	Guy Canyon	43°23'39.00"N; 114°24'43.94"W
IDFG Craig MT2019	West Fork Deer Creek	46° 6'56.09"N; 116°48'24.17"W
IDFG Craig MT2019	West Fork Deer Creek	46° 6'56.09"N; 116°48'24.17"W
IDFG Craig MT2021	West Fork Deer Creek	46° 7'19.81"N; 116°48'35.98"W
IDFG Craig MT2021	West Fork Deer Creek	46° 7'19.81"N; 116°48'35.98"W
LSWCD	Corral Creek/ Smith Meadow	46°51'1.03"N; 116°31'30.36"W
LSWCD	Corral Creek/ Smith Meadow	46°51'10.13"N; 116°31'34.63"W
LSWCD	Corral Creek/ Wet Meadow	46°51'37.14"N; 116°31'58.16"W
Sharps Fire 2020 Restoration	Thompson	43°32'56.79"N; 113°56'6.35"W
Sharps Fire 2020 Restoration	Thompson	43°33'8.45"N; 113°56'17.61"W
Sharps Fire 2020 Restoration	Thompson	43°33'17.05"N; 113°56'29.14"W
Sharps Fire 2020 Restoration	Thompson	43°33'26.42"N; 113°56'38.25"W
Sharps Fire 2020 Restoration	Thompson	43°33'37.70"N; 113°57'4.93"W
Sharps Fire 2020 Restoration	Cold Springs	43°30'26.26"N; 114° 4'2.97"W
Sharps Fire 2020 Restoration	Cold Springs	43°30'26.74"N; 114° 4'25.41"W
Sharps Fire 2020 Restoration	Cold Springs	43°30'28.28"N; 114° 4'58.71"W
Sharps Fire 2020 Restoration	Cold Springs	43°30'26.31"N; 114° 5'26.28"W
Sharps Fire 2020 Restoration	Cold Springs	43°30'23.73"N; 114° 6'17.62"W
Sharps Fire 2020 Restoration	Cold Springs	43°30'19.04"N; 114° 6'31.50"W
Sharps Fire 2020 Restoration	Cold Springs	43°30'10.04"N; 114° 6'56.22"W

Sharps Fire 2020 Restoration	High Five	43°29'4.14"N; 114° 3'42.23"W
Sharps Fire 2020 Restoration	High Five	43°29'1.64"N; 114° 3'56.81"W
Sharps Fire 2020 Restoration	High Five	43°28'54.29"N; 114° 4'10.49"W
Sharps Fire 2020 Restoration	High Five	43°28'38.31"N; 114° 4'35.54"W
Sharps Fire 2020 Restoration	High Five	43°28'14.34"N; 114° 4'58.26"W

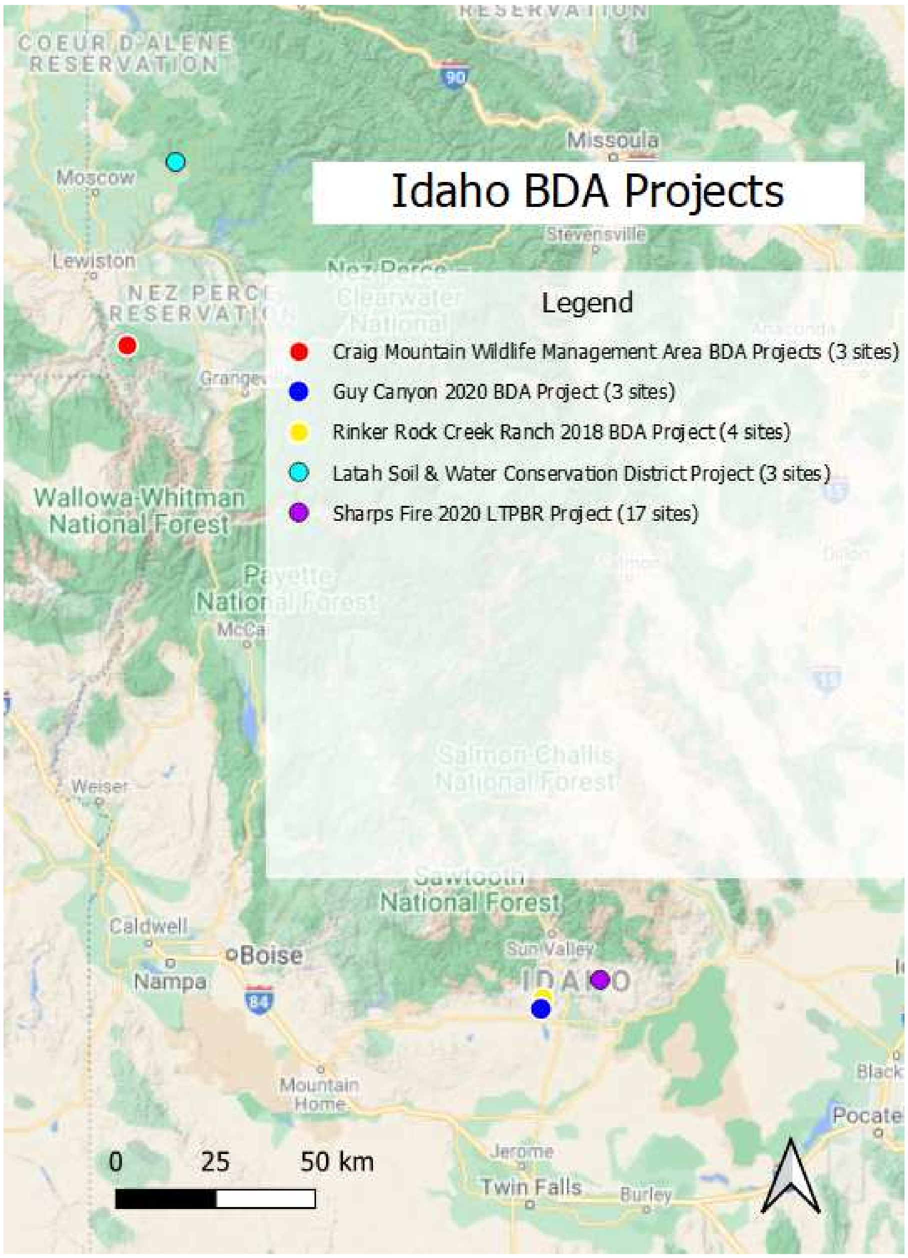

Figure 3. Map of the state of Idaho with locations of 6 BDA projects in yellow used in the study.

Study Areas by Project:

Sharps Fire 2020 Restoration Project

This restoration project is utilizing BRR to help with the restoration of lands in southern Idaho from the 2018 Sharps fire. The project is a collaborative effort lead by the Wood River Land Trust on portions of private, state, and federal land east of Bellevue, ID and covers three tributaries of the Little Wood River Watershed: Cold Springs Creek (3 miles of stream), High Five Creek (1.3 miles of stream), and Thompson Creek (1.5 miles of stream) (Figure 4). Upstream drainage areas total roughly 23 square miles and restoration efforts have the potential to directly impact roughly 200 acres. Streamstats categorized Cold Springs and High Five Creek as intermittent, and Thompson Creek as a perennial stream. Current land uses include recreation and ranching. No upstream influences were detected from a review of satellite imagery. The project area is in the Foothills Shrubland Ecosystem (Omernik et al., 2018).

Overall, the project goals aim to mitigate the impacts from the wildfire and future fires; catch sediment; improve overall riparian condition, stream channel geomorphology, stream/floodplain connectivity, water quality, fish habitat, and greater sage's habitat; and to increase wet meadow habitat, plant productivity (i.e., forage for cattle and wildlife), and stream meandering. This project planned to install BDAs in fall 2020 in Cold Springs and High Five, then install BDAs in Thompson Creek in 2021 alongside post-assisted log structures (PALS), and woody-debris structures. With this project just beginning, complex objectives have not yet been set.

From this project, I included 17 sites. Cold Springs Creek provided 7 sites evenly distributed throughout the stream's project area. High Five Creek provided another 5 sites evenly distributed again throughout the stream's project area. Thompson Creek then provided 5 sites focused primarily in the lower 80% of the stream's project area.

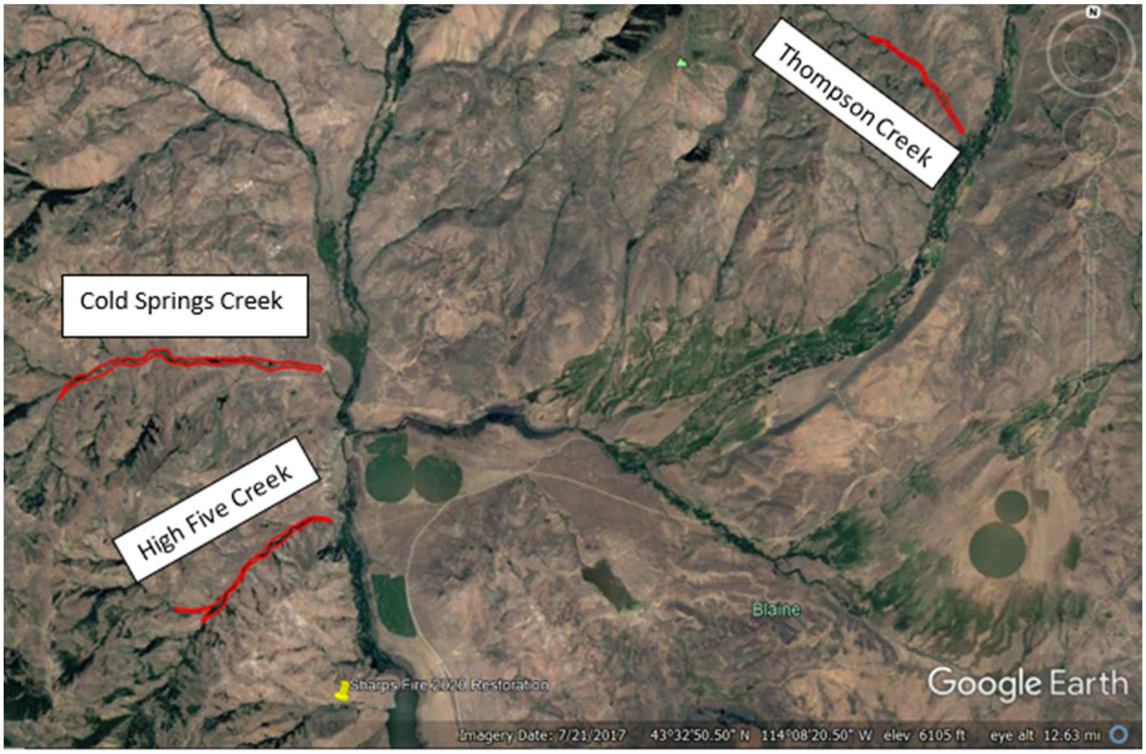

Figure 4. Sharps Fire 2020 Restoration Project area is located east of Bellevue spanning High Five Creek, Cold Springs Creek, and Thompson Creek.

Rinker Rock Creek Ranch Post-Line Weaves Project

West of Bellevue, ID on the University of Idaho's Rinker Rock Creek Ranch, a 2018 BDA project consisted of sections of the main channel of Rock Creek (1.0 mile of stream) and sections of a tributary, West Fork Rock Creek (0.2 miles of stream) (Figure 5). Upstream drainage areas total roughly 14 square miles and restoration efforts have the potential to directly impact roughly 41 acres. Rock Creek and West Fork Rock Creek are perennial streams (Streamstats 2021). Old small mine operations present potential upstream influences based on a review of satellite imagery. Current land uses include recreation, ranching, and wildlife conservation. This project area is in the Foothill Shrublands Ecosystem (Omernik et al., 2018).

Installed primarily as a demonstration project for University researchers, land managers, and the public, the primary project objectives were to increase floodplain connectivity, increase riparian extent to promote beaver movement upstream, aid in the recovery of upstream and downstream beaver complexes, slow flows, and promote deposition of sediment. Along with roughly 15 BDAs in 4 complexes, other techniques including Zeedyk structures, small woody debris, and PALS were installed in 2018. Specific locations to install were selected based on levels of channelization present in streams pre-installation.

Each complex was relatively small, so I sampled all four complexes and the entire project area. Rock Creek provided 2 sites and West Fork Rock Creek provided 2 more sites. From downstream up, RRCR1 has an objective to increase riparian extent and move beaver upstream. RRCR2 has an objective to aid in the recovery of current beaver dams. On West Fork Rock Creek, both RRCR3 and RRCR4 aim to slow flows, promote deposition of sediment.

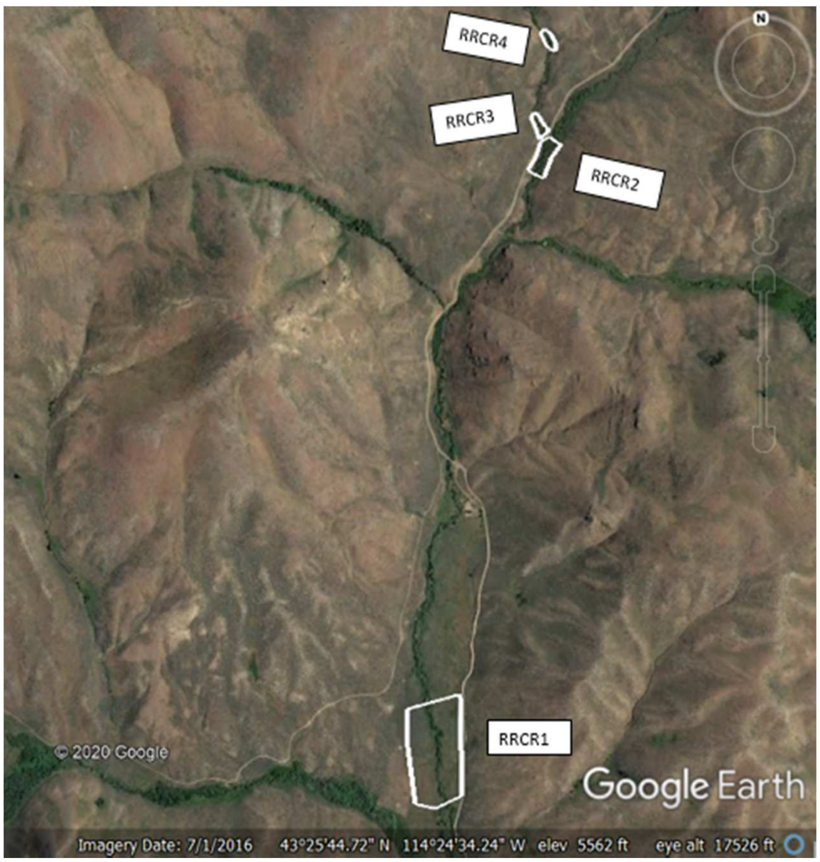

Figure 5. A map of the Rinker Rock Creek Ranch Post-Line Weaves project area located west of Bellevue, ID on the University of Idaho's Rinker Rock Creek Ranch showing the 4 complexes sampled.

Guy Canyon BDA Project

The 2020 Guy Canyon BDA project is an extension of the earlier 2018 work at Rinker Rock Creek Ranch funded separately as a study involving BRR, monitoring the impacts, and comparing the effectiveness of different types of monitoring by evaluating the restoration technique at two different areas: Hawley Creek (Lemhi County, Idaho) and Rock Creek (Blaine County, Idaho).

At the university's Rinker Rock Creek Ranch, roughly 800 m of a tributary to the main Rock Creek, Guy Canyon, will have BDAs installed from 2021-2023 (Figure 6). Specific reaches were selected because they did not meet potential hydrologic function, desired plant community composition and vigor, or had incised channels. The total project area was roughly 10 acres over 3 different sites and an upstream drainage area of roughly 2.7 square miles. Streamstats categorized Guy Canyon as an intermittent stream. Recreation, ranching, and wildlife are the main operations on the landscape currently. Old small mine operations present potential upstream influences from the satellite perspective. According to the EPA ecoregion level IV classification, the project area is in the Foothill Shrublands Ecosystem (Omernik et al., 2018).

Project goals include stopping active head-cuts, reducing sections of incised stream banks, increasing riparian vegetation, and increasing the length of time when upper reaches of the stream are flowing. Three separate complexes make up the 800 m of project area where BDAs, PALS, and Zeedyk structures will be installed over the three-year period. All three complexes have the same general complex goals which included increasing water retention, increasing lateral movement of wetted areas, increasing sedimentation, increasing greenline riparian areas, slowing water increasing duration of time water passes, and increasing riparian area across valley bottom.

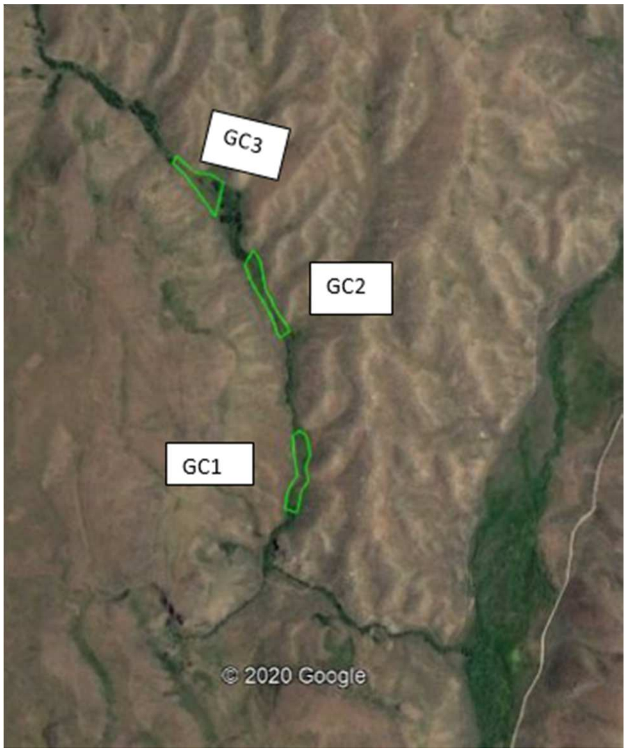

Figure 6. The Guy Canyon Project area located west of Bellevue, ID on the University of Idaho's Rinker Rock Creek Ranch.

Idaho Department of Fish & Game (IDFG) Craig Mountain BDA 2019 & 2020 Projects

This project is in response to meadow alteration and channel incision within mountain wet meadow systems south of Lewiston, Idaho. Within the Craig Mountain Wildlife Management Area managed by the state of Idaho, IDFG has two BRR projects on the West Fork Deer Creek (totaling 1.0 mile of stream) aiming to help hydrology and ecological function and specifically cool water temperatures (Figure 7). Upstream drainage areas total roughly 2.37 square miles and restoration efforts have the potential to directly impact roughly 12 acres. Streamstats categorized West Fork Deer Creek as a perennial stream. Historically heavy timber and logging operations along with significant summer grazing present potential upstream influences from the satellite perspective. According to the EPA ecoregion level IV classification, the project area is in the Canyons and Dissected Highlands Ecosystem (Omernik et al., 2018). Wildlife habitat conservation is the primary use and recreation a secondary use of these mountainous wet meadow areas covered with grasses and herbaceous vegetation surrounded by a thick forest.

Along with roughly 57 BDAs in one complex installed in 2019 (lower 0.4 miles of stream), other techniques implemented included: plant manipulation (thinning), burning the meadow boundary, plantings, and installing large woody debris. This group of techniques is also planned to be used on the upper 0.6 miles of stream as well in 2021. Both complexes have the same general complex goal which includes increasing water retention and increasing lateral movement of wetted areas. With a smaller project area, I included the full project area, but separated both the 2019 and 2021 complex due to their large sizes totaling 4 sites for the study.

Figure 7. Idaho Department of Fish & Game (IDFG) Craig Mountain BDA Projects (2019 & 2021) located south of Lewiston, ID on the Craig Mountain Wildlife Management Area.The lines indicated where BDAs are and will be installed. The upper area is the 2021 project, and the lower area is the project that was implemented in 2019.

Latah Soil and Water Conservation District (LSWCD) BDA Project

North of Deary, ID on US Forest Service land, the LSWCD Restoration Project, located on Corral Creek (1.25 miles of stream), is in response to warm waters, channelization, railroad burns, decreased pools, and head cuts (Figure 8). The total project area was roughly 66 acres over 3 different sites and an upstream drainage area of roughly 3.36 square miles. Streamstats categorized Corral Creek as an intermittent stream. Timber operations, recreation, wildlife, and grazing are the main uses of the landscape currently. Old small mine operations present potential upstream influences from the satellite perspective. According to the EPA ecoregion level IV classification, the project area is in the Northern Idaho Hills Ecosystem (Omernik et al., 2018). With these grassy, herbaceous wet meadow areas in northern Idaho, it is surrounded by a forest dominated by Douglas-fir (*Pseudotsuga menziesii*), subalpine fir (*Abies lasiocarpa*), and ponderosa pine (*Pinus ponderosa*).

Project objectives aim to improve aquatic habitat, rehydrate meadows, cool habitat, improve steelhead juvenile habitat, increase native vegetation, and attract beaver. Three complexes separated by installation year (2018, 2019, control) were detailed having 63 total BDAs along with planting riparian woody species. The two complexes in the upper sections of the project area have similar complex objectives including increasing pool water area, collecting sediment, increasing inundation area, increasing green riparian area across floodplain, and promoting floodplain connectivity.

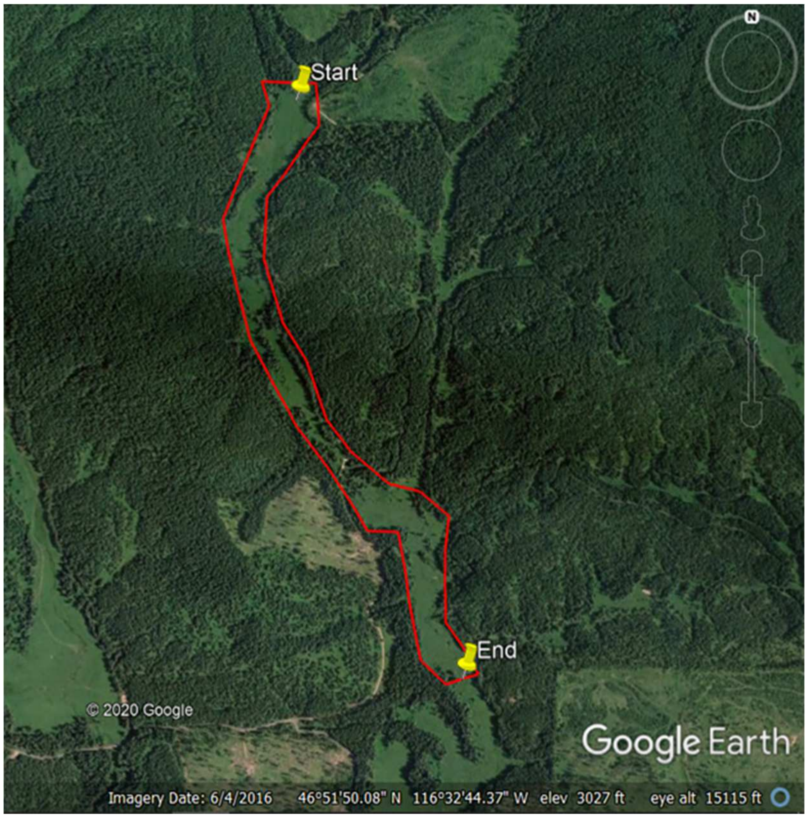

Figure 8. The Latah Soil and Water Conservation District (LSWCD) BDA Project located north of Deary, ID on Wet & Smith Meadows.

UAS Image Acquisition:

Overlapping aerial photographs were collected at each site to construct 3D models of the site, digital elevation models, and orthomosaics using structure-from-motion digital photogrammetry. A Phantom 4 Pro drone was used throughout the project as our UAS with its original 20MP one-inch sensor capable of sensing and recording three spectral, RGB, bands (https://www.dji.com/phantom-4-pro/info).

Structure-from-motion (SfM) photogrammetry relies on multiple overlapping photographs of the flight area to correct for image angle and sensor distortion to construct 3D models and orthomosaics (Aber et al., 2010). To ensure maximum image overlap within the flight areas, I used a double-grid flight pattern. For more reliable data at the edges, it is recommended to have a flight plan larger than the area of interest (Cunliffe et al., 2016). Each mission covered slightly more than the width of the valley bottom. Flight area was extended along the length of the stream until the estimated flight time reached the UAS's maximum flight time given battery capacity. Flight time for Phantom 4 Pro in ideal conditions is 30 minutes (https://www.dji.com/phantom-4-pro/info). I limited the mission to 23 minutes of flight time to account for non-ideal conditions (e.g., wind) and normal battery degradation over time. Some mission plans covered multiple small BDA complexes, while larger complexes required more than one mission plan. Flight mission planning was conducted using Pix4dCapture (https://www.pix4d.com/product/pix4dcapture) on an Android tablet.

Mission parameters were set to ensure a resolution of roughly 1 cm/pixel while considering the altitude needed to clear the tallest object at a safe altitude. Images were captured with 80% front and side overlap at roughly a 45-meter altitude above ground and the sensor capture angle was set to 15% off nadir. These settings allowed enough image overlap and angle for the photogrammetry software to accurately produce 2D and 3D imagery products (Cunliffe & Anderson, 2019).

Although UASs provide relatively accurate and high-resolution imagery products, repeated surveys that aim to analyze change in landform surfaces over time need accurately scaled and geolocated image products (James et al., 2017). Ground control points (GCPs) are precisely georeferenced points collected separately and entered during the photogrammetric image processing to enhance the location and spatial accuracy of the final imagery products (James et al., 2017). GCPs are important for co-registering image products from different dates and will facilitate monitoring of BDA projects. At least 7 GCPs were needed for each flight, one situated close to each of the upper and lower most boundaries and five spread throughout the intended flight mission area (see James et al., 2017). As each GCP was placed, their coordinates (latitude and longitude) were recorded using an Emlid Reach RS2 real-time kinematic (RTK) global navigation satellite system (GNSS, https://emlid.com/reachrs2/). The Reach RTK device consisted of a base station with either a calculated or known fixed location that broadcasts positional corrections at a rate of 5 Hz to a rover unit to achieve cm-level positioning accuracy.

To fly the mission, a pilot in command certified with the FAAs Part 107 certificate was required. Each mission was approved by the University of Idaho UAS Committee and every flight followed a COVID-19 mitigation plan.

Field Data Collection:

The following observations were recorded in the field at each site to further understand stream conditions around BDA complexes at the time of UAS data collection. Evidence of beavers and natural dams were noted per reach. The channel's roughness was estimated in the form of Manning's Equation N coefficient (Marcus et al., 1992; Arcement & Schneider, 1989). The roughness coefficient, determined by bed material, size of material and complexity, vegetation, other obstructions, and channel bends (Coon, 1998), is useful for understanding the channel's ability to impact flow at the time of the UAS image acquisition. Using a reference sheet, the roughness coefficient was visually estimated and recorded per reach (Coon, 1998).

Three discharge measurements were made per project or stream in each project to represent the flow across the entire project area. Flow across the entire project represents a broader impact from the project. Discharge measurements were taken at the upstream and downstream boundaries of each project area and a third measurement at the midpoint. This allowed for not only assessment of current climate conditions, but the three measurements also provided in versus out measurements enabling the interpretation of whether the reach was contributing to flow output during low-flow conditions. Discharge was measured using the natural cross-section velocity-area method described by Rantz et al. (1982) using a Marsh-McBirney flow meter, wading rod, stakes, and a measuring tape.

UAS Image Processing:

Agisoft Metashape is a photogrammetric software application that can produce orthomosaics from a sequence of images using SfM and scale invariant feature transformation processing (SIFT) (https://www.agisoft.com/). Unlike basic stereoscopic photogrammetry, SfM calculates 3D positions during processing using a bundle adjustment procedure on a set of multiple overlapping images (Westoby et al., 2012). The SIFT algorithm identifies "tie points" which represent the same features viewed in multiple images, determines the location and orientation of all cameras through a bundle adjustment, and calculates 3D coordinates of features resulting in a sparse point cloud (Gillan et al., 2017). GCP coordinates were imported and the points manually located on a subset of the photos. Using the GCP coordinates, another bundle adjustment was completed to optimize the scene and accurately scale the stereo model.

A high-density point cloud was then derived by implementing the Clustering View for Multi-view Stereo (CMVS) algorithm (Westoby et al., 2012). This process dissects overlapping images into subsets to then reconstruct 3D data in manageable sizes resulting in a significant increase in point density (Westoby et al., 2012). A digital elevation model (DEM) based on the dense cloud was then made, followed by an orthomosaic which used the DEM surface to correct for terrain displacement in the original images (Figure 9).

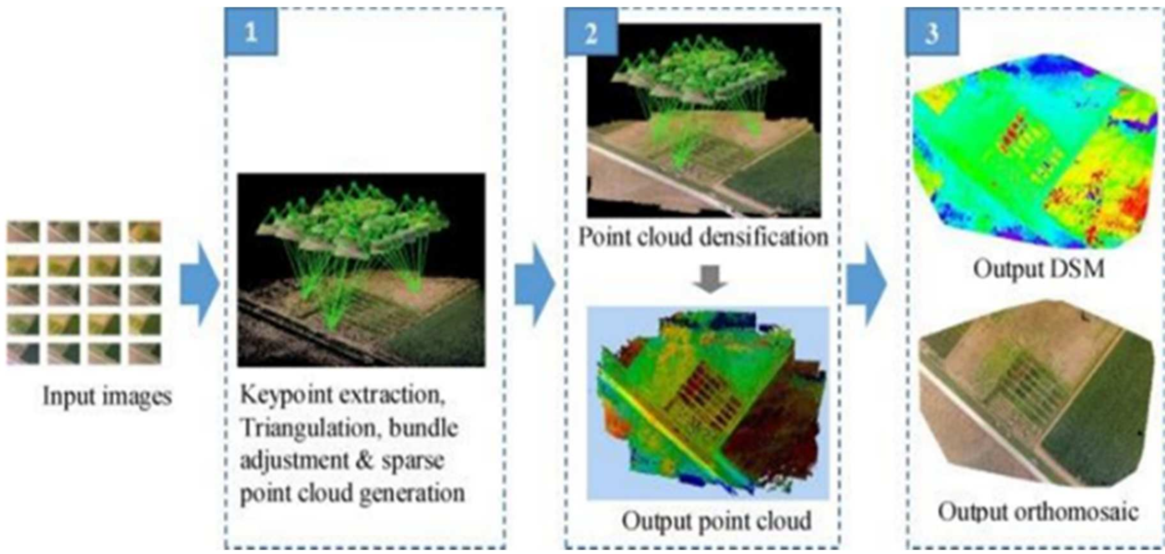

Figure 9. The major stages of the Structure from Motion (Sfm) workflow and orthomosaic processing procedure.

Indicator Calculations:

Using QGIS (https://qgis.org/en/site/) measurement tools and the DEM and orthomosaic for each site, I manually identified channel-spanning structures and delineated the channel lengths, riparian vegetation groups, different surface water types, potential riparian/stream area and inaccessible area within the valley bottom (Table 1).

Each site's valley bottom area was first delineated from the original orthomosaic setting the upper and lower most boundary of the reach and exceeding the valley bottom. This section of stream was delineated by the ends of the project area or ends of a complex. Using both the orthomosaic and DEM, the valley bottom was delineated by observing and matching changes in slope within the DEM to vegetation changes in the corresponding orthomosaic. Sharp changes in elevation highlight different primary forces influencing the resulting landform, which in this case resulted in upper terrestrial, riparian, and aquatic areas. Then, the inaccessible valley bottom areas were delineated. Next, pools, free flows, and bare channel areas were delineated.

Total green riparian area was found by visually delineating green riparian vegetation including the riparian deciduous trees and shrubs on the edges of the valley bottom. From the total riparian vegetation, I then delineated woody deciduous riparian vegetation and what was wet vegetation for that ecosystem. Delineating wet riparian vegetation is challenging across different ecosystems because of differences in appearance of vegetation occupying the 'wet riparian zone'. Wet riparian cover type was classified as herbaceous vegetated area inundated or barely inundated, or where wet, soggy, or moist ground was present indicating the area was previously inundated. In most systems, wet riparian areas had a different vegetation composition compared to those in woody or green riparian areas usually adapted for wet conditions. To help with delineation of this indicator, it is vital for the observer to see in the field which areas are in this 'wet riparian zone.'

Lastly, I delineated short- and long-term potential recovery areas using the DEM. Total potential recovery area was recorded as area within the valley bottom accessible to being restored by the restoration project and not already classified as an area detailed above. Short-term potential area was measured and subtracted from the total to get long-term potential. Total potential area was straightforward, while the delineation of short-term potential area was subjective based on manually depicting small elevation shifts in the floodplain and noticing how far these shifts were from other areas in the floodplain. The idea behind these delineated indicators was that sections lower in elevation and closer to active riparian and inundated areas within the valley bottom were expected to be affected by BDA installation sooner than areas higher in elevation and further away from the channel. Short-term and long-term potential recovery area were then separated based on the elevation differences in the floodplain and proximity area classified as another area-based indicator. This approach to defining potential recovery area presumes it would take less time and fewer treatments involving the installation of new structures to effect or restore areas within the valley bottom closer to the channel than those farther away and at a greater elevation difference before impact from restoration.

Once the map was delineated and proportional area indicators were measured, linear measurements were found using the measuring tool in QGIS. Average valley bottom width was calculated by averaging roughly 8-12 measurements. Average channel width was calculated from averaging roughly 20+ channel measurements. Primary, non-primary, and wet channel length was then recorded along with valley bottom length. Lastly, gradient was measured by dividing the difference between the upper most elevation with the lower most elevation by the valley bottom length.

The area indicators were turned into proportional area indicators within the valley bottom, which included the total potential, total riparian area, total inundation area, long-term potential area, short-term potential area, woody riparian area, wet riparian area. Density of channel-spanning structures was calculated from the number of structures and the length of the total channel length. Sinuosity was calculated and percent channel length wet was calculated from the total channel length. Flow percentile was retrieved by comparing the flow measured in-field to data collected and estimated by Streamstats during the month monitored. Table 1 displays indicators corresponding to their calculated indications.

Analysis:

Indicator values were summarized for each site, and area-based indicators were normalized by the total valley-bottom area to obtain proportional-area estimates. Correlation matrices were calculated between all indicators to evaluate potential information redundancy. Additional bivariate comparisons of indicators were completed using scatter plots and ordinary least-squares regression. Differences among pre- and post-installation sites were evaluated on an indicator-by-indicator basis comparing means and 90% confidence intervals. Summary statistics, plots, correlation matrices were completed using Microsoft Excel 365 and R version 4.0.1 (R Core Team, 2020).

Using the indicator values for each site, I performed a multivariate ordination to reduce data dimensionality, increase interpretability, and better represent separation between sites. Ordination also helped evaluate which indicators explained the most variability in the indicator results and whether sites showed differences by treatment (pre- versus post-installation of BDAs) and ecoregion. Principal coordinates analysis was selected as the ordination technique because it handles variables of different scales better than principal components analysis while still providing loadings of the original input variables on the composite principal coordinate axes (as opposed to multi-dimensional scaling techniques)

(Johnson & Wichern, 2002). Indicator values except for structure density were used for each site in the principal coordinates analysis. The resulting principal coordinates were evaluated based on the cumulative proportion of variation explained and any principal coordinate explaining more than 2% of the total variation was retained. Meaning of each retained principal coordinate axis was interpreted based on loadings of the original indicator variables on the principal coordinate axis. Ordination plots with sites coded by treatment (pre- versus post-installation) and ecoregion were used to examine separation between site groupings. All ordination analysis was performed in R using the 'vegan' package version 2.5.7 (Oksanen et al., 2020).

Results

Imagery Products:

Orthomosaics for each site ranged in resolution from 0.842 to 1.68 cm/pixel, while the digital elevation models ranged in resolution from 3.37 to 6.72 cm/pixel (Table 4, Figure 10). Within each site, map delineations quantified the area and proportion of each indicator (Figure 11).

Table 4. Orthomosaic and Digital Elevation Model's resolution per site displays photo acquisition date and number of photos.

Area	Site	Photo	Date	Ortho res (cm/pix)	DEM res (cm/pix)
Rock Creek Ranch	**RRCR1**	596	16-Jul	1.31	5.25
Rock Creek Ranch	**RRCR2**	181	16-Jul	1.04	4.17
Rock Creek Ranch	**RRCR3**	131	15-Jul	0.993	3.97
Rock Creek Ranch	**RRCR4**	117	15-Jul	1.22	4.89
Rock Creek Ranch	**GC1**	330	21-Jul	1.35	5.42
Rock Creek Ranch	**GC2**	343	21-Jul	1.37	5.49
Rock Creek Ranch	**GC3**	295	21-Jul	1.44	5.77
Craig Mountain	**CM2019L**	485	7-Aug	1.42	5.69
Craig Mountain	**CM2019U**	643	8-Jul	1.1	4.39
Craig Mountain	**CM2021L**	803	10-Aug	1.29	5.17
Craig Mountain	**CM2021U**	1000	10-Aug	1.29	5.17
Smith Meadow	**LSWCD1**	252	21-Sep	1.68	6.72
Smith Meadow	**LSWCD2**	504	21-Sep	1.68	6.72
Wet Meadow	**LSWCD3**	1103	5-Sep	1.29	5.16
Sharps Fire (Thompson Creek)	**TC A**	365	16-Aug	1.15	4.61
Sharps Fire (Thompson Creek)	**TC B**	358	16-Aug	0.842	3.37
Sharps Fire (Thompson Creek)	**TC C**	282	16-Aug	1.29	5.18
Sharps Fire (Thompson Creek)	**TC D**	380	16-Aug	1.68	6.71
Sharps Fire (Thompson Creek)	**TC E**	371	16-Aug	1.05	4.2
Sharps Fire (Cold Springs Creek)	**CS A**	352	17-Aug	1.35	5.42
Sharps Fire (Cold Springs Creek)	**CS B**	702	17-Aug	1.23	4.9
Sharps Fire (Cold Springs Creek)	**CS C**	382	17-Aug	1.48	5.92
Sharps Fire (Cold Springs Creek)	**CS D**	347	17-Aug	1.27	5.07
Sharps Fire (Cold Springs Creek)	**CS E**	362	17-Aug	1.26	5.03
Sharps Fire (Cold Springs Creek)	**CS F**	378	17-Aug	1.22	4.9
Sharps Fire (Cold Springs Creek)	**CS G**	343	17-Aug	1.38	5.52
Sharps Fire (High Five Creek)	**HF A**	325	15-Aug	1.19	4.76
Sharps Fire (High Five Creek)	**HF B**	363	15-Aug	1.54	6.17
Sharps Fire (High Five Creek)	**HF C**	349	15-Aug	1.24	4.98
Sharps Fire (High Five Creek)	**HF D**	368	18-Aug	1.36	5.46
Sharps Fire (High Five Creek)	**HF E**	380	18-Aug	0.902	3.61

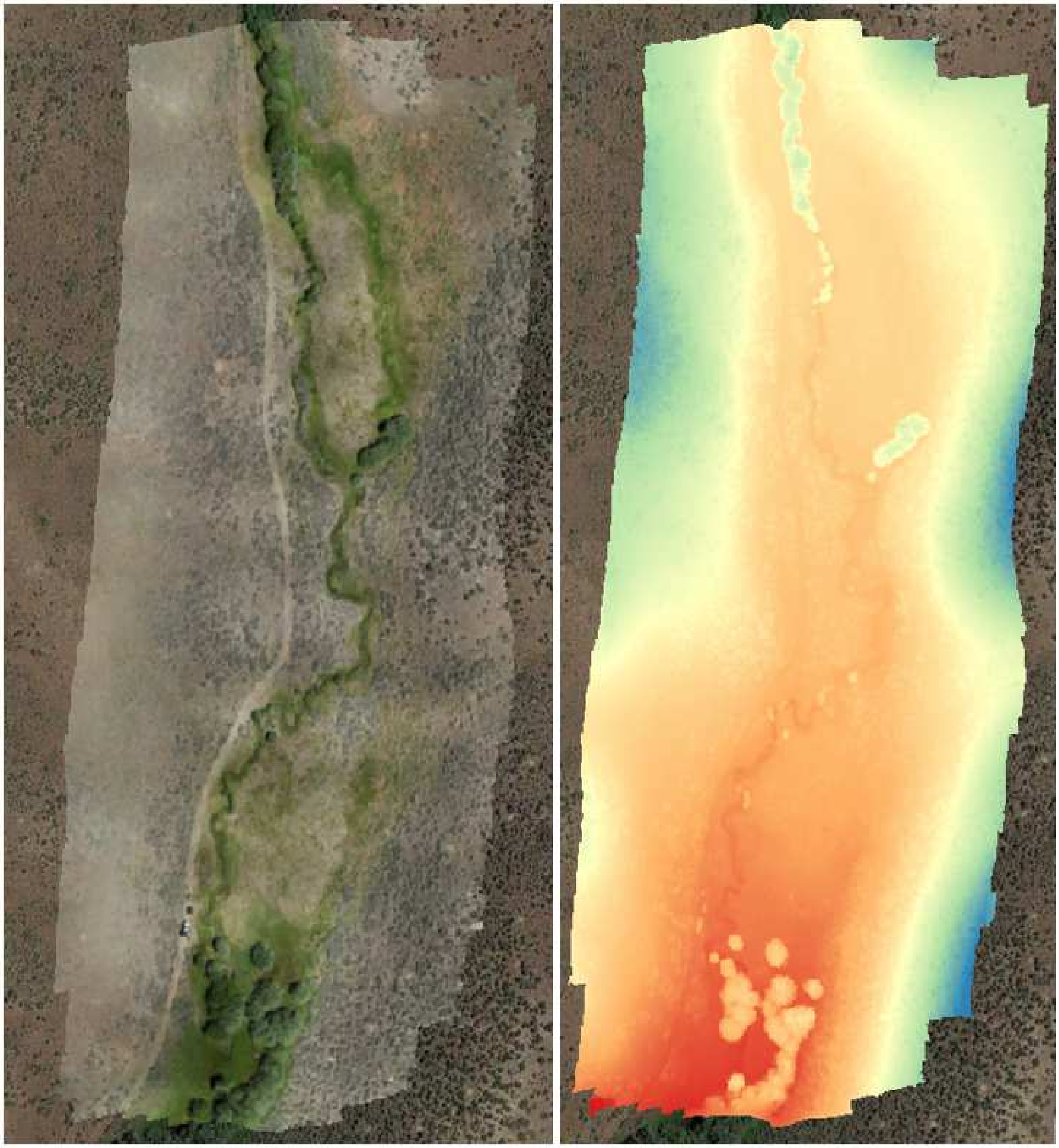

Figure 10. Example orthomosaic (left) and digital elevation model (DEM) (right) created from UAS images collected on the Guy Canyon 2020 Restoration Project's site 1. The ortho displays the RGB spectral wavelengths, while the DEM displays elevation differences.

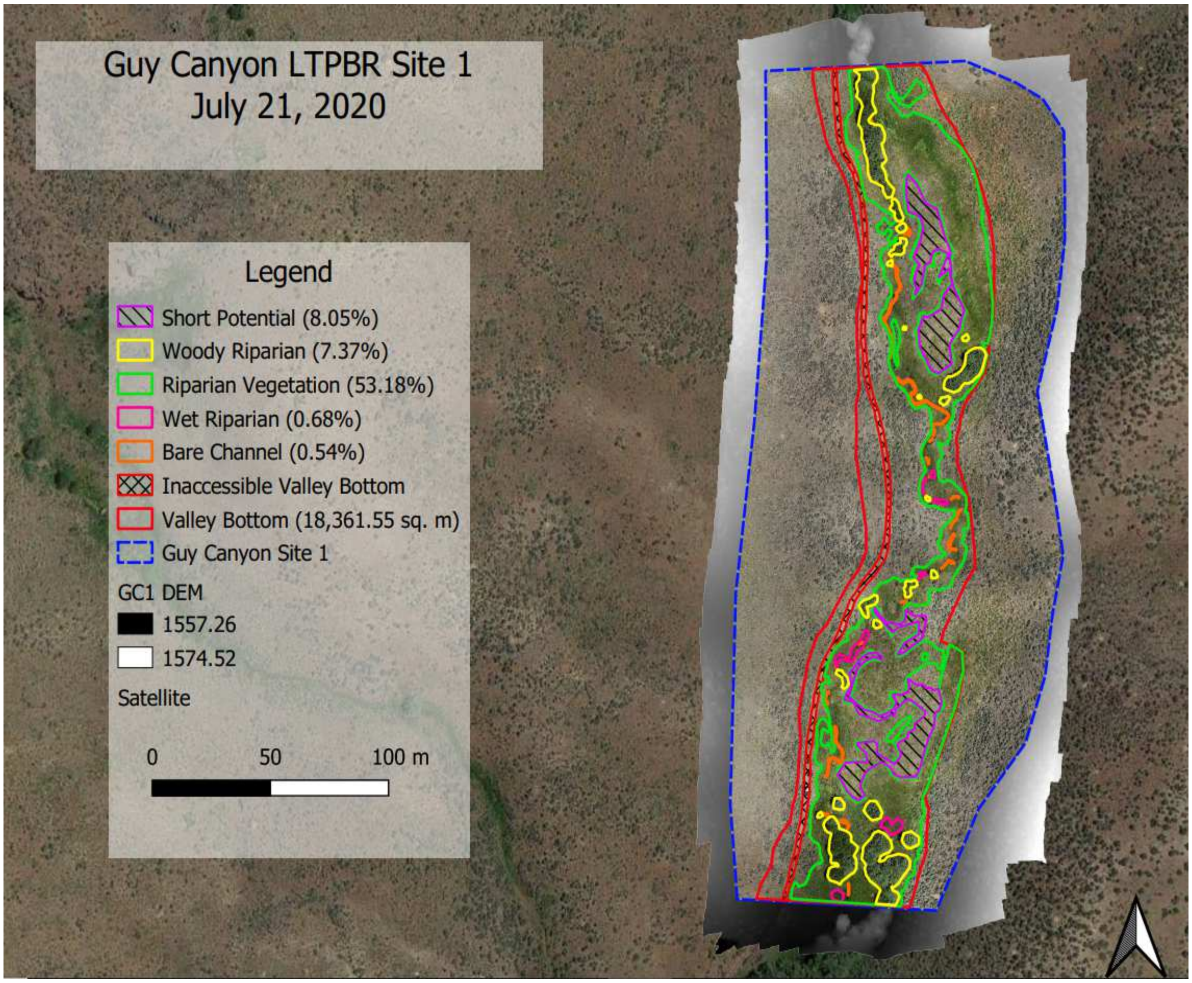

Figure 11. Stream channel and riparian indicators were delineated from the orthomosaic and digital elevation map for each site. Example shows the proportional-area indicators for the Guy Canyon site 1 (GC1 in Table 4).

Indicator Analysis:

Of the 31 total sites visited, only two sites had signs of beaver activity, and BDAs had been installed at 8 sites (Table 5, Appendix A). Variability of indicator area values generally corresponded to the variability in valley bottom sizes.

Depending on the site, recorded flow was below the 99th percentile for most sites compared to Streamstats estimations within the month assessed (Table 5). A 99-exceedance flow percentile meant 99 percent of all Streamstats estimated flows were higher than the flow recorded during the site visit. Flow percentile was retrieved by comparing the flow measured in-field to data collected and estimated by Streamstats during the month monitored. Steamstats estimations are subjective, however, to measurements being made in much larger basins suggesting estimations could be overestimating for smaller drainage areas, like those where our sites are located. Five sites, all post restoration, measured at the 20th percentile and higher stream flow. Average stream discharges ranged from 0 to 2.8 ft^3/s and average in versus out flow ranged from -0.15 to 0.22 ft^3/s. Error in flow calculations could be +/- 0.05 ft/sec due to the Marsh-McBirney velocity reader.

The average estimated channel roughness ranged from 0.043 to 0.085 +/- 0.01. Manning's roughness coefficient is subjective based on my reference estimation sheet and the complex environment compared to a pre-engineered channel to which the method was originally developed for estimating the coefficient. Grain size, bed material, and riparian vegetation, especially those along the stream channel were important to consider when estimating n. For this, an error of +/- 0.01 was used. Average valley bottom width ranged from 10 to 117 m +/- 1 m and average channel width ranged from 0.77 to 5.18 m +/- 0.25 m (Table 5). Valley bottom length ranged from 80 to 712 m +/- 1 m and gradient along the reach ranged from 0.68 to 4.59 percent. Error for linear-based indicators were used by corresponding the scale to which each indicator was taken at.

Table 5. In-field and image-measured covariates for the 31 beaver-dam analog sites.

Site	Valley Bottom Width	Channel Width	Inundated Channel Length	Total Channel Length (m)	Valley Length (m)	Valley Bottom Gradient	# of Structures	N Coefficient	In vs Out Flow	Avg Flow	Flow Percentile
RRCR1*	174.63	5.18	330.62	382.91	254.84	2.04	5	0.075	-0.08	2.85	20
RRCR2*	29.60	2.03	266.11	290.95	167.08	4.42	8	0.07	-0.08	2.85	20
RRCR3	16.71	0.86	103.86	103.86	79.65	2.62	3	0.048	0.22	2.28	5
RRCR4	9.58	0.96	146.28	149.43	118.53	3.75	4	0.065	0.22	2.28	5
GC1	52.56	0.77	0	461.37	346	2.7	0	0.055	0	0	99
GC2	46.32	0.89	18.54	409.3	344.46	2.48	0	0.05	0	0	99
GC3	87.34	0.72	58.93	609.7	289.44	2.21	0	0.05	0	0	99
CM2019L	82.88	1.99	505	592.68	347.43	4.36	33	0.085	-0.02	0.0134	99
CM2019U	72.67	3.71	509	509	289	2.2	21	0.085	-0.15	0.59	5
CM2021L	81.70	1.33	569.64	999.18	711.9	3.02	0	0.075	0	0	99
CM2021U	90.45	2.03	310.7	503.78	438.76	2.19	0	0.07	0	0	99
LSWCD1	93.96	1.2	254.81	462.52	355.46	0.78	0	0.055	0	0	99
LSWCD2	116.53	1.03	693.15	1152.87	637.4	0.83	21	0.06	0	0	99
LSWCD3	86.36	1.78	915.83	1492.8	711.19	0.68	50	0.06	0	0	99
TC A	85.87	1.49	343.2	343.2	249.9	1.94	0	0.043	-0.019	0.09	99
TC B	81.74	1.81	395.85	438.14	228.78	3.18	0	0.043	-0.019	0.09	99
TC C	62.03	1.98	289.28	340.87	188.41	3.02	0	0.043	-0.019	0.09	99
TC D	42.44	1.45	486.96	653.98	382.21	3.04	0	0.043	-0.019	0.09	99
TC E	41.74	1.38	386.75	433.99	270.06	4.04	0	0.043	-0.019	0.09	99
CS A	63.53	2.18	413.27	612.77	336.9	2.19	0	0.05	0	0	99
CS B	85.48	2.11	338.13	898.88	415.58	2.93	0	0.05	0	0	99
CS C	55.15	1.27	519.7	720.15	345.75	2.02	0	0.05	0	0	99
CS D	39.54	1.52	134.21	625.74	295.07	2.35	0	0.05	0	0	99
CS E	41.58	1.38	378.7	479.81	321.65	2.79	0	0.05	0	0	99
CS F	100.64	1.13	536.88	692.04	270.17	2.31	0	0.05	0	0	99
CS G	70.95	1.25	0	573.96	285.75	1.85	0	0.05	0	0	99
HF A	82.20	1.53	290.69	378.59	289.1	2.99	0	0.045	0	0.013	99
HF B	47.53	1.94	458.26	501.35	314.67	3.03	0	0.045	0	0.013	99
HF C	38.44	1.45	401.86	487.22	329.28	3.25	0	0.045	0	0.013	99
HF D	49.57	1.61	290.82	614.37	364.42	3.02	0	0.045	0	0.013	99
HF E	100.49	1.32	478.66	575.48	229.71	4.59	0	0.045	0	0.013	99

Proportional area indicators relativized the area indicators by the total valley bottom area (Table 6). In relation to the other indicators, no site showed more than 5% of the valley bottom as inundation, wet riparian and potential channel. Percent total potential area, long-term potential recovery area, and total riparian area recorded the highest percentages with some sites experiencing > 70% for one or more of these indicators.

Table 6. Proportional area indicators of the valley bottom, structure density, sinuosity, and percent channel length wetted were calculated from measured values taken from imagery products or in-field measurements. Indicators are in percentages except structure density, which is number of structures per 100 meters, and sinuosity, which is unitless.

Site	Total Potential	Total Riparian	Total Inundation	Long-term Potential	Potential Channel	Short-term Potential	Woody Riparian	Wet Riparian	Structure Density	Sinuosity	Channel Wet
RRCR1	84.3	12.2	1.0	78.8	0.1	5.5	4.4	0.2	1.3	1.5	86.3
RRCR2	19.3	76.2	4.5	15.9	0.5	2.9	35.2	2.5	2.7	1.7	91.5
RRCR3	41.3	54.3	3.0	34.1	0.0	7.3	3.4	4.5	2.9	1.3	100.0
RRCR4	35.2	64.0	0.8	27.9	0.0	7.3	37.0	0.8	2.7	1.3	97.9
GC1	43.2	53.2	0.0	34.6	0.5	8.0	7.4	0.7	0.0	1.3	0.0
GC2	35.3	63.2	0.1	30.0	0.0	5.3	11.0	1.4	0.0	1.2	4.5
GC3	42.8	55.3	0.1	35.4	0.2	7.3	15.8	1.5	0.0	2.1	9.7
CM2019L	45.1	54.7	0.2	37.8	0.0	7.2	0.0	2.9	5.6	1.7	85.2
CM2019U	27.3	69.9	0.4	22.8	0.0	4.5	0.0	9.5	4.1	1.8	100.0
CM2021L	23.8	72.4	0.0	19.0	0.1	4.7	0.0	2.4	0.0	1.4	57.0
CM2021U	33.1	66.9	0.0	30.0	0.0	3.1	0.0	1.3	0.0	1.1	61.7
LSWCD1	93.1	6.7	0.2	86.9	0.2	6.0	0.3	0.1	0.0	1.3	55.1
LSWCD2	90.4	9.4	0.2	86.2	0.1	4.0	3.0	0.2	1.8	1.8	60.1
LSWCD3	28.3	71.6	0.0	23.7	0.1	4.5	3.2	5.6	3.3	2.1	61.3
TC A	89.8	8.1	0.7	81.2	0.1	8.5	1.3	0.0	0.0	1.4	100.0
TC B	71.0	28.2	0.8	61.6	0.2	9.3	4.7	0.4	0.0	1.9	90.3
TC C	56.7	39.6	0.9	52.9	0.1	3.6	6.3	0.6	0.0	1.8	84.9
TC D	45.3	51.4	1.1	41.8	0.6	2.9	10.9	0.3	0.0	1.7	74.5
TC E	53.0	46.2	0.8	45.7	0.2	7.1	22.4	0.1	0.0	1.6	89.1
CS A	84.1	14.9	1.0	76.3	0.6	7.2	1.9	0.4	0.0	1.8	67.4
CS B	82.5	16.1	0.5	68.2	1.4	13.0	4.4	0.2	0.0	2.2	37.6
CS C	53.5	44.7	1.8	43.3	0.4	9.8	13.2	1.6	0.0	2.1	72.2
CS D	66.1	27.3	0.7	45.5	1.6	19.0	13.4	0.2	0.0	2.1	21.4

CS E	41.9	56.3	0.6	36.5	0.2	5.2	37.1	0.2	0.0	1.5	78.9
CS F	68.2	27.4	0.3	61.1	0.2	6.8	9.5	1.9	0.0	2.6	77.6
CS G	82.1	15.9	0.0	65.0	1.4	15.7	10.7	0.0	0.0	2.0	0.0
HF A	85.9	12.4	0.7	82.5	0.7	2.8	5.6	0.0	0.0	1.3	76.8
HF B	59.9	38.8	1.3	47.3	0.8	11.7	21.9	0.1	0.0	1.6	91.4
HF C	62.2	36.1	1.6	52.4	1.1	8.7	16.6	0.1	0.0	1.5	82.5
HF D	70.3	27.4	0.3	62.7	1.5	6.2	16.8	0.1	0.0	1.7	47.3
HF E	42.9	56.2	0.1	38.2	0.1	4.6	35.9	0.8	0.0	2.5	83.2

High correlations were found between percent total potential and total riparian (ρ = -0.997), percent total potential and long-term potential (ρ = 0.983), and long-term potential and total riparian area ρ = -0.977 (Table 7). Percent wet riparian and structure density showed a strong correlation as well with ρ = 0.704. Sinuosity displayed the least correlation compared to all other indicators ranging from ρ = -0.109 to 0.301.

Table 7. Correlation matrix comparing indicator values for all sites.

(High Correlation; *Low Correlation)*	Total Potential	Total Riparian	Total Inundation	Long-term Potential	Potential Channel	Short-term Potential	Woody Riparian	Wet Riparian	Structure Density	Sinuosity	Channel Wet
Total Potential	1.000										
Total Riparian	**-0.997**	1.000									
Total Inundation	*-0.188*	*0.162*	1.000								
Long-term Potential	**0.983**	**-0.977**	*-0.188*	1.000							
Potential Channel	0.391	-0.412	*0.046*	0.274	1.000						
Short-term Potential	0.343	-0.362	*-0.064*	*0.170*	**0.650**	1.000					
Woody Riparian	-0.327	0.326	0.326	-0.348	*0.099*	*0.009*	1.000				
Wet Riparian	**-0.575**	**0.572**	*0.091*	**-0.552**	-0.385	-0.254	-0.240	1.000			
Structure Density	-0.387	0.396	0.205	-0.360	-0.367	-0.217	*-0.098*	**0.704**	1.000		
Sinuosity	*0.099*	*-0.109*	*-0.100*	*0.045*	0.249	0.301	*0.129*	*0.082*	*-0.047*	1.000	
Channel Wet	*-0.072*	*0.079*	0.452	*0.000*	-0.415	-0.378	0.142	0.221	0.362	*-0.097*	1.000

Manning's roughness coefficient was only slightly correlated with percent total riparian (R^2= 0.1631, Figure 12a) and percent wet riparian area (R^2=0.3292, Figure 12b). No correlation was found between Manning's roughness coefficient and sinuosity (R^2=0.0333, Figure 12c). Percent total riparian area within the valley bottom had a weak to no correlation with slope (R^2=0.1384, Figure 13), suggesting sites with higher slope had a higher percent total riparian area.

Correlations between some indicators changed when looking at pre- versus post-installation sites (see Appendix B for full pre/post correlation information). The pre-installation site correlation between percent channel length wet and percent total inundation of ρ = 0.57 indicated that wet channel area corresponded with inundation area. The post-installation sites showed more moderate correlations including percent bare channel and percent total inundation, percent woody riparian and percent total inundation, percent woody riparian and percent bare channel, sinuosity and short-term potential recovery area, and percent channel length and sinuosity with ρ = 0.67, ρ = 0.53, ρ = 0.50, ρ = -0.68 and ρ = -0.72, respectively. However, this could be due to the small number of post-installation sites (n=8). Structural density also correlated only moderately with a few indicators including percent total potential recovery area, percent total riparian, percent long-term recovery area, and percent wet riparian area with ρ = -0.55, ρ = 0.59, ρ = -0.57, and ρ = 0.56, respectively indicating that sites show relationship to the top three indicators due to the large size of their areas in relation to the other proportional-area indicators, but the moderate positive relationship between density and wet riparian and obvious relationship similar to increasing the channel roughness coefficient.

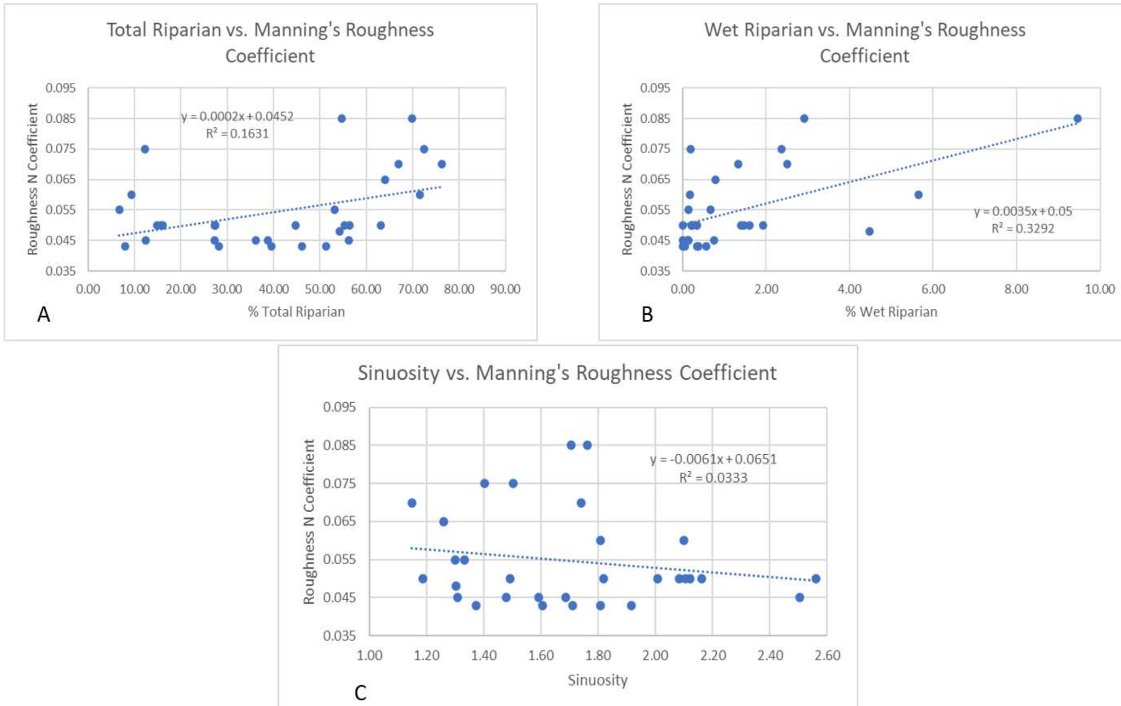

Figure 12. Relationship of Manning's roughness coefficient to percent total riparian (A), percent wet riparian (B), and sinuosity (C) for all 31 sites.

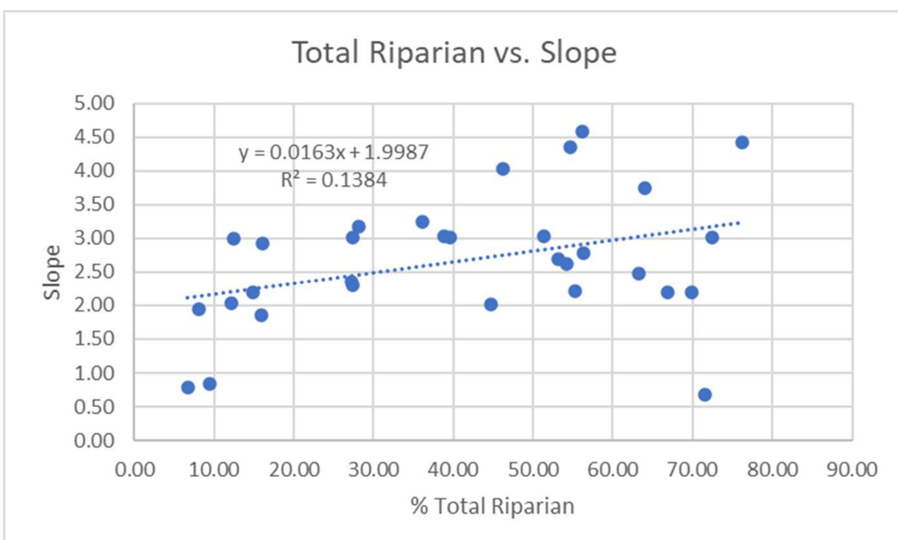

Figure 13. Scatterplot of the percent total riparian within the valley bottom vs slope for all 31 sites.

Pre/Post Analysis:

Pre-installation sites were characterized by a lower percent channel inundation, percent wet riparian area, percent total inundation, and percent total green riparian area than post-installation sites (Table 8). Pre-installation sites also had higher percent potential channel area, percent short-term potential recovery area, long-term potential recovery area and total potential recovery area than post-installation sites. Pre- and post-installation sites did not show significant differences in sinuosity or percent area of woody riparian.

Table 8. Mean indicator estimates (90% confidence interval in parentheses) for pre-installation sites and post-installation sites.

	Pre-installation Sites	**Post-installation Sites**
Total n=31	n=23	n=8
Channel Wet (% length)	59.3 (47.9 – 70.7)	85.3 (74.4 – 96.1)
Sinuosity	1.73 (1.58 – 1.87)	1.65 (1.46 – 1.83)
Structure Density (structures/100m)	N/A	3.06 (2.17 – 3.95)
Wet Riparian (% area)	0.628 (0.378 – 0.878)	3.27 (1.13 – 5.41)
Woody Riparian (% area)	11.6 (7.9 – 15.3)	10.8 (0.2 – 21.3)
Bare Channel (% area)	0.528 (0.343 – 0.712)	0.103 (-0.001 –0.206)
Short-Term Recovery Area (%)	7.69 (6.22 – 9.15)	5.41 (4.28 – 6.55)
Long-Term Recovery Area (%)	52.1 (45.4 – 58.8)	40.9 (23.1 – 58.7)
Total Potential (% area)	60.3 (53.2 – 67.4)	46.4 (28.6 – 64.2)
Total Inundation (% area)	0.589 (0.400 – 0.779)	1.260 (0.169 – 2.350)
Total Riparian (% area)	37.6 (30.5 – 44.7)	51.6 (33.9 – 69.2)

Pre/Post Multivariate Analysis:

Principal coordinates analysis showed that the first 4 principal coordinates accounted for 93.5% of total variation. Accordingly, other principal coordinates were dropped from further consideration (Table 9). Based on the loadings on the original indicators (Table 10), interpretations of the principal coordinate axes are as follows:

- MDS1 – Percent total potential and percent bare channel vs percent total riparian (as percent total riparian increases, the others decrease)
- MDS2 – Percent channel length wetted
- MDS3 – Percent woody riparian and percent channel length wetted
- MDS4 – Also percent woody riparian

The fact that MDS4 had the same interpretation as MDS3 and only accounted for 3.6% of total variation in the data suggests that only 3 principal coordinates may be necessary. None of the other indicators loaded strongly on the coordinates.

Table 9. Eigenvalues and proportion of total variation explained from the first six principal coordinates (MDS1 through MDS 6) of the 31 beaver-dam analog sites.

	MDS1	**MDS2**	**MDS3**	**MDS4**	**MDS5**
Eigenvalue	0.9754	0.4693	0.15419	0.06346	0.03553
Proportion Explained	0.5486	0.264	0.08673	0.0357	0.01998
Cumulative Proportion	0.5486	0.8126	0.89933	0.93503	0.95501

Pre- and post-installation sites showed similar values for the first principal coordinate (MDS1), suggesting that they had similar amount of total potential, total riparian, and percent long-term recovery area (e.g., pre-installation sites tended to have more total potential, less total riparian, and less percent channel length than post-installation sites).

Table 10. Loadings of the first five principal coordinates on the original indicators.

	MDS1	**MDS2**	**MDS3**	**MDS4**	**MDS5**
% total recovery	-1.23557	0.04215	-0.00721	0.07049	0.074647
% total riparian	1.227757	-0.03056	-0.02378	-0.06151	-0.054136
% total inundation	0.009536	0.01901	0.030175	-0.0109	-0.003739
% long-term recovery	-1.13364	0.14399	-0.09943	0.07652	0.256471
% channel potential	-0.01348	-0.01032	0.006957	-0.01596	-0.008770
% short-term potential	-0.08846	-0.09152	0.085261	0.00994	-0.173054
% woody riparian	0.207975	-0.01525	0.545538	-0.4798	0.139968
% wet riparian	0.063824	0.02503	-0.03481	0.05889	-0.068518
% channel inundated	0.189416	1.44536	0.616176	0.19548	0.179048

Pre- and post-installation sites showed the most separation along MDS2, which was related to percent of the channel length wetted. There was little difference in the MDS3 and MDS4 when comparing pre- and post-installation sites.

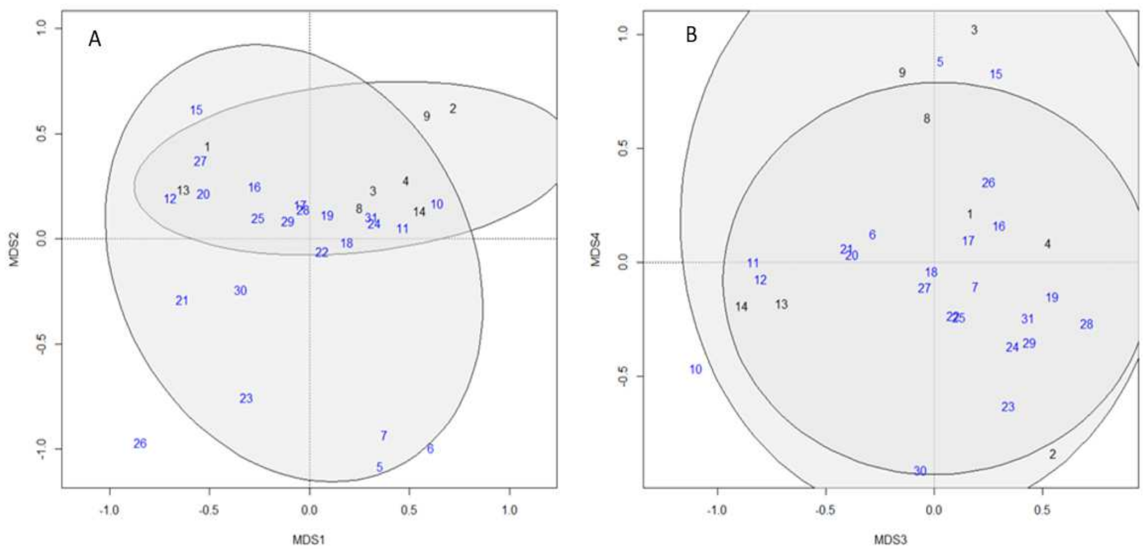

Figure 14. Plots of the 31 beaver-dam analog sites according to principal coordinates axes one and two (MDS 1 vs. MDS 2, Panel A) and axes three and four (MDS 3 vs. MDS 4, Panel B). Blue numbers indicate pre-installation sites, black numbers are post-installation sites. Ellipses represent 90% confidence intervals for the different types.

Ecosystem Multivariate Analysis:

Ecoregion plots highlighted separation between sites based on principal coordinate values (Figure 15). The MDS2 (percent of the channel length wetted) showed the most separation between the Foothill Shrublands sites and sites in the other two ecoregions. The MDS3 (percent woody riparian and percent of the channel wetted) showed each ecoregion having its own range.

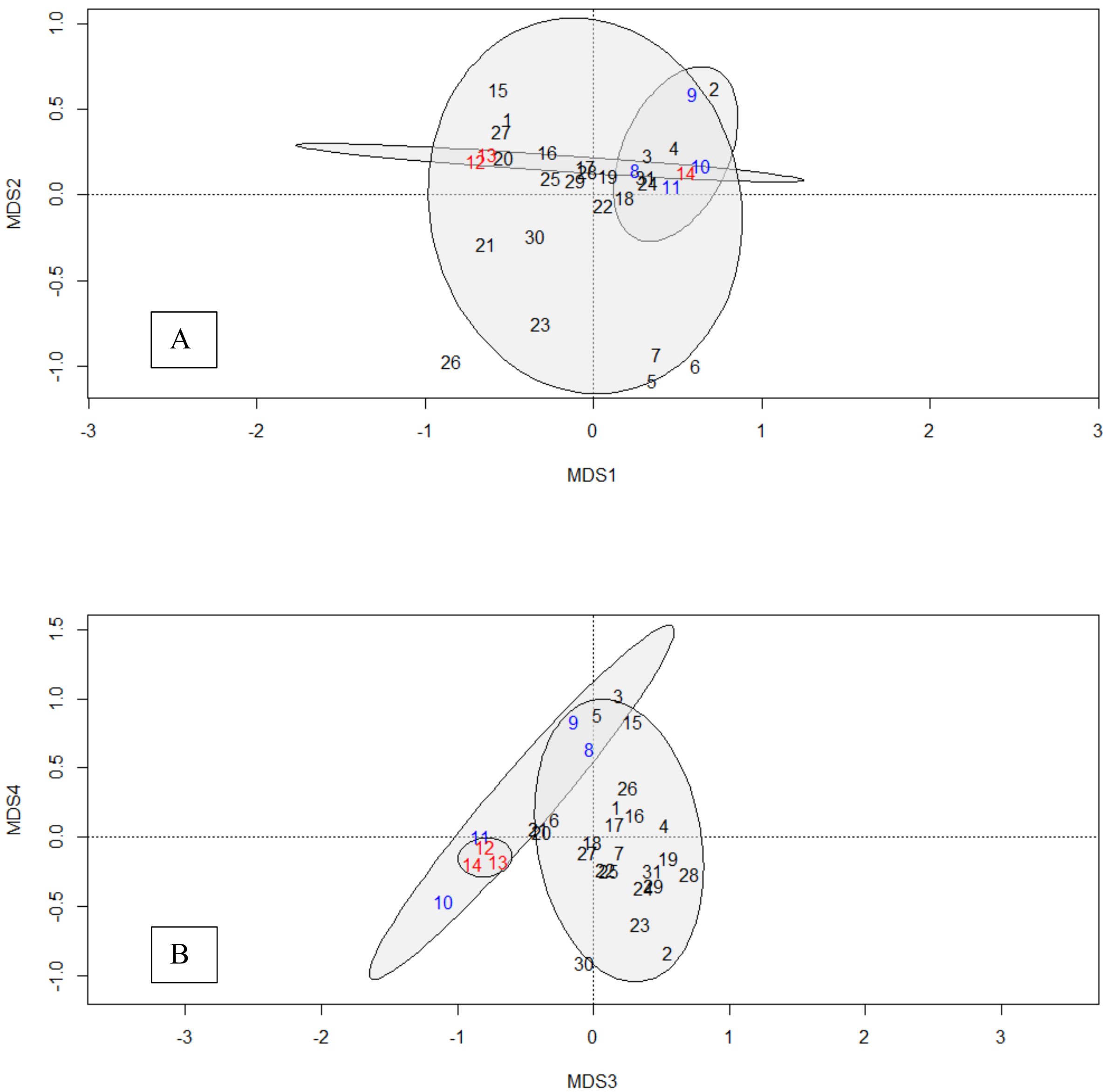

Figure 15. A) Plots of the 31 beaver-dam analog sites according to principal coordinates axes one and two (MDS 1 vs. MDS 2). B) Plots of the 31 beaver-dam analog sites according to principal coordinates axes three and four (MDS 3 vs. MDS 4). Blue numbers indicate sites in the Blue Mountains Forest ecoregion, red numbers are sites in the North Idaho Forest ecoregion, and black numbers are sites in the Foothill Shrublands ecoregion. Ellipses represent 90% confidence intervals for the different types.

Discussion

The proposed protocol developed and implemented on 31 reaches across Idaho proved to be an effective quantitative method to begin monitoring the effectiveness of using BDAs as a restoration technique at the reach scale. This study adds to the knowledge of how to measure effectiveness of BDAs across different spatial and temporal scales while leveraging the benefits of UAS as a means of collecting data. Considering the limitations of sample size and number of sites with BDAs installed, results and interpretations are best suited toward project sites within the ecoregions and at similar locations to those of the sites sampled. However, findings should also highlight to other project managers from different systems how expectations and outcomes of BDA can be measured and tracked. From the research and background information gathered and results presented, the selected group of indicators are the best representations of possible changes to the key processes influencing riverscape formation, evolution, and ecosystem services.

Correlation matrices were insightful in understanding the possible relationships between indicators. Strong relationships between percent total recovery area and total riparian, percent total recovery area and long-term recovery area, and long-term recovery area and total riparian area indicate information redundancy (i.e., measuring one is representative of measuring others). This suggests measuring total riparian area is sufficient to collect a measurement of both total potential area and long-term potential area. These three percent areas covered the majority of total valley bottom area (Table 6). This correlation was expected and reaffirms the process of measuring percent total riparian area.

Comparing correlations of indicators from pre- and post-installation sites provided an idea of which indicators may be impacted by BDA installations. Percent short-term potential recovery area and percent bare channel correlation for pre-installation sites was $\rho = 0.67$ and for post-installation sites $\rho = -0.73$ indicating BDA installation effects the relationship between short-term recovery area and bare channel area. BDAs likely also impact at least one of these two indicators after being installed. An increase in total inundation should ultimately increase woody riparian area, so an increase in bare channel should not correlate with an increase in woody riparian area in the long term. The observed high correlation between these two indicators here is likely due to low sample size, the short timeframe of the study, or post-installation sites not being representative of the projects. Percent short-term potential recovery area and sinuosity showed differences between pre- and post-installation correlations as well. The short-term potential area is more likely to have an effect directly post installation due to the short-term recovery being classified as area being impacted by restoration in 1 to 2 treatments. Sinuosity could also be indirectly impacted by the installation of structures, but, in theory, impacts would be longer-term. Considering our sites represent short-term changes due to the low range in treatment ages, percent wet riparian and percent woody riparian along with percent total riparian showing no differences between the pre-site and post-site correlation matrices could indicate they are long-term indicators of change, compared to indicators representing short-term impacts.

Indicators showing a significant difference between mean percentages pre- and post-installation (Table 8) suggest it is possible to begin measuring BDA effects in the short-term, including percent channel length wet, percent wet riparian, percent bare channel, and percent short-term potential recovery area. Little difference in sinuosity and percent woody riparian could be due to the short range of treatment ages indicating these could be measures of long-term change instead of short-term. Indicators showing a slight difference in mean percentages between pre- and post-installation sites may be useful as measures for longer-term potential effects, and included percent long-term potential recovery area, percent total potential recovery area, percent total inundation, and percent total riparian.

My results suggest that BDA installation directly increases total riparian and total inundation, and decreases percent total potential recovery area, long-term potential recovery area, and short-term potential recovery area. They also suggest BDA installation directly decreases the percent bare channel, increases percent wet riparian, and increases the percent channel length wet. These results generally support expectations practitioners have suggested concerning short-term impacts from using BDAs at the reach scale. Expectations suggest percent woody riparian and sinuosity should also increase post BBA installation, but due to the 3-year range of treatment ages, results found here cannot support or deny long-term expectations. Indicator interpretations are subject, however, to the study's sample size (n = 8 post-installation sites).

The principal coordinates analysis suggested percent total potential recovery area, percent long-term recovery area, and percent total riparian area which loaded most heavily on the first principal coordinate accounted for approximately 55% of the observed variability in the data, followed by percent channel length wet and percent woody riparian which loaded heavily on the second principal coordinate. The main differences between the sites are related to overall potential followed by total amount of wet channel and woody riparian vegetation. In terms of monitoring, this could be useful because the first principal coordinate may account for broader-scale differences between different types of sites and the lower principal coordinates then reflect indicators that would be expected to be impacted by BDA installation. This matches well with the proportional-area indicators in Table 6 suggesting for my reaches the largest cover types were percent total potential recovery area, percent long-term recovery area, and percent total riparian area. The remaining principal coordinates include less influential indicators suggesting they are either less sensitive or useful for monitoring changes due to BDA installations or the indicators have not had enough time to represent effects due to my low range of treatment ages.

Utilizing the same principal coordinates, plots were made delineating the sites by ecoregion as well highlighting the influence each ecoregion had on the principal component analysis and each principal coordinate. Where MDS1 and MDS2 were graphed, the ordination plot suggests the sites of each of the three systems monitored were equally influenced by the principal components. Where MDS3 and MDS4 were graphed, this plot showed the sites in the Foothill Shrublands Ecoregion slightly different than those of the Canyons and Dissected Highlands and Northern Idaho Hills ecoregions across the MDS3 axis suggesting there were slight differences between these systems and their proportion of woody riparian within the valley bottom and the percent channel wet. Interpretations could be explained by riparian forests in each ecoregion being different, how I categorized cover types, the sample size, or sites potentially not being representative of the average ecoregion effect.

This test of the BDA monitoring protocol highlighted which indicators are important to retain and those that could be omitted. High correlations between the three indicators loading heavily on the first principal coordinate, suggest only one of these indicators, percent total riparian, is needed to effectively monitor changes. With a significant difference between pre and post installation site means, five differences greater than 0.5 between pre- and post-site correlation matrices and loading highly on the second principal coordinate, the percent channel length wet is the most obvious indicator that is an indicator for short-term changes and did report impacts of BDA use. Other indicators show positive results, but no other indicator proved to be solely a short-term indicator of change. With our ecoregion analysis, ecosystem specific indicators highlighted differences to be aware of for sites within different ecoregions, like how percent woody riparian was different proportionally within the valley bottom between sites of different ecoregions. Percent woody riparian area could benefit from a longitudinal study because it would say definitively whether there was a change from pre- to post-installation. With the space-for-time design I did, I could have missed this change because the effect of a BDA on woody riparian would depend on how much was present at a site to begin with. The study's design is likely insensitive to this indicator, even over the long-term.

Most sites included in this study had low stream flow and few or no structures installed at the time of my visit (Table 5, Appendix A). Sites used in this study were characteristic of mid to upper watershed, low order streams across Idaho during the late summer season. With low flow, bare channel area was present, but it is possible that at every stage in Cluer & Thorne's (2014) stream evolution model, the presence of bare channel could be due simply to the hydrologic regime.

Unexpected results arose comparing calculated proportional area indicators to certain site-specific indicators. Slope showed little to no correlation with the other indicators (Figure 13). This could be a result of selection bias in the sites (i.e., only low-gradient streams were included in this study) or the use of BDAs and similar techniques are restricted to low gradient reaches and systems restricted by a valley bottom and hydrologic dominated forces. Flow percentile showed no correlation with other indicators likely because most sites recorded flow at or below the 99th percentile (i.e., 99% of all recorded or estimated measurements of flow in Streamstats during the month assessed were greater than the flow I recorded; Table 5). Future monitoring should establish base flows for each site and also consider that an increase in area of inundation could simply occur due to greater flow during that monitoring visit rather than marking restoration success. Thus, an increase in one indicator might be due to the site-specific indicators being different from baseline monitoring.

Manning's roughness is useful for determining how channel parameters influence stream velocity and corresponding flow (Coon, 1998). In theory, the roughness of a channel should increase due to the installation of structures like BDAs and natural beaver dams. With the roughness coefficient relating to conditions effecting flow, this indicator should be better used as a covariate rather than indicator of success. The most interesting comparison came from comparing the roughness coefficient to percent wet riparian, where Figure 12 highlights a possible nonlinear relationship between them. Increases in wet riparian area may be due to an increase in channel roughness over the short term because the installation of structures directly results in an increase in the channel's ability to slow and redirect stream flow across the floodplain enabling more water to reach the riparian areas. When comparing the roughness coefficient to sinuosity, there was no correlation, suggesting there might not have been enough time for these two geomorphic indicators to show a relationship. Three years does not give good insight on how long-term geomorphic processes respond to BDAs.

This protocol was developed to assess and monitor conditions of a reach that relate to three key processes influencing riverscape dynamics (Hydrologic, Geomorphic, & Ecologic) and quantifiably represent effectiveness of using BDAs at the reach scale. Specifically, this protocol can be used to document base conditions and make spatially-explicit predictions about which indicators might change. The protocol can also be used for consecutive monitoring of changes before, following, and after installation of BDAs and similar structures. While the use of BDAs is constant throughout the sites used in my study, stream and riparian restoration techniques of all sorts situated in low order stream systems have the potential to be monitored similarly. While the main goal of this protocol concerns the effectiveness of using BDAs, the protocol is also suited to monitor indicators representing riverscape dynamics highlighting the potential ecosystem services produced. Essentially, it can be used to monitor indicators related to a reach's hydrologic regime, geomorphic condition, and ecological threshold over time providing a quantifiably derived report of conditions and map of reach. The protocol can be used to interpret if the restoration of these areas improves resiliency and ecosystem function value stabilizing ecosystem process by increasing productivity of riparian plant species and/or native aquatic and terrestrial species habitat. The UAS-derived image products and protocol described above will facilitate consecutive monitoring of BDA effectiveness through detailed comparisons over time. The delineated map of indicators can be used directly by land managers to understand the current state of projects and how they are changing over time.

Limitations of this procedure are similar to most other monitoring protocols where quality assurance, quality control, and limiting bias is necessary for effective monitoring.

Delineations of each area indicator were subjective based on how each cover type was described in the methods. The use of AI is a future possibility limiting this subjectivity increasing the precision of collecting each area-based indicator. Storage and computer processing of UAS imagery and derived products is not trivial and must be considered when implementing a UAS-based protocol. Number of photographs and file sizes of derived products are dependent on the flight mission details and specifically the number of photos per site. For this study, number of photos ranged from 150 to over 1000 photos per site (Table 4). With the use of a UAS-based monitoring protocol, storage dedicated to large digital datasets and time specifically focused on image processing stages are requirements on top of acquiring the UAS and image processing software.

Sources of monitoring sites depended on project area size, location, and resources at hand. The goal would be to monitor the entire project area, but limitations are inevitable when dealing with inaccessible terrain and limited resources. Stakeholders can help frame feasible monitoring plans that might focus resources to certain areas, while other areas are excluded all together. These details should be in the design of the monitoring objectives where perspectives from all those involved and effected are valued and considered. While each reach is monitored, project changes can be derived from monitoring across the project area and averaging the resulting differences. Analysis of monitoring results should not focus solely on the prioritized objectives and correlating indicators but apply a broader scope to understanding how the ecosystem is changing the indicators of importance.

Developing a product that can be used immediately was a primary goal of this study. By talking to managers and understanding limitations in budget and time, we selected a minimal set of indicators that could be collected with the least amount of equipment and also considered the effort and time required for each step. Depending on the monitoring objectives, the protocol can be implemented to report changes seasonally and/or annually. Using the protocol, each site consisted of a pre-installation and monitoring planning stage lasting an hour to a few weeks, site visitation stage lasting 1-2 hours for a 300-meter reach, image processing taking 1 day to a week depending on the size of the site and number of photographs acquired, indicator calculation and map making stage lasting 1-2 hours depending on size of site, and finally the analysis stage lasting 15 minutes. Even though the timeline is short, the site visitation, image processing, and indicator calculation/map making stages are completed per site.

While seasonal monitoring could prove to be vital in informing managers of restoration success, annual monitoring could potentially provide information concerning both short-term and long-term effectiveness of using BDAs and other beaver related restoration. Monitoring at multiple times throughout a year could prove beneficial for collecting season changes and variation, but annual monitoring around times of low annual flow provides details on late season flow conditions important to many natural resource managers. Baseflow conditions provide insight on habitat suitability for riparian and stream systems in a given stream segment (Choi et al., 2018). At lower flows, UAS imagery products represented more of the channel geometry and vegetated areas that are normally inundated most the year. At high flows, monitoring represents maximum area of inundation structures are forcing across the floodplain. Short-term potential recovery area would be at its lowest during high flows due to inundation and riparian areas being at their maximum extent across the floodplain. Monitoring at both high and low flows could allow hydraulic modeling enabling managers to gain extensive information concerning current and future water resources impacted from restoration.

Future directions should focus broadly on understanding impacts from BDAs and exploring the indicators in the protocol for a better means of acquisition. More research is needed in understanding impacts and how to monitor the effectiveness of BDAs and similar techniques across different scales and landscapes. The restoration of any system involves understanding that system and at what stage the system is in at the time of monitoring. The digital elevation model was used extensively as a helpful tool to locate indicators such as valley bottom area and woody riparian area boundaries. Tools for quantitatively delineating these indicators based on elevation changes and patterns within specific systems are needed, specifically in the Foothill Shrublands ecoregion. Vegetation indices could be helpful to provide more of a precise quantitative measurement of specific vegetation indicators like total, wet, and woody riparian areas. Because vegetation across the different ecoregions reflected different indices, I was unable to make a vegetation index that covers each vegetation category within a specific spectral range. This could be made for each project area considering the indices might be different at different times of the year.

Conclusion

This study investigated correlations between indicators found to represent key processes influencing how riverscapes change and produce ecosystem services, while moderately supporting current BDA expectations considering the short time since their installation. The work presented here highlights the need for managers to understand site-specific covariates that influence indicators when interpreting results and making decisions related to the project success rate. Through the study, correlations between indicators and covariates suggested key functions and processes of a riverscape are intertwined and changes to one (e.g., installing artificial beaver dams) has the potential to alter the system like that of beavers and their dams.

As technology advances and more tools for measuring natural systems become available, monitoring protocols should leverage the benefits of using multiple tools to assess and monitor changes in natural resources over time. UAS provided a fine-detailed, high-resolution look at BDA-effectiveness indicators such as vegetation structure and channel morphology. Additionally, satellite imagery may provide a historical record and timeseries information to look at broader landscape-level changes. Each of these information sources augment the limited set of indicators on BDA effectiveness that can be measured in the field. Accordingly, in management of riparian systems and monitoring effectiveness of BRR techniques, it will be key to combine field, satellite, and drone imagery to obtain information from multiple scales to enable a more complete representation of how ecosystems are being impacted by multi-level BRR projects.

This study highlights the need for more supporting data and standardized monitoring to justify expectations and overall effectiveness of BDAs across scales and systems. While broad generalizations are being made concerning BDA impacts, project managers should be aware of the lack of information detailing the changes to expect across different landscapes, temporal scales, and degradation levels when using BDAs. The implementation of standard protocols for measuring the effectiveness of BDAs and related BRR techniques is needed to address this information gap.

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Appendix A. Raw data of indicator values before calculations were made to create proportional area indicators within the valley bottom.

Site	Signs of Beav	Beaver Dar	Year Insta	VB_Area	Inaccessible VB A	Total Active Riparian A	Inundation Area	Potential Recovery	Woody Riparian A	Green Active	Wet Riparian	Pool Area	Free Flow	Bare Channel	Short-term	Long-term
RRCR1	Yes	Yes	2018	45678.60	1125.44	5587.60	444.93	38520.63	1999.43	3497.64	90.53	428.70	16.23	41.27	2490.37	35988.99
RRCR2	No	Yes	2018	5237.98	0.00	3992.38	235.21	1010.39	1844.93	2016.27	131.18	171.99	63.22	24.28	152.81	833.30
RRCR3	No	No	2018	1562.15	21.24	847.83	47.46	645.62	53.03	724.82	69.98	18.77	28.69	0.00	113.57	532.05
RRCR4	No	No	2018	1357.66	0.00	869.09	10.69	477.88	501.99	356.51	10.59	1.08	9.61	0.00	99.47	378.41
GC1	No	No	2021	18361.55	664.58	9765.39	0.00	7931.58	1352.44	8288.55	124.40	0.00	0.00	99.91	1477.97	6353.70
GC2	No	No	2021	16178.46	233.59	10224.23	13.44	5707.20	1780.72	8217.23	226.28	13.44	0.00	2.89	854.85	4849.46
GC3	No	No	2021	26213.22	465.36	14504.24	17.90	11225.72	4148.68	9972.46	383.10	17.90	0.00	44.33	1912.55	9268.84
CM2019L	No	No	2019	31434.71	0.00	17204.48	53.67	14176.56	3.54	16286.13	914.81	47.97	5.70	12.91	2276.69	11886.96
CM2019U	No	No	2019	22088.78	516.92	15448.64	87.07	6036.15	3.66	13355.65	2089.33	66.62	20.45	0.00	1000.47	5035.68
CM2021L	No	No	2021	60723.50	2316.71	43963.12	2.52	14441.15	4.29	42518.62	1440.21	2.52	0.00	32.42	2852.26	11556.47
CM2021U	No	No	2021	41564.86	0.00	27803.20	7.73	13753.93	0.00	27246.68	556.52	7.73	0.00	2.52	1294.21	12457.20
LSWCD1	No	No	control	32648.88	0.00	2194.65	55.10	30399.13	113.86	2034.02	46.77	55.10	0.00	63.12	1973.13	28362.88
LSWCD2	No	No	2019	77988.02	0.00	7360.37	139.17	70488.48	2331.21	4896.88	132.28	139.17	0.00	108.21	3152.92	67227.35
LSWCD3	No	No	2018	64682.52	52.28	46307.24	21.62	18301.38	2044.11	40608.71	3654.42	21.62	0.00	56.50	2920.11	15324.77
TC A	No	No	2021	21403.04	318.89	1723.97	146.16	19214.02	282.55	1441.42	0.00	90.34	55.82	14.36	1824.42	17375.24
TC B	No	No	2021	19595.68	0.00	5523.50	150.40	13921.78	911.61	4539.06	72.83	92.61	57.79	32.19	1816.52	12073.07
TC C	No	No	2021	12148.70	344.35	4807.53	103.41	6893.41	767.54	3970.23	69.76	60.52	42.89	18.18	443.34	6431.89
TC D	No	No	2021	16741.60	383.48	8603.02	176.21	7578.89	1820.12	6725.64	57.26	81.11	95.10	95.18	482.92	7000.79
TC E	No	No	2021	11961.11	0.00	5524.60	96.21	6340.30	2677.45	2839.75	7.40	48.35	47.86	27.56	852.12	5460.62
CS A	No	No	2020	21273.71	0.00	3162.88	214.51	17896.32	399.04	2688.99	74.85	214.51	0.00	131.48	1540.96	16223.88
CS B	No	No	2020	36956.17	322.26	5948.13	180.84	30504.94	1625.98	4239.37	82.78	180.84	0.00	506.92	4791.45	25206.57
CS C	No	No	2020	18665.63	0.00	8345.15	337.53	9982.95	2461.23	5585.21	298.71	337.53	0.00	70.93	1838.05	8073.97
CS D	No	No	2020	12188.44	724.54	3323.05	81.32	8059.53	1632.93	1661.49	28.63	70.65	10.67	190.63	2317.60	5551.30
CS E	No	No	2020	15716.37	173.20	8851.89	101.97	6589.31	5827.49	2990.77	33.63	101.97	0.00	26.46	818.99	5743.86
CS F	No	No	2020	27139.41	1127.87	7433.83	68.86	18508.85	2590.99	4317.51	525.33	68.86	0.00	67.75	1858.75	16582.35
CS G	No	No	2020	21830.66	435.81	3470.03	0.00	17924.82	2331.58	1138.45	0.00	0.00	0.00	300.42	3433.62	14190.78
HF A	No	No	2020	20936.50	187.70	2602.85	156.59	17989.36	1167.19	1435.66	0.00	87.85	68.74	139.23	582.32	17267.81
HF B	No	No	2020	15140.57	0.00	5878.74	199.72	9062.11	3308.91	2551.90	17.93	139.06	60.66	126.59	1767.17	7168.35
HF C	No	No	2020	14238.10	0.00	5142.68	233.78	8861.64	2370.11	2752.10	20.47	227.59	6.19	161.46	1240.26	7459.92
HF D	No	No	2020	21040.34	412.68	5758.29	71.49	14797.88	3542.77	2188.17	27.35	71.49	0.00	310.08	1303.88	13183.92
HF E	No	No	2020	24306.39	179.80	13668.87	30.58	10427.14	8719.87	4765.51	183.49	23.00	7.58	32.16	1120.86	9274.12

Appendix B. Pre & Post correlation matrices comparing indicators against each other.

post-installation sites

	Total Potential	Total Riparian	Total Inundation	Long-term Potential	Potential Channel	Short-term Potential	Woody Riparian	Wet Riparian	Structure Density	Sinuosity	Channel Wet
Total Potential	1.0000										
Total Riparian	-0.9974	1.0000									
Total Inundation	-0.3619	0.3055	1.0000								
Long-term Potentia	0.9982	-0.9962	-0.3511	1.0000							
Potential Channel	-0.1625	0.1376	0.6653	-0.1214	1.0000						
Short-term Potenti	0.0277	-0.0158	-0.2236	-0.0318	-0.7329	1.0000					
Woody Riparian	-0.3918	0.3816	0.5259	-0.3884	0.5039	-0.0938	1.0000				
Wet Riparian	-0.6240	0.6210	-0.0770	-0.6139	-0.2513	-0.1251	-0.3697	1.0000			
Structure Density	-0.5500	0.5781	-0.2175	-0.5672	-0.2406	0.2998	-0.2470	0.5579	1.0000		
Sinuosity	-0.1021	0.1325	-0.3069	-0.0607	0.3126	-0.6762	-0.3562	0.3497	0.2431	1.0000	
Channel Wet	-0.4300	0.3884	0.4543	-0.4548	-0.1503	0.4101	0.3291	0.2501	0.1895	-0.7182	1.0000

Pre-installation sites

	Total Potential	Total Riparian	Total Inundation	Long-term Potential	Potential Channel	Short-term Potential	Woody Riparian	Wet Riparian	Structure Density	Sinuosity	Channel Wet
Total Potential	1.0000										
Total Riparian	-0.9971	1.0000									
Total Inundation	0.1930	-0.1912	1.0000								
Long-term Potentia	0.9756	-0.9659	0.1713	1.0000							
Potential Channel	0.4270	-0.4526	0.1926	0.2818	1.0000						
Short-term Potenti	0.3678	-0.3946	0.1349	0.1554	0.6698	1.0000					
Woody Riparian	-0.3241	0.3313	0.1493	-0.3518	0.0524	0.0196	1.0000				
Wet Riparian	-0.6231	0.6112	-0.2926	-0.5909	-0.4916	-0.2781	-0.1724	1.0000			
Structure Density	NA	NA	NA	NA	NA	NA	NA	NA	1.0000		
Sinuosity	0.1322	-0.1545	0.0467	0.0519	0.2313	0.3789	0.3002	0.1498	NA	1.0000	
Channel Wet	0.1408	-0.1226	0.5668	0.2378	-0.3248	-0.3585	0.1480	-0.1748	NA	0.0055	1.0000