CWS TECHNICAL REPORT:

A Demonstration of the Carbon Sequestration and Biodiversity Benefits of Beaver and Beaver Dam Analogue Restoration Techniques in Childs Meadow, Tehama County, California

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A Demonstration of the Carbon Sequestration and Biodiversity Benefits of Beaver and Beaver Dam Analogue Restoration Techniques in Childs Meadow

Executive Summary

The primary goal of this demonstration project was to restore a portion of Childs Meadow, a 290-acre meadow complex near Lassen National Park in California, in order to increase carbon storage, improve water holding capacity, and increase populations of riparian birds and sensitive meadow-dependent species. The study used a modified Before-After-Control-Impact (BACI) design to test the impacts of two restoration treatments on carbon sequestration, hydrology, and sensitive species: cattle exclusion and cattle exclusion + beaver dam analogue installation. A positive control was located where beaver naturally occupy a portion of the meadow, and a negative control was located where cattle grazed at recent historic utilization levels. Two years of pre-restoration data were collected in 2015-2016, and three years of post-restoration data were collected in 2017-2019. Specific project objectives included: (1) quantify and evaluate changes in above and below ground carbon storage following habitat restoration treatments, (2) compare the within meadow carbon results from Childs Meadow to carbon sequestration values in existing restored and unrestored mountain meadows across the Cascade and Sierra Nevada range, and (3) measure the response of hydrogeomorphic conditions (e.g. groundwater, temperature, habitat) and two imperiled species (Cascades Frog and willow flycatcher) to restorative actions.

The largest observed effect of restoration treatments was the increase in vegetation and carbon sequestration associated with the cattle exclusion. The grazing effect on vegetation in unfenced areas was visually apparent and evidenced by data on plant biomass, height, and CO_2 uptake. Within the controlled experiment, vegetation that was fenced off and ungrazed grew on average 40 cm taller, contained approximately 1500 lbs/acre (170 g/m^2) more residual dry aboveground biomass, and net-stored about 300 grams more CO_2-Ceq per m^2. Analysis of satellite aerial imagery from 2017-2019 corroborated these results and showed higher NDVI (Normalized Difference Vegetation Index) values within the treatments and along the wetter stream channels in summer than outside the fenced exclusion in mesic areas where grazing was heaviest.

The effect of the BDA treatment was most notable in the local groundwater elevation data. The five years of the study from 2015-2019 included highly variable climate and precipitation conditions ranging from critically dry conditions in 2015 to the wettest year of record in 2017. As a result, variable surface and groundwater elevations were observed throughout the study area across years, but water elevations in the positive control study reach were highly mediated by the degree of beaver activity and groundwater elevations near the BDA ponds were higher when ponds were maintained. In particular, summer groundwater elevations near the natural beaver ponds were significantly higher in the drought year of 2015 when the beaver were actively maintaining their ponds, and statistically lowest in the wet year of 2017 when the dams were breached and not maintained. Similarly, summer groundwater elevations near the BDA ponds were 0.25 m-0.30 m higher at the end of the summer season in 2017 after installation than in 2016 pre-restoration, while groundwater elevations were not significantly different at the end of the season in 2016 and 2017 in the exclusion treatment reach without BDA ponds. In both the

study reaches with ponds, the influence of the ponds on groundwater elevations extended approximately 10-20 m lateral from the channel.

The impacts of the treatments on avian habitat were more subtle than the observed impacts on vegetation and water elevations. The highest territory densities of meadow focal bird species were 4.0 territories per ha in the positive control reach with beavers, while the treatments and negative control reaches had very low densities or no territories in all years. Results from habitat assessments at nests and random locations demonstrated strong selection by focal species for high shrub cover and low to moderate amounts of water cover within 5 m of the nest site. This combination of habitat attributes remained generally unavailable to birds in the negative control reach and the two treatment reaches in the four years of study monitoring, though the BDA treatment reach did provide standing water approaching that found in the positive control reach. The positive control reach illustrated the large potential of the treatment reaches to support bird habitat in a restored condition and the role of ponded water and shrubs in creating those conditions. As woody shrub vegetation height in particular increases over time in the two treatment reaches, avian habitat will become more suitable.

Similarly, the impact of the treatments on amphibian habitat was limited by the short study duration as well as confounding impacts of Chytridiomycosis (Bd) disease. Throughout the study, Cascades frogs (*Rana cascadae*) were predominantly found in the positive control reach and were closely associated with aquatic habitats adjacent to the beaver dams. This was most evident in 2015 when beavers maintained near constant water levels across the meadow even during severe drought conditions. After beavers disappeared from the reach in 2017, the frog population started to decline. Without active maintenance, some of the shallow backwaters that had been used by Cascades frogs for breeding dried before larvae had a chance to metamorphose, and we saw a reduced number of juvenile frogs. In 2018 and 2019, beaver returned to maintaining several of the dams and some frogs were seen nearby, however, Bd loads on frogs spiked during these years and apparently had devastating effects on the Cascades frog population. We recaptured fewer frogs and saw a near complete loss of juvenile frogs in 2019. In the BDA treatment reach, however, we observed juvenile Cascades frogs using the shallow backwater habitat created by the BDAs in the fall of 2017 and 2018 and found two Cascades frog egg masses in the reach in the spring of 2019. Over time, as the riparian habitat becomes more structurally diverse, we expect amphibian habitat conditions to improve.

Functioning as a pilot demonstration project, we prioritized sharing information about the Childs Meadow project to a diversity of audiences. We hosted field workshops and tours with the Department of Water Resources, Army Corps of Engineers, Bureau of Land Management, California Department of Fish and Wildlife, USDA Forest Service, and interested stakeholders. During these tours and our regular monitoring and maintenance activities, the project served as an outdoor classroom for process-based restoration training lead by members of our team. Overall, over 100 people were involved in touring Childs Meadow and learning about this project over the course of the study. The project further served as a pilot by sharing permitting documents and launching an additional project to guide beaver-based restoration throughout California to the most appropriate stream reaches. The results of this project will be used to inform additional large-scale restoration throughout the Childs Meadow complex and in other montane meadow locations throughout the region.

Introduction

In mountain watersheds, meadows and other wide floodplain and riparian areas represent only 25% of the river area, but store approximately 75% of the riverine organic carbon in floodplain sediment and coarse wood (Wohl et al. 2012). Due to extensive livestock grazing and widespread removal of beaver and willows, headwater meadows have transformed from multi-thread channels with seasonally active floodplains into single thread, incised channels that store less carbon and are lower in habitat quality for a diverse suite of meadow-dependent wildlife. In a study in the Rocky Mountains, Wohl (2013) estimated that in the past beaver meadows with active beaver stored ~23% of the carbon in the landscape. With the removal of beaver, and conversion of meadows from wet to dry grasslands, the carbon storage decreased by a factor of three and today represents only ~8% of the total storage in the landscape.

Beaver were thought to be non-native to the Sierra Nevada until 2012 when radiocarbon dating of two buried beaver dams, unearthed during a 'pond and plug' restoration, was dated to before the Gold Rush time, 1850±70 years for the first dam and 1820±30 years for the second dam (James and Lanman 2012). Additionally, recent research from the Rocky Mountains illustrates the role beaver have played over thousands of years in alluvial sediment storage and formation of meadow landscapes and the long-term carbon storage provided by beaver ponds, even after they are abandoned (Wohl 2013, Kramer et al. 2012, Polvi and Wohl 2012).

There are several mechanisms by which the activity of beaver or creating structures that mimic their behavior can increase the carbon storage, habitat value, water supply reliability and resilience of meadows. Beaver dams increase the vertical and lateral connectivity of rivers and create heterogeneous habitat for riparian birds and frogs. Beaver dams increase surface and groundwater storage, store sediment and organic material, and increase the frequency and magnitude of overbank flow. The dams attenuate moderate and small flood flows and support late-season flows, sometimes converting intermittent streams into perennial ones (Naiman et al. 1988). By raising the water table around dams, beaver increase the productivity of riparian and aquatic vegetation that they rely on for forage, which in turn increases above-ground carbon storage. Finally, when beaver create wetland ponds they increase methane emissions, yet the combined contributions of beaver to both carbon storage and methane emissions requires additional research (Whitfield et al. 2014).

Management of grazing on meadows, and balancing this with restoration and natural processes that facilitate the recovery of meadow function, will also be important for the capacity of meadows to serve as carbon sinks and critical habitat. Cattle congregate and forage more intensively in the riparian areas where vegetation is most productive. Beaver populations where they have been reintroduced or survived naturally have failed to recover in riparian areas that are heavily grazed by cattle or ungulates like elk. This, combined with active and persistent removal of willows from meadow systems by landowners has limited beaver populations and other ecosystem processes (Baker et al. 2005, Beschta and Ripple 2011, Ripple and Beschta 2004). As a result of these broad-scale changes to meadow function, their capacity to serve as natural sinks for greenhouse gases, to provide water during the summer months, and to provide habitat for meadow-dependent wildlife have been severely compromised across the Sierra Nevada mountain range.

The primary goal of this demonstration project was to restore a portion of Childs Meadow, a 290-acre meadow complex near Lassen National Park, in order to increase carbon storage, improve water holding capacity, and increase populations of riparian birds and sensitive meadow-dependent species. Childs Meadow was an ideal location to conduct a pilot restoration study for several reasons. It was typical of many Sierra meadows, having been grazed at levels common to other meadows, yet it was relatively recently been colonized by beavers in the lower section of the meadow, creating an area where the carbon and habitat value of seasonally grazed meadow and natural beaver ponds could be compared to restoration. Also, Childs Meadow remains one of the few remaining strongholds for two severely imperiled meadow species, Cascades frog and willow flycatcher. In 2014, more than 40 individual Cascades frogs were found in one day near a newly constructed natural beaver pond that spanned more than 100 feet across the meadow. All of the willow flycatcher and Cascades frog observations prior to this study were located where beaver built and maintained ponds creating an expanse of meadow wetland.

The study used a modified Before-After-Control-Impact (BACI) design to test the impacts of two restoration treatments in the central upper meadow on carbon sequestration, hydrology, and sensitive species (Figure 1). The upper portion of the upper meadow remained unrestored to provide a negative control, and the lower meadow with willow flycatcher, Cascades frogs, and beavers served as the positive control or desired condition. The treatments included (1) riparian cattle exclusion only and (2) riparian cattle exclusion and placement of beaver dam analog (BDA) structures in the stream channel. We limited the number of BDA structures to six to qualify as a demonstration project under CEQA categorical exclusion. The two treatment reaches and the grazed negative control reach were planted with willows to promote rapid vegetation growth and to test for the impacts of grazing on willow plantings. Carbon, hydrogeomorphic conditions, and sensitive species habitat were quantified and compared across the Childs Meadow treatments and controls. The BACI study design allowed a comparison of the benefits of low-cost restoration strategies to business as usual grazing (upper meadow) and the impacts of grazing exclusion combined with natural beaver activity (lower meadow).

The primary objective of this study was to increase carbon sequestration benefits in a demonstration mountain meadow using cost-effective beaver dam analogue restoration techniques. Specific project objectives included: (1) quantify and evaluate changes in above and below ground carbon storage following habitat restoration actions using beaver dam analogues and changes in grazing management via riparian exclusion fencing, (2) compare the within meadow carbon results from Childs Meadow to carbon sequestration values in existing restored and unrestored mountain meadows across the Cascade and Sierra Nevada range, and (3) measure the response of hydrogeomorphic conditions (e.g. groundwater, temperature, habitat) and two imperiled species (Cascades Frog and willow flycatcher) to restorative actions.

The remainder of this report is organized as follows. A summary of restoration activities completed by study task are provided below. Results and findings from the study are summarized in the following section, while detailed methods and results for each of the primary monitoring objectives are provided in appendices.

Restoration Activities

The following restoration project activities were performed from July 1, 2015 to December 31, 2019:

Task 1 – Project Management and Administration

Quarterly invoices, quarterly progress reports, and annual progress reports were provided to CDFW in a timely manner.

Task 2 - Environmental Compliance and Permitting

The Nature Conservancy (TNC) worked extensively with the Army Corps of Engineers, USFWS, CDFW, and Collins Pine (landowner) to complete work on obtaining the various required permits for installation of the beaver dam analogues (BDAs). Information on the permits is summarized below.

Lead Federal Agency: The Nature Conservancy worked with Sheli Wingo (sheli_wingo@fws.gov, 530-52601615) from the US Fish and Wildlife Service (FWS) to designate the lead Federal Agency for the Childs Meadow Beaver Dam Analogue Project. A letter was sent on June 14, 2016 from Nancy Haley, Army Corps of Engineers, to Kristen Podolak (The Nature Conservancy, TNC) confirming the designation of the US Fish and Wildlife Service as the lead Federal agency acting on behalf of the Army Corps of Engineers on the compliance with Section 7 of the Endangered Species Act and Section 106 of the National Historic Preservation Act. The contact for the Army Corps of Engineers is Robert Chase (Robert.D.Chase@usace.army.mil, 530-223-9536) who toured the project site in summer 2015 with Kristen Podolak from The Nature Conservancy and Sheli Wingo.

Section 7 and 106 status: Sheli Wingo submitted a request for Cultural Resources Compliance to Virginia Parks with the FWS on June 3, 2016. Virginia requested a sacred lands and tribal consultation list on June 27, 2016. Tribal and individual consultation memos were sent in July 2016. No concerns were raised after the 30-day review period, and Virginia prepared an Appendix A compliance memo.

401 Clean Water Act Technically Conditioned Water Quality Certification for discharge of dredged and/or fill materials was issued on May 20, 2016. The contact with the State Water Board is Guy F. Chételat (gchetelat@waterboards.ca.gov). Requirements listed below include:

1. TNC will notify the Central Valley Regional Water Quality Control Board in writing 7 days in advance of the start of any in-water activities related to construction.
2. Keep a copy of the certification on site.
3. Erosion and sediment control best management practices must be implemented during construction.
4. TNC will perform surface water sampling upstream and 300 feet downstream of the active work area. Sampling results shall be submitted to the water board within two

weeks of initiation of sampling. The parameter is "turbidity" in NTU units using a grab sample every 4 hours during in water work.

a. Activities shall not increase turbidity by identified threshold limits based on the natural turbidity, see certification.

b. An exceedance of 15 NTU over background levels is allowed during construction in the samples collected downstream.

5. Staff of the Water Board may enter the project site for inspection during or after construction.

Notice of Categorical Exemption, CEQA: Daniel Burmester with the CA Department of Fish and Wildlife and this grant manager issued the NOE under the 15333 Small Habitat Restoration Projects category on April 14, 2016.

Streambed Alteration Agreement 1602: Eda Eggeman from the CA Department of Fish and Wildlife (CDFW) completed the Streambed Alteration Agreement on July 18, 2016. Eda and three other people with CDFW (Mike Harris, Steve Baumgartner, and Andrew Jensen) toured the project site with Kristen Podolak from TNC on June 24, 2016. Below is a copy of an email forwarded from Eda to Daniel Burmester regarding fish passage.

From: Baumgartner, Steven@Wildlife
Sent: Friday, June 24, 2016 8:33 AM
To: Eggeman, Eda@Wildlife; Harris, Mike D.@Wildlife; Jensen, Andrew@Wildlife
Subject: Fish Passage on Gurnsey Creek, Tehama County

Good Morning Eda,

California Department of Fish & Wildlife personnel from our Inland Fisheries Group have long been involved in fisheries issues in Child's Meadow, Tehama County. Our management direction has been to prioritize the conservation of Cascades frogs over the introduced and naturalized brook trout in Gurnsey Creek which flows through the major portion of the meadow. Brook trout are no longer stocked in Gurnsey Creek. After reviewing the Child's Meadow Beaver Dam Analog Project, the Department is not requiring fish passage through the beaver dam analog structures. In addition, the Department is on record to support brook trout eradication in the CEQA documentation for the greater meadow restoration project. Please don't hesitate to contact me if you have any questions or concerns.

Steve

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Task 3 - Complete Fencing on the Lower Meadow

Sheep and cattle have grazed Childs meadow since the 1850s. Rangeland deterioration was noted in a 1949 Annual Grazing Report for Childs Meadow, and herbicides were commonly used to eradicate willows to increase forage production in the 1940-1950s. TNC bought the Childs Meadow property in 2007 and subdivided it into two properties with conservation easements on both. In July 2015, a split-rail fence was constructed at the downstream end of the beaver dam analogue treatment reach in the upper meadow to exclude grazing from the southern portion of the property that includes the lower meadow where the positive control reach with beavers was located. Collins Pine Timber Company currently manages the logging on the forested areas adjacent to the meadow.

Task 4 - Install Fencing on Central Treatment Meadow

TNC installed fencing to exclude cattle from the main channels in the two treatment reaches in early October 2015. The electrical fences were up and live during the cattle grazing season from June 1 to November 30, for each season from 2015-2018. Figure 1 shows the locations of each control and treatment study reach. The cattle exclusion fencing encompasses the two treatment reaches shaded in green in Figure 1. The positive and negative control reaches and locations of monitoring wells along transects are also delineated in Figure 1. During the late summer in both 2017 and 2018, we repeatedly found cattle in the exclusion area as the electrical fencing was continually shorting out. In fall 2018, TNC replaced the electrical fence with permanent barbed wire fencing to exclude the cattle. Although more expensive up front to install, the barbed wire fence did not require any maintenance over the 2019 study season, and it successfully kept the cattle out of the treatment areas. Future restoration projects that include fencing should consider the advantages of this option.

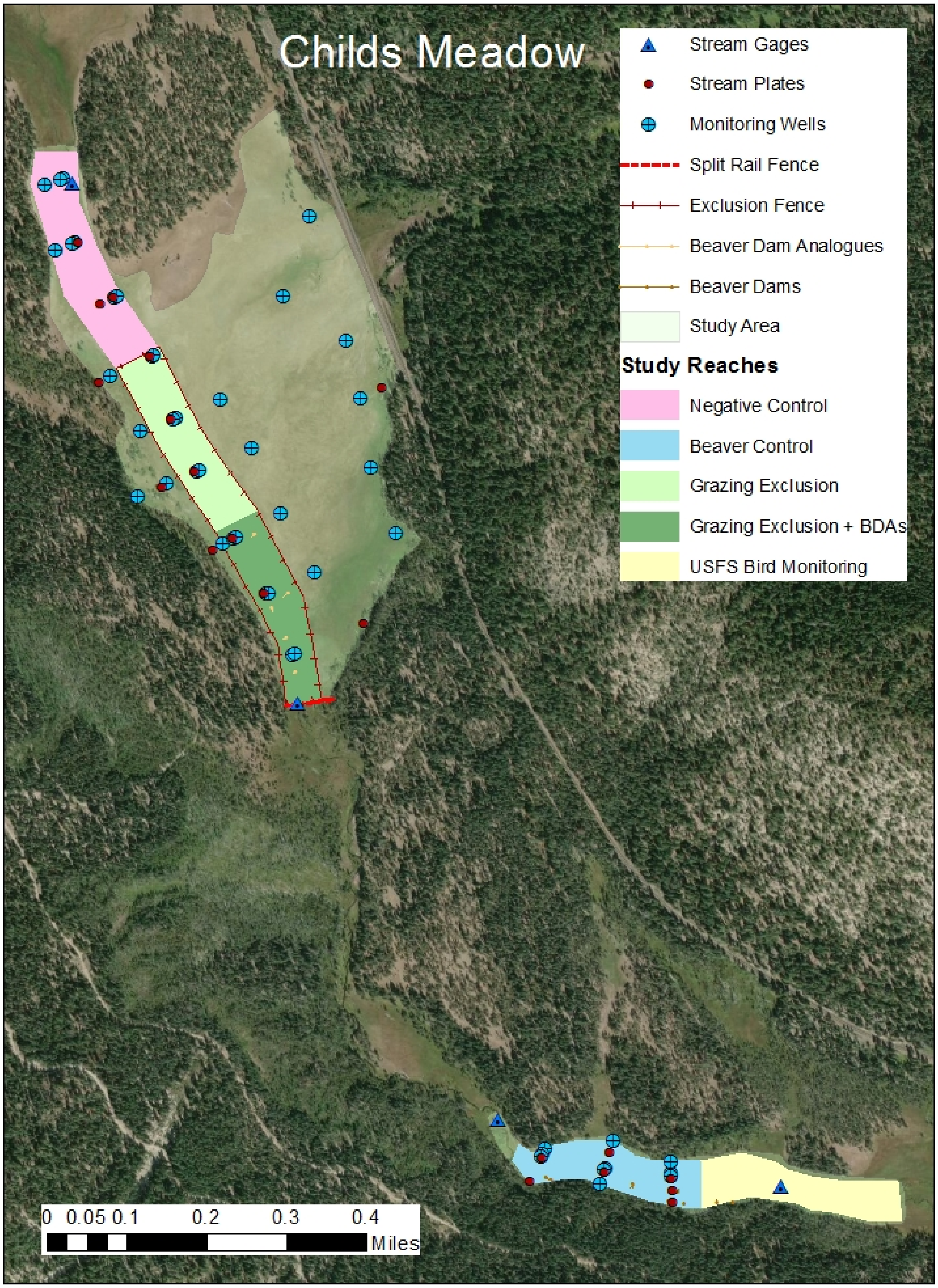

Figure 1. Overview of the study area and experimental design. Four study reaches were established: two treatment reaches (exclusion only, exclusion+BDAs), one negative control reach (grazed), and one positive control reach (beaver).

Task 5 - Complete Willow Planting in the Central Meadow

A willow planting design for the treatment reaches was completed in September 2015 that took into account the existing stream location and the placement of the beaver dam analogue (BDA) structures. Willow planting in the treatment and negative control reaches in the upper meadow was completed on October 23-24, 2015. Volunteers coordinated by TNC cut willows from stream locations downstream of the study area on October 23, 2015 and planted almost all the willows in the study reaches the following day. Crews from Point Blue finished the plantings the following week. In each of the three study reaches in the upper meadow (two treatments, one negative control), four 'pods' (groupings) of willow stems were planted along the primary channel. Each pod contained three sub-pods (groups) of 15 willow stems each, creating a total of 540 willows planted in the study area. Each sub-pod paralleled the channel and was approximately 4 m wide and 7 m long. Additional willows were planted in each study reach on April 27, 2016 to increase willow density and complete the original design. We determined the fate of the willows planted in fall 2015 after the snow was off the meadow on June 9, 2016; approximately 85% of the willows survived the winter and leafed out in spring. In spring 2018, Point Blue worked with local community members, elementary students, and teachers within the STRAW program to plant an additional 750 willows throughout the two treatment reaches and the negative control reach in the upper meadow.

The fate of these and previously planted willows was assessed in summer 2019. We were able to relocate between 40 and 70% of the willow planting to assess their survival and measure height. Willow survival declined significantly from 2016 to 2019 in the grazed and BDA reaches (Figure 2). In the grazed reach, survival dropped from 90% to 22%, while in the BDA reach, survival declined from 78% to 35%. Survival in the exclusion (fence only) reach also declined, from 90% to 70%, but remained significantly higher than the other two reaches. The plants within the two fenced treatment reaches (exclusion, BDA) had significantly greater height than the plants within the grazed reach. The willows in the grazed reach were visibly damaged from cattle browsing and were less than 40 cm tall on average, while willows in the exclusion and BDA reaches were 86 cm and 97 cm tall on average, respectively. We attribute the low survival in the BDA reach to permanent flooding of several of the near-channel willow pods; however, the willows that survived at the BDA pond margins grew taller than any other plants.

Based on our observations throughout this study, planted willows take approximately 3-5 years to establish roots and grow enough to provide vegetative structure above the surrounding sedges. The density of planting should be very high with willow stems spaced approximately 1-2 m apart and up to 10 m away from the channel assuming groundwater elevations remain fairly close to the surface across the summer. We had better survival with willow cuttings planted in spring versus fall, and recommend that soil moisture conditions be taken into account when planning planting times.

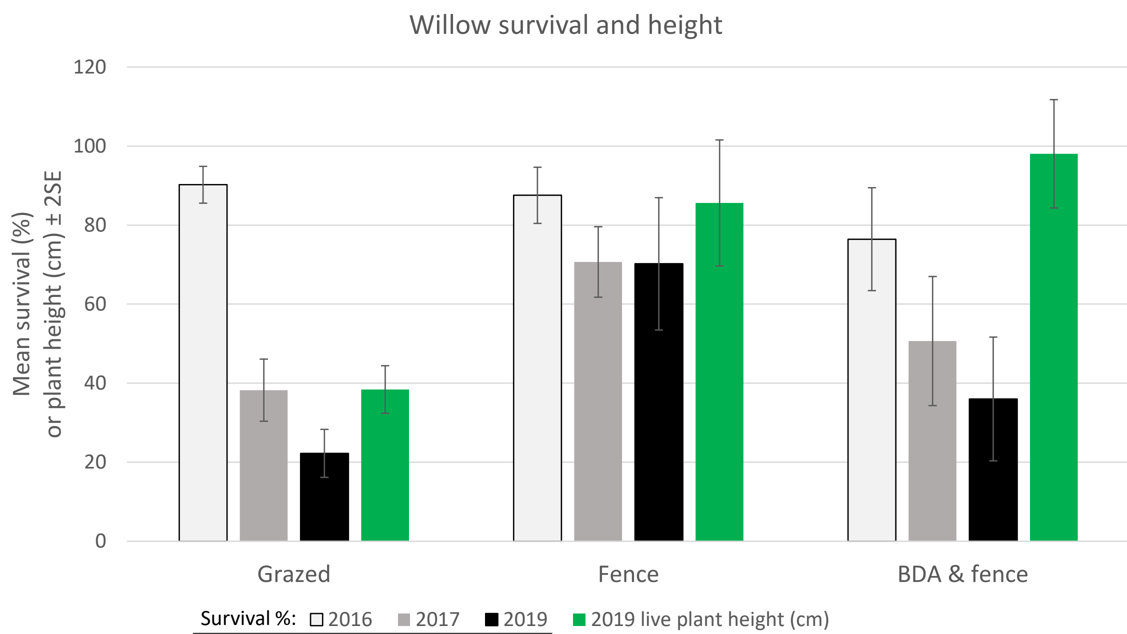

Figure 2. A comparison between treatment and negative control reaches of willow transplant survival from 2016 to 2019 (grey to black bars) and live stem height in 2019 (green bars). The two cattle exclusion treatment reaches (Fence, BDA & Fence) had significantly greater plant height than the unfenced grazed negative control reach.

Task 6 – Install Beaver Dam Analogue Structures

Construction on the beaver dam analogues (BDAs) was started under contract with the Scott River Watershed Council (SRWC) on September 13-14, 2016 when the vertical posts for each BDA were pounded into place per the design specifications. Two of the six BDA post-lines were pounded into dry secondary channels minimizing potential aquatic impacts. The remainder of the installation took place on October 6-8, 2016 with SRWC and a volunteer labor crew. SRWC and the volunteers wove willows between the posts and added sediment (matching the grain size and type from instream) to the upstream end of each BDA. Throughout the installation, USFWS provided pumps to dewater the sites as needed, Collins Pine Timber Co. provided sandbags, and the US Forest Service monitored the turbidity downstream of the work locations per the permitting requirements. Water began ponding behind each BDA almost immediately, and within 24-hours of completion, each BDA pond was full. Over the course of the study, several tours of the completed BDA structures were led by TNC and the project collaborators for agency representatives and other stakeholders involved in meadow restoration. Additional details on tours and public outreach is provided in the Results section below.

Task 7 – Monitoring and Quantification of Co-benefits

Four key research areas were monitored over the course of the study to assess the co-benefits of the restoration project, including above and below-ground carbon (Task 7.1), hydrogeomorphic conditions (Task 7.2), abundance and distribution of Cascade frogs (Task 7.3), and avian monitoring (Task 7.4). Summary results from these monitoring activities are described in the Results section below, and detailed results from each research area are provided in the final report appendices. Additionally, an analysis of the greenhouse gas and carbon results from this demonstration study with regard to the regional context (Task 7.5) is provided in the Results section below.

Task 7.6 – Long-Term Maintenance of Restoration Activities

Originally owned by The Nature Conservancy (TNC), Childs Meadow was sold to Collins Pine Company in 2016. The Collins Pine Company owns the surrounding timberland and manages it sustainably using selective harvest techniques with no clear cutting. Following this sale, TNC retained a permanent TNC conservation easement on Childs Meadow under which TNC retains a legal and affirmative right to fence out the riparian channel, as well as conduct additional restoration actions on the meadow.

With regard to the long-term maintenance of the BDAs specifically, the goal of the BDA installation was to increase flow resistance and initiate channel aggradation that will better support willows planted in and around the BDAs. Over time, as the willows grow and colonize the area and cattle are excluded from grazing on the willows, we expect the habitat to become more attractive to potential colonization by beaver located downstream. The BDA treatment is not intended to be permanent and may not be colonized by beaver in the near-term. However, the BDAs have been an important action to jumpstart riparian vegetation recovery and support changes in the local hydrogeomorphic conditions in the meadow, and so their long-term maintenance is not essential. As observed during the course of this study, beaver dams are often breached by high flows, but some of the stored sediment remains in place due to established vegetation, lower channel gradients, and easily accessible floodplains. The sediment that does move downstream within the channel serves to diversify downstream habitat and create new opportunities for vegetation establishment. BDAs, like natural beaver dams, are temporary features "intended to invoke a process response, not to remain as a permanent hard structure" (Pollock et al. 2014). We expect that when a BDA eventually breaches, it will create heterogenous habitat similar to the processes observed at natural beaver dams. As such, we worked to ensure the maintenance of the BDA ponds during this study to support above-ground woody vegetation recruitment, and we will continue to monitor their effectiveness during the next phase of restoration within the Childs meadow complex.

Results and Findings

Above and Below-Ground Carbon

At 24 locations in four treatment reaches in Childs Meadow, we installed permanent subplots for the collection of a suite of environmental, vegetation, and greenhouse gas (GHG) flux data. Each of the four study reaches (positive control, two restoration treatments, and negative control) contained three randomly placed but evenly spaced transects, 135 m apart (Figure 1). The treatment and control reaches were 400 m long in the direction of stream flow, and there was a 40 m buffer on either end where no subplots were located, to minimize any edge effect. The position of transects along the flow channel within each study reach was determined by a random number between 1 and 50. The location of the first transect within the upstream most study reach (grazed negative control reach) was 40 + (1 to 50, determined randomly) meters into the reach from the upstream end. The next transects within the reach were spaced 135 m and 270 m downstream of the randomly-located first transect. The three transects within each study reach were perpendicular to the stream flow direction within the reach. Additional details on the spatial design of transects and infrastructure for monitoring are included in Appendix A.

Each of the 12 transects contained at least two GHG subplots linked to groundwater monitoring wells located 5 m and 10 m lateral from the stream channel longitudinal axis. At each 5 m and 10 m subplot, CO_2 flux (and CH_4 and N_2O samples taken for lab analysis) were measured at a fixed point, 2 m north (approximately upstream) of a groundwater well. The GHG measurement point at each subplot was marked with PVC stakes at the edges of a 30 cm diameter circular measurement area.

Carbon dioxide flux was measured periodically during the growing season. During each sampling round all subplots within the reaches were measured for carbon dioxide flux. Measurements were made during the peak insolation period, between 10am and 4pm. At each subplot a full-sun and full-shade reading were taken in succession. Each reading consisted of a 2-minute measurement interval where a clear plastic cylindrical chamber, 30 cm in diameter and 30 cm tall, open only on the bottom, was placed on the meadow subplot. The contact between the chamber and the meadow was sealed with a combination of pressing the chamber into the soft soil and using moist fine sand to fill any gaps. The full-sun measurement was made during clear-sky conditions. The full-shade measurement was made immediately after the full-sun reading, with a blackout cover placed over the entire plastic chamber, blocking all light from entering. All readings were made with an infrared gas analyzer (PP Systems EGM-5) with inlet and outlet hoses attached to the chamber to maintain constant ambient pressure, with 2 battery-operated circulating fans mixing the air within the chamber at all times. Flux rates of CO_2 were determined by measuring the change in chamber headspace concentration over the 2-minute measurement period.

At each subplot during the carbon dioxide flux measurements, soil temperature and soil moisture were measured using a thermometer and a TDR soil moisture probe (Spectrum Technologies, FieldScout TDR 100), and photosynthetically active radiation (PAR) was measured using a light probe attached to the EGM-5. Air temperature and PAR data were acquired from nearby weather stations. Soil temperature was logged hourly at two subplots per study reach and correlated with hand-read soil temperature readings at the carbon measurements to create continuous datasets of soil temperature at the carbon sites.

Methane (CH4) and nitrous oxide (N2O) samples were collected at each subplot for lab analysis. Samples were collected throughout the growing season to validate the hypothesis that fluxes of these two gasses would be minor, but may show peaks associated with flooded or recently flooded conditions. Gas samples were collected from the chamber using a syringe, and injected into an evacuated 12 mL glass vial. Because the concentrations and fluxes of these gases were expected to be small, samples were taken at 20-minute time steps: 0, 20, 40, and 60 minutes after placing the chamber onto the meadow subplot. The samples were immediately transported, and the concentrations of the gases was determined on a gas chromatograph at UC Davis.

At the end of each growing season, soil carbon samples were collected. Samples were collected 1 m from wells at specific coordinates that changed each year to ensure that previously disturbed soil was not sampled. For example, in the first year, the samples were taken 1 m due north of every well, and the following year northeast. Sample areas were cleared to mineral soil, and a 5 cm diameter, 20 cm deep soil core was taken following the USFS Forest Inventory Act Forest Health Monitoring protocol for soils (O'Neill et al. 2005). The core sampler contains two sections, which allows for easy splitting of the core into 0-10 cm and 10-20 cm depth sections of known volume (81 cm3). Short-term changes due to project implementation were expected to be observed in the top layer of soil and longer term changes in the more stable lower soil layers. The samples were analyzed at the UC Davis Stable Isotope Facility for total carbon and nitrogen.

Over the four-year treatment period, the most significant greenhouse gas (GHG) flux was carbon dioxide (CO2), with comparatively minor carbon-equivalent fluxes of methane (CH4) and nitrous oxide (N2O) (Table 1). Concentrations of CH4 and N2O were converted to CO2-C equivalent using 100-year warming potential factors of 25 (CH4) and 298 (N2O). Note that the values reported here for CH4 differ from the figures reported annually in project progress reports because a warming potential factor of 34 was used in the annual progress report calculations.

Table 1. The four individual years and the four-year average gas flux values for the different study reaches at Childs Meadow. 'Beaver' was the positive control reach; 'Fence & BDA' was the BDA treatment reach; 'Fence' was the Exclusion only treatment reach; 'Grazing' was the negative control reach.

Year and section of project	Area m2	Daily CO2 flux g CO2-C m-2 day-1	Daily CH4 flux g CO2-C eq m-2 day-1	Daily N2O flux g CO2-C eq m-2 day-1	180-day CO2 emissions Mg CO2-C eq	180-day CH4 emissions Mg CO2-C eq	180-day N2O emissions Mg CO2-C eq	Total 180-day GHG emissions Mg CO2-C eq
2016								
Beaver	37600	0.309	-0.009	0.042	2.089	-0.058	0.285	2.316
Fence & BDA	37600	-0.913	0.001	-0.003	-6.176	0.006	-0.017	-6.188
Fence	37600	0.288	0.009	0.000	1.949	0.063	0.000	2.012
Grazing	37600	1.964	0.050	0.019	13.293	0.336	0.129	13.758
2017								
Beaver	37600	0.617	0.000	0.004	4.178	0.003	0.024	4.205
Fence & BDA	37600	-0.477	0.107	0.002	-3.229	0.726	0.011	-2.492
Fence	37600	-0.242	0.077	0.021	-1.641	0.521	0.140	-0.980
Grazing	37600	2.795	0.957	-0.003	18.920	6.475	-0.017	25.377
2018								
Beaver	37600	-0.425	0.001	0.004	-2.877	0.003	0.024	-2.851
Fence & BDA	37600	-0.524	-0.125	0.000	-3.549	-0.846	0.001	-4.395
Fence	37600	-0.509	0.001	0.003	-3.443	0.004	0.017	-3.423
Grazing	37600	1.023	0.369	-0.002	6.926	2.501	-0.012	9.415
2019								
Beaver	37600	0.167	-0.003	0.002	1.130	-0.018	0.015	1.127
Fence & BDA	37600	-0.612	-0.006	0.001	-4.139	-0.038	0.004	-4.173
Fence	37600	-0.234	0.029	0.008	-1.587	0.196	0.052	-1.339
Grazing	37600	1.116	0.050	-0.001	7.554	0.336	-0.007	7.884
Four-year average								
Beaver	37600	0.167	-0.003	0.013	1.130	-0.018	0.087	1.200
Fence & BDA	37600	-0.631	-0.006	0.000	-4.273	-0.038	0.000	-4.312
Fence	37600	-0.174	0.029	0.008	-1.180	0.196	0.052	-0.932
Grazing	37600	1.725	0.356	0.003	11.673	2.412	0.023	14.108

The beaver reach had an average net loss to the atmosphere (positive values) of about 25 g carbon-equivalent per square meter per growing season. However, the variability was high enough to result in a value not significantly different than zero. The reach that received both beaver dam analogs (BDAs) and fencing (BDA reach) showed a net carbon storage of about 100 gCO2-Ceq m-2 per growing season, while the fence-only treatment (Exclusion reach) had a net storage of 30 gCO2-Ceq m-2 per growing season, but not significantly different than zero. The grazed plots were more variable, but had an average net loss of about 400 gCO2-Ceq m-2 per growing season, about 20% of which was attributable to CH4 emissions. The fencing treatment (difference between grazed and fenced treatments) resulted in a shift towards net storage of about 430 gCO2-Ceq m-2 per growing season. The BDA treatment resulted in a net storage effect of about 70 gCO2-Ceq m-2 per growing season. The combined effect of the two treatments was a net storage of about 500 gCO2-Ceq m-2 per growing season, with 86% of that effect attributable to the fence preventing grazing, and 14% attributable to the hydrologic effects of the BDAs (Figure 3). This indicated that plant productivity was the primary driver of GHG flux at Childs Meadow, because the largest net loss of carbon occurred when the photosynthesizing leaves were removed by grazing. The hydrologic effect of BDAs increasing saturation and reducing decompositional carbon losses by creating anaerobic soil conditions was a measurable but smaller component of the experimental treatment effects.

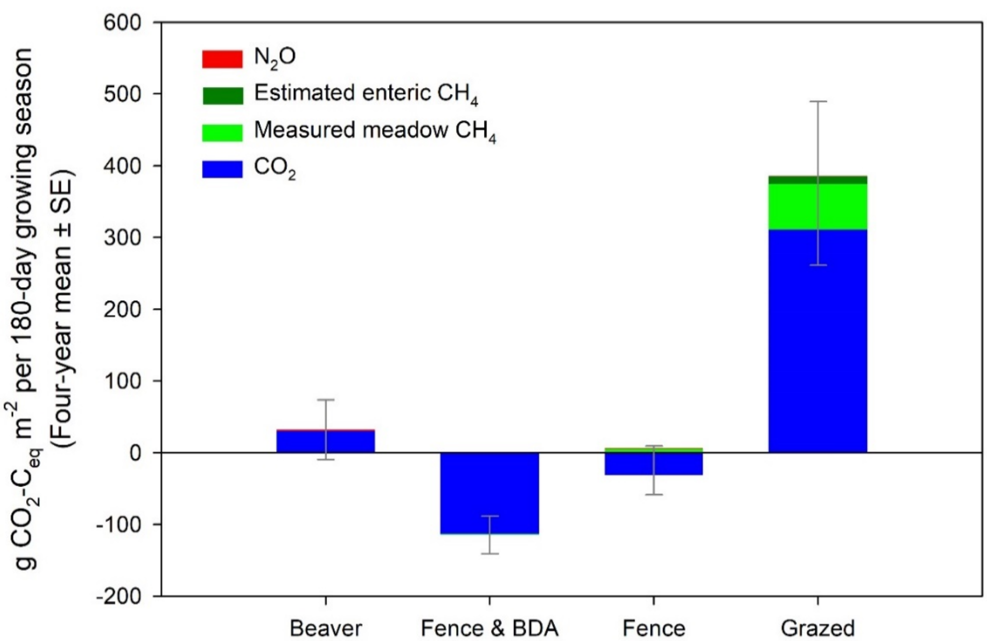

Figure 3. A comparison of the four-year average carbon-equivalent gas fluxes between the four study reaches.

The observations of higher methane production in the Childs Meadow grazed plots compared to fenced plots were similar to findings from other Sierra Nevada wetland studies comparing grazed and ungrazed areas (Allen-Diaz et al. 2008; Oates et al. 2008). The cause of the increase in measured meadow methane emissions in grazed plots was due to clipped stems of wetland plants providing an efficient conduit for efflux of methane via plant tissues from saturated soil conditions in the root zone to the atmosphere (Hirota et al. 2005; Dingemans et al. 2011).

To estimate the amount of cattle enteric methane production (not directly measured by us) in the grazed control plot, we used Childs Meadow grazing lease management data to estimate the number of cattle and duration of seasonal grazing. We used a measurement of 200 g CH4 produced per animal-unit-day (AUD) (Wolf et al. 2017) and scaled the estimated emissions from the whole of Childs Meadow down to our control plot, based on proportional area. From these values, we estimated that cattle grazing within our control plot emitted 10.5 g CO2-C eq per m-2 per growing season of enteric methane (Table 2).

Table 2. Series of measurements, approximations, and calculations used to estimate the enteric methane production by cattle in the grazed control plot of Child Meadow.

Total Childs Meadow area	2082000	m^2
Grazed control plot	37600	m^2
Control plot proportion of meadow area	0.018060	
Approximate Cow-calf pairs (1 Animal-unit) grazed in Childs Meadow per season	100	Animal-units
Grazing season	160	Days
Animal-unit-days in Childs Meadow per season	16000	Animal-unit-days (AUD)
AUDs in control plot per season	288.95	AUD
Approximate standard methane emissions (Wolf et al. 2017)	200	g CH_4 AUD^{-1}
Seasonal control plot methane emissions	57791	g CH_4 $season^{-1}$
Methane 100-year warming potential factor	25	
Seasonal CO2 eq control plot enteric methane emissions	1444765	g CO_2 eq $season^{-1}$
Seasonal CO2-C eq control plot enteric methane emissions	394027	g CO_2-C eq $season^{-1}$
Seasonal Mg CO2-C eq control plot enteric methane emissions	0.4	Mg CO_2-C eq $season^{-1}$
Total 208.2 ha Childs Meadow enteric methane emissions	21.8	Mg CO_2-C eq $season^{-1}$
Seasonal enteric methane emissions per grazed square meter	10.5	g CO_2-C eq $season^{-1}$ m^{-2}

Lastly, we estimated annual herbaceous production and utilization by cattle based on a paired plot design (USDA, 1999), for comparison with the carbon flux data. Exclosure cages were constructed annually in early June from 2015-2019. Two cages were located close to the stream channel (8 m away from the streambank), and two cages were located in the meadow, 46 m and 91 m from the stream channel. All cages were 150 m apart and were moved annually at least 100 m. We caged a one square meter area from grazing and clipped herbaceous material to ground level in a 50 cm^2 area within these "ungrazed" plots. Paired grazed plots were located 30 m away from ungrazed plots. Plots were clipped in mid-October close to the end of the grazing period. All clipped material was force-air dried and dry weights were recorded. Utilization was calculated as the percent of ungrazed biomass and categorized as light <30%, moderate 30-60%, and heavy >60%. Percent cover of rush (juncus), sedge (carex), grass, forbs, moss, thatch, and bare were estimated in each plot before clipping. The effect of cattle grazing on herbaceous production was analyzed using two-way Anova with year and treatment as factors, and year times treatment as an interaction.

Seasonal cattle grazing occurred on Childs meadow from June 1 to November 15 with a limit of ~500 animal unit months (AUM) for cow/calf pairs, with bulls counted as 1.5 AUMs. The grazing limit was established in October 2015 in a conservation easement by TNC. Grazing decreased from 577 AUMs in 2015 to between 466 and 518 AUMs from 2016-2019 (Table 3). Herbaceous production varied by year ($p=0.013$) and by grazing treatment ($p<0.001$), with no significant interaction between year and treatment. Production ranged from 1,988 lbs/acre (±774) in 2015 to 4,389 lbs/acre (±886) in 2019 with an average of 2,896 lbs/acre across all years (Table 4, Figure 4). Utilization varied from 36% (±7) in 2016 to 77% (±13) in 2017 (Table 3). Utilization across all years was 46%, or a 'moderate' grazing level. Only one year was categorized as 'heavy' grazing, 2017, when the grazing intensity at one time was the highest observed at 311 AUMs from mid-June to mid-July. Percent cover of different vegetation types did not vary between grazed and ungrazed plots. Sedge was the most dominant at 34%, then roughly equal amounts of grass and rush at 18% each. Forbs (12%), moss (7%), bare ground (7%), and thatch (5%) together represented 30% of the total cover.

Table 3. Percent utilization of aboveground biomass and grazing pressure (animal unit months, AUMs) by year in Childs Meadow.

Year	Mean (%)	SE (%)	Grazing level	Total AUMs	Max AUM
2015	40	8	moderate	577	212
2016	36	7	moderate	518	152
2017	77	13	heavy	466	311
2018	41	17	moderate	484	224
2019	38	12	moderate	493	261
All years	46	6	moderate		

Table 4. Herbaceous production, estimated as average residual dry biomass (lbs/acre) in ungrazed plots in mid-October, across years. Utilization was calculated as the percent of ungrazed biomass, and categorized as light <30%, moderate 30-60%, and heavy >60% (see Table 3).

Year	Grazed	Ungrazed	Ungrazed - grazed
2015	1,003	1,988	985
2016	1,758	2,697	939
2017	642	2,762	2,120
2018	1,017	2,646	1,629
2019	2,384	4,389	2,006
All years	1,361	2,896	1,536

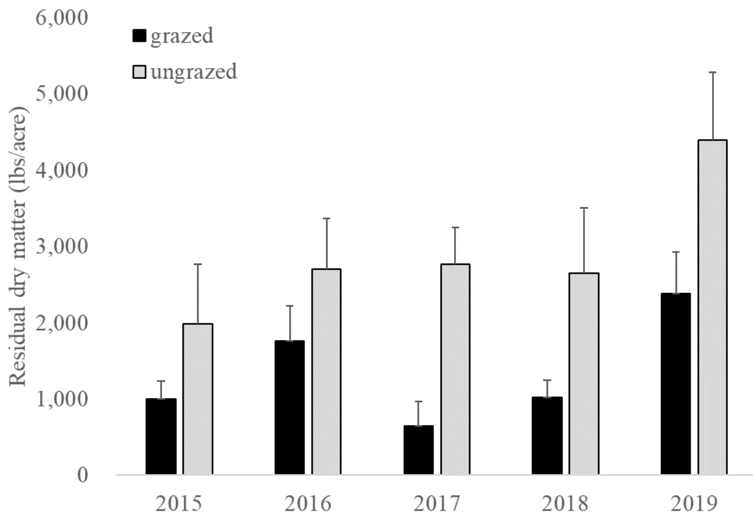

Figure 4. Herbaceous production in grazed and ungrazed paired plots in Childs Meadow.

Hydrogeomorphic Conditions

A summary of the hydrogeomorphic conditions across the study is provided below, and a detailed description of hydrogeomorphic monitoring methods and results is provided in Appendix A.

The five years of the study from 2015-2019 represented some of the most variable climate and precipitation conditions typically observed in California. 2015 was the driest year of the 2012-2015 drought with the very low annual precipitation and the lowest recorded annual snowpack in the Sacramento basin. Annual precipitation in 2016 was slightly above average, but 2017, in contrast, had the highest precipitation on record for the Sacramento basin, with several 5- to 10-year recurrence interval floods occurring in the study area between December 2016 and March 2017. 2018 was below average with regard to annual precipitation, while 2019 had above average annual precipitation that largely fell as snow between January and March contributing to delayed runoff into early summer. These varying precipitation conditions contributed to corresponding variable surface and groundwater elevations observed throughout the study area across years, but water elevations in the beaver (positive control) study reach were also highly mediated by the degree of beaver activity.

In general, water entered the upper meadow primarily from stream channels and from groundwater discharge at the base of the hillslopes. The main stream channel at the upstream end of the upper meadow provided the bulk of the surface flow until additional side channel flow entered the western side of the meadow near the exclusion reach and water from the eastern side ditch entered at the downstream end near the BDA reach (Figure 1). Shallow subsurface flow entered the meadow along the base of the western hillslope and near a fen located upslope from the treatment reaches. As snowmelt and spring runoff decreased each year, these groundwater contributions supported much of the observed summer streamflow through the upper meadow. In the beaver reach in the lower meadow, water entered primarily within the main stream channel, with some groundwater discharge entering from the eastern meadow lobe approximately halfway down the study reach and from the base of the western hillslope along the length of the study reach. The natural beaver ponds served to slow and spread the stream flow onto the adjacent meadow surface, while multiple side channels created additional small pools of surface water. Following the installation of the BDAs in the BDA reach, surface flows in the main channel were similarly spread onto the adjacent floodplain, with initial signs of increasing side channel formation.

An annual pattern of gradual decline in water elevations following snowmelt runoff as the summer progressed was evident at most wells and stream monitoring locations, with the exception of those locations near groundwater discharge at the base of the hillslopes or adjacent to channelized flow in ditches. For those locations with seasonal variation in water elevations, the degree to which water elevations changed across each season also varied across years. Wells near the meadow edges of the upper meadow (treatment reaches) varied with water year type, such that they had statistically significant higher summer groundwater baselevels in the wetter years (2017, 2019), lower summer groundwater baselevels in the drier years (2016, 2018), and the lowest groundwater baselevels in 2015 during the drought. However, for those wells located near the channel ponds in the beaver reach, groundwater baselevels were highest in years when the beaver dams were actively maintained, including 2015, 2018, and 2019. In particular, wells near the channel had statistically significant *higher* groundwater baselevels in 2015 versus any other year, while groundwater baselevels were statistically *lowest* in 2017 when the dams were breached despite the extremely wet climate conditions.

The installation of BDAs in the lower treatment reach in late 2016 resulted in ponds that when maintained helped to keep groundwater elevations in the adjacent meadow high across the season. Groundwater elevations near the channel were 0.25 m-0.30 m higher at the end of the summer season in 2017 than 2016 in the lower BDA reach, while groundwater elevations were not significantly different at the end of the season in 2016 and 2017 in the exclusion reach. At the reach scale, lateral groundwater gradients were consistently sloping away from the stream channel, such that losing stream conditions were prevalent at most cross-sections across each season in each year. In each of the study reaches, the influence of the stream channels and ponds on the adjacent groundwater levels appeared to only extend approximately 10-20 m lateral from the channel.

The surveyed cross-sectional and thalweg topographic profiles showed little change across the study, with the exception of the channel thalweg in the beaver reach, where breaching of the beaver dams resulted in local erosion and deposition in the channel. Despite the flood flows in winter 2017, the general channel morphology in both the upper and lower meadows remained consistent. Cross-sectional changes were not noted at any transect, including those in the beaver reach where some changes might have been expected due to breaching of the dams. Similarly, no changes were observed in the thalweg profiles in the grazed and exclusion reaches; however, some small amounts of erosion and deposition (+/- 10 cm vertically over several meters) were observed in the BDA reach following the high winter flows in 2017.

In the beaver reach, more substantial erosion and deposition was noted in the channel thalweg profile following the breaching of the dams in winter 2017. Approximately 1 m of vertical erosion occurred downstream of the large beaver dam near transect 3, while 10-40 cm of vertical deposition occurred on the riffles located about 50 m downstream. Similarly, sediment was eroded out of the large pond adjacent to the beaver lodge downstream of transect 2 and deposited throughout much of the main channel downstream through the rest of the study reach. On average, 10-20 cm of vertical deposition occurred in the lower half of the beaver reach following the breaching of the dams.

The channel complexity, specifically the length of stream channel as digitized from UAV imagery collected in 2015 and 2019, did not change substantially over the length of the study. Although both sets of images were collected in late fall when vegetation senescence had occurred, the degree to which vegetation growth within the exclusion may have obscured remnant or new channels was uncertain. A similar analysis using LiDAR data would provide a more accurate representation of the ground topography and the potential changes in channel complexity over time.

Throughout the upper treatment meadow, stream channel temperatures fluctuated with air temperature seasonally showing large diurnal fluctuations, while the groundwater wells maintained consistently cooler temperatures that fluctuated seasonally but minimally daily. In wells nearer to the channel, temperatures were slightly higher than wells closer to groundwater-dominated locations, indicating some degree of exchange with the surface water. In wetter years, temperatures in wells adjacent to the stream channels were more similar to the stream temperatures than in drier years suggesting greater interconnection during higher stream flows. In all years, warmer stream channel temperatures were observed at the downstream end of the upper meadow than at the upstream end where groundwater comes to the surface and enters the stream channel. Stream channel temperatures were generally cooler in the lower beaver meadow than in the upper meadow in all years, likely due to greater exchange with the groundwater.

In general, the vegetation patterns observed in satellite and UAV-based aerial imagery mimicked the differing surface and groundwater water sources, with greener vegetation near the channel, and groundwater discharge locations. Drier mesic vegetation was observed by late-season in the areas with more variable groundwater elevations. An analysis of trends in vegetative condition across the growing seasons from 2017-2019 using calculated NDVI (Normalized Difference Vegetation Index) values from satellite aerial imagery showed no significant changes in average annual NDVI values by year across or within treatments, due to the high variation in NDVI seasonally within any given year. In contrast, late-season NDVI values (greater than 130 days after snow-off) were significantly different from all early- and mid-season NDVI values within all study reaches. Late-season NDVI values in the beaver reach were also statistically similar to mid-season values (70-129 days after snow-off) in the grazed and exclusion reaches, suggesting greener vegetative conditions persisted later in the growing season in the beaver reach.

The satellite imagery from Planet provided a much higher spatial (3 m) and temporal resolution (daily) than any available previously, and will be a good source of data to compare vegetative changes seasonally at the larger meadow and reach scales in the future. However, imagery at a 3-meter resolution was too coarse to capture changes due to small stream channels or within smaller vegetation patches. An analysis of LANDSAT, NAIP, and UAV imagery found that even 1-meter resolution imagery from NAIP generally did not accurately identify features with an area less than 9 m^2, and narrow, shallow stream channels were often misclassified (Bell et al. 2016). For analysis of changes at smaller scales, including changes in extent of willow cover, vegetation types, or channel morphology, UAV imagery provides the higher resolution required for identification and manual digitization of features.

Abundance and Distribution of Cascades Frogs

In treatment and control reaches, we conducted visual surveys for all amphibians and all life stages and conducted capture-mark-recapture surveys for post-metamorphic Cascades frogs (*Rana cascadae*). We used a robust design whereby each survey period included two fully repeated surveys within a couple days of each other so that we could account for probability of detection differences when assessing population metrics. We conducted one fall survey in 2014, seven surveys between May and October in 2015, eight surveys in 2016, seven in 2017, four in 2018, and seven in 2019 (Appendix B). For Cascades frogs, all breeding locations and frog locations were mapped, and post-metamorphic frogs were measured and marked with either a Passive Integrated Transponder (PIT tag) or Visual Implant Elastomer (VIE). Post-metamorphic Cascades frogs were also swabbed for *Batrachochytrium dendrobatidis* (Bd), the cause of the amphibian disease Chytridiomycosis.

We identified three amphibian species in the Childs Meadow study area; Cascades frogs, Pacific chorus frogs (*Pseudacris regilla*), and western toads (*Anaxyrus boreas*), and one garter snake species, *Thamnophis sirtalis*. Pacific chorus frogs were found breeding in all four study reaches, and western toads were found in all reaches, but breeding locations were not identified. Cascades frogs were primarily found in the beaver (positive control) reach, but a few adults were also found in the BDA reach, and one was observed in the exclusion reach (Table 5). The highest number of Cascades frogs observed in any one survey occurred in 2016 with 11 adults and 34 juveniles in the beaver reach. During surveys, we only found Cascades frogs 8 times in the two treatment reaches, and none were recaptured again during a later survey. Breeding was only observed in the beaver reach, until the spring of 2019 when two Cascades frog egg masses were found in the BDA reach in a backwater associated with the BDAs. Juvenile frogs were found in the BDA reach only after installation of the BDAs.

Following the beaver dam breaches during high flows in winter 2017, surface water habitat in the beaver reach was very different in 2018 and 2019 compared to previous years. In most off-channel pools, surface water depth decreased earlier in the season compared to when the dams held water. This contrasted with the change associated with the BDA reach where groundwater elevations remained higher longer behind the BDAs (Appendix B). Even with new and variable surface water conditions within the positive control reach, Cascades frogs bred in the reach in 2018 in old beaver channels off the main channel, and some larvae successfully metamorphosed. However, no juvenile frogs were recovered in the beaver reach in 2019 (Appendix B). Numbers of post-metamorphic animals also greatly declined in the beaver reach in 2018 and 2019 as the abandoned beaver dams broke apart and off-channel aquatic habitats decreased (Table 5).

However, these observed patterns in habitat use and frog presence are confounded by the Chytridiomycosis (Bd) disease results. We have qPCR results from skin swabs for Bd from 332 frogs between 2015 and 2019. The prevalence and loads of Bd on Cascades frogs increased dramatically in 2017 and 2018, also coincident with the decrease in frogs in the beaver control reach (Appendix B). Juvenile frogs appear to be the hardest hit, similar to patterns of Bd-associated mortality that we have observed at other nearby populations: recapture rates for first- and second-year frogs after 2016 were close to zero (Appendix B).

Table 5. Annual mean and maximum number of Cascades frogs (*Rana cascadae*) observed per reach.

	2015		2016		2017		2018		2019	
Reach	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Beaver (Pos Cntrl)										
Adult	4	7	7	11	6	8	6	8	6	8
Subadult	6	9	6	9	3	5	5	7	1	1
YOPY	4	5	2	4	2	3	3	3	1	1
Metamorph	29	68	15	21	10	14	43	43	0	0
Egg mass		10		10		6		3		1
BDA, Exclusion										
Adult	1	2	0	1	0	1	0	0	0	1
Subadult	0	0	0	1	0	0	0	0	0	0
YOPY	0	0	0	0	0	0	0	0	0	0
Metamorph	0	0	0	0	1	2	1	2	0	0
Egg mass										2
Exclusion										
Adult	0	0	0	0	0	0	0	0	0	0
Subadult	0	0	0	0	0	0	0	0	0	0
YOPY	0	0	0	0	0	0	0	1	0	0
Metamorph	0	0	0	0	0	0	0	0	0	0
Egg mass										
Grazed (Neg Cntrl)										
Adult	0	0	0	0	0	0	0	0	0	0
Subadult	0	0	0	0	0	0	0	0	0	0
YOPY	0	0	0	0	0	0	0	0	0	0
Metamorph	0	0	0	0	0	0	0	0	0	0
Egg mass										

Avian Monitoring

From 2015 to 2018, we completed pre-restoration and short-term post-restoration avian monitoring at seven demographic monitoring study plots in five study reaches in the Childs Meadow complex along Gurnsey Creek. Each study reach was approximately 10 hectares. Reaches covered the range of meadow conditions and restoration treatments including: historic grazing exclusion with long-active beavers (USFS positive control), recent grazing exclusion with recently active beavers (beaver positive control), riparian fencing with BDAs and planted willows (BDA), riparian fencing with no BDAs and planted willows (exclusion), and actively grazed with no change in management (grazed negative control). Within the study plots in each reach, we located and monitored nests and determined territory densities for seven meadow focal bird species known to breed in Childs Meadow: Yellow Warbler, Song Sparrow, Lincoln's Sparrow, Warbling Vireo, MacGillivray's Warbler, Wilson's Warbler, and Willow Flycatcher. We monitored these plots from early May – July 31, the peak of bird breeding activity in the region. In July and August, we created final territory density maps for each species in each of the study plots and measured habitat around each nest and at 20 randomly selected locations in each study plot. We produced annual reports during years surveyed (2015-2018) that are summarized in Appendix C.

Among the five study reaches, through 2017, the highest territory densities of meadow focal bird species were in the USFS positive control reach with 6.7 territories per ha, followed by 4.0 territories per ha in the beaver reach. The grazed, exclusion, and BDA reaches had very low densities or no territories in all years. We found a total 229 nests through 2017. The proportion of nests resulting in at least one fledged young was higher in USFS positive control reach (0.69) than the beaver reach (0.56), both of which were high relative to other riparian habitats in California. Sample sizes of nests in the other three reaches in the upper meadow were too low to make inference. Results from habitat assessments at nests and random locations demonstrated strong selection by focal species for high shrub cover and low to moderate amounts of water cover within 5 m of the nest site. This combination of habitat attributes remained generally unavailable to birds in the grazed reach and the two treatment reaches in all four years of monitoring, though the BDA reach did provide standing water approaching that found at the highest quality habitat in the USFS positive control reach. The beaver and USFS positive control reaches illustrated the large potential of the upper meadow treatment reaches to support bird habitat in a restored condition and the role of ponded water and shrubs in creating those conditions. As woody shrub vegetation height in particular increases over time in the two treatment reaches (see vegetation results in Appendix C), avian habitat will become more suitable. Our first four years of data provide a strong foundation from which to evaluate whether the treated reaches will achieve that potential.

Our fourth year of monitoring, in 2018, was the second breeding season following BDA construction, and the third season since fencing was installed and willows were first planted in the two treatment reaches. As expected, we did not detect any effects of these restoration efforts on our seven focal species, because the restoration was too recent and essential habitat components (i.e. willows) were insufficiently developed to provide suitable nesting habitat by 2018. We expect habitat suitable for the focal species to manifest in the following 3–10 years, based on the survival and growth of planted willows. While meadow focal species use in the two treatment reaches was still far below the positive control reaches, we documented colonization by Red-winged Blackbird, Wilson’s Snipe, Sora, and Virginia Rail. These species were likely responding to the dramatic increase in herbaceous vegetation vigor, density, and height as a result of excluding cattle from these reaches as well as increased ponded water in the BDA reach.

We documented substantial changes in Song Sparrow density as a result of the redistribution of beaver dams (loss in some locations, new construction in others) following large flood events in the winter of 2016-17. The flood events served as a natural before-after control-impact experiment that demonstrated the positive effect of high groundwater elevations, an objective of hydrologic restoration, on the bird community. We also noted two Willow Flycatcher nests in 2018; one nest was located in the USFS positive control reach downstream of the beaver reach, and one nest was in the grazed reach at the upstream end of the upper meadow. The nest in the USFS reach successfully fledged two young, while the nest in the grazed reach failed after hatching. This nest had been parasitized by cowbirds, which may or may not have been the cause of failure.

Results in Regional Context

Due to time and funding constraints, we were unable to collect carbon samples at other Cascade region meadows as proposed in the grant agreement, but we were able to compare the Childs Meadow gas flux results with the findings from a range of other Sierra Nevada meadow projects where gas flux was measured over the past five years. These other projects have also determined that the primary GHG flux in their meadows is from CO2 and that plant productivity is the main determinant of CO2 flux. These concurrent studies spanned a range of meadow conditions through the Sierra Nevada range, but did not experimentally exclude grazing as in our study. As a result, their measurements include a wider range of natural site variability, as well as a range of grazing impacts. Consequently, the Sierra Nevada study sites ranged from net losing 200-600 gCeq m^2 per year to gaining 300-1000 gCeq m^2 per year (Reed et al. 2018; Merrill et al. 2019; Oliphant et al. 2019; Reed & Sullivan 2019). The GHG flux values measured within the different experimental reaches in Childs Meadow fall within these ranges.

Additionally, we were able to compare the hydrogeomorphic conditions at Childs Meadow from 2015-2017 with hydrogeomorphic conditions observed at two other cascades meadows and three meadows in the Sierra Nevada for a study comparing amphibian habitat funded by the National Fish and Wildlife Foundation. The final project report for that study was provided to CDFW upon its completion in summer 2018.

Additional Co-benefits from this Demonstration Study

Childs Meadow Outreach & Community Engagement

Functioning as a pilot, we prioritized sharing information about the Childs Meadow project to a diversity of audiences through a number of approaches. We hosted field workshops and tours with: Department of Water Resources, Army Corps of Engineers, Bureau of Land Management, California Department of Fish and Wildlife, USDA Forest Service, and interested stakeholders (Figure 4). During these tours and our regular monitoring and maintenance activities, the project served as an outdoor classroom for process-based restoration training lead by members of our team (Figure 5). Overall, over 100 people were involved in touring Childs Meadow and learning about this project over the course of the study. In addition, we made presentations at various scientific meetings and conferences: American Geophysical Union annual fall meeting, Association of Water Resource Agencies annual conference, annual Riparian Conference at UC Davis, two Sierra Meadows Partnership annual gatherings, and the Salmonid Restoration Federation annual conference.

In addition we hosted a journalist which resulted in an article in Audubon Magazine about the project, (https://www.audubon.org/news/can-restored-meadows-fight-climate-change-california-seeks-find-out), we described the project to author Ben Goldfarb who wrote about it in a recent book titled *Eager: The surprising secret life of beaver and why they matter,* and articles were produced for both The Nature Conservancy Blog (https://blog.nature.org/science/2016/05/20/beaver-dam-nature-conservancy-is-restoring-streams-water-freshwater/) and Point Blue Quarterly (https://rdjzr2agvvkijm6n3b66365n-wpengine.netdna-ssl.com/wp-content/uploads/2018/06/PointBlueQuarterly_2016_Fall.pdf).

As part of this restoration process, we prioritized including the human community in the restoration process. We had local community engagement through three different events. TNC organized a willow harvest and planting day in October 2015 that engaged over 50 people including Collin's Pine employees, and other local residents from Chester. We then included the community in beaver dam analog construction in October 2016, where over 30 people participated, including local residents (Figure 6). Finally, we held a Point Blue Students and Teachers Restoring a Watershed (STRAW) restoration at Childs Meadow and engaged 150 students, teachers, and parents from Chester in willow planting in the project area in May 2018 (Figure 7).

The project further served as a pilot by sharing permitting documents and launching an additional project to guide beaver-based restoration to the most appropriate stream reaches. We shared permitting documents from the Childs Meadow project with other restoration practitioners who asked for the documents, including American Rivers, Sierra Foothill Conservancy, Plumas National Forest, Shasta Trinity National Forest, and two private consultants. The Childs Meadow project also lead to a collaborative effort by the National Forest (Region 5), The Nature Conservancy, Point Blue Conservation Science, Institute for Bird Populations, and Occidental Arts and Ecology Center to map priority stream reaches for conservation and restoration focused on beaver dam building (https://tinyurl.com/brat-ca) and to study the relationship between beaver dams and willow flycatcher habitat. This effort was funded by a grant from the National Fish and Wildlife Foundation and The Nature Conservancy.

Figure 4. Field tour of BDAs in fall 2018 with community members, resource agency personnel, and project stakeholders.

Figure 5. Maintenance of the BDAs by project team members in October, 2017.

Figure 6. Beaver Dam Analogue (BDA) construction in fall 2016 with community members and project stakeholders.

Figure 7. Local community members planting willows in spring 2018 with the Students and Teachers Restoring a Watershed (STRAW) program.

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Appendix A - Hydrogeomorphic Conditions

Hydrology

Methods

We established a sampling network throughout the four study reaches (two treatments, one positive control, and one negative control) with permanently monumented cross-sections providing the basis of the network. We placed a total of 9 evenly spaced cross-sections within the upper meadow adjacent to Highway 36 (three transects per each of three study reaches) and 3 evenly spaced cross-sections in positive control reach in the lower meadow (Figure 1). Cross-sections were spaced 135 m apart, oriented perpendicular to the valley slope, and the distance from the upstream study boundary to the first transect was randomly determined.

We installed groundwater monitoring wells along each transect such that a well was located near the meadow edges, 5 m lateral from the main channel, and 10 m lateral from the main channel. Additionally, we installed 1-2 wells between the cattle exclosure and the meadow edge at each transect in the two treatment reaches where the meadow was particularly wide (Figure 1). Wells were hand augered to a depth of 3m or until coarse sediment blocked further augering. In all cases, wells were installed to at least 1.5m. Well casings were made of 1.5-inch diameter polyvinyl chloride (PVC) pipe that was slotted but unscreened at the deep end to allow for water to enter. Wells were capped with fitted PVC caps and marked with their corresponding well ID. We installed staff plates on all transects within the main channel and any perennial side channels to measure surface water conditions. Each staff plate consisted of a T-post hand pounded into the channel near the bank, or in a few cases, a PVC pipe hand-pounded into a shallow channel. A total of 45 wells and 16 staff plates were installed throughout the study area. Additional zoomed maps of each study reach showing the locations and IDs of each well and staff plate are provided in the supplemental data.

The wells and transects served at the basis for the hydrogeomorphic, water quality, and greenhouse gas sampling that occurred throughout the study. The wells, transects, and other primary features in the study area, including equipment locations, stream lines (thalweg and bank), channel and pond topography, BDA locations, and soil sampling locations, were surveyed with a real-time kinematic GPS (RTK-GPS) survey system (Topcon), and plotted in ArcGIS (ESRI 2019). The topographic surveys were repeated annually in late summer as needed to document changes in equipment locations, sampling locations, or geomorphic conditions.

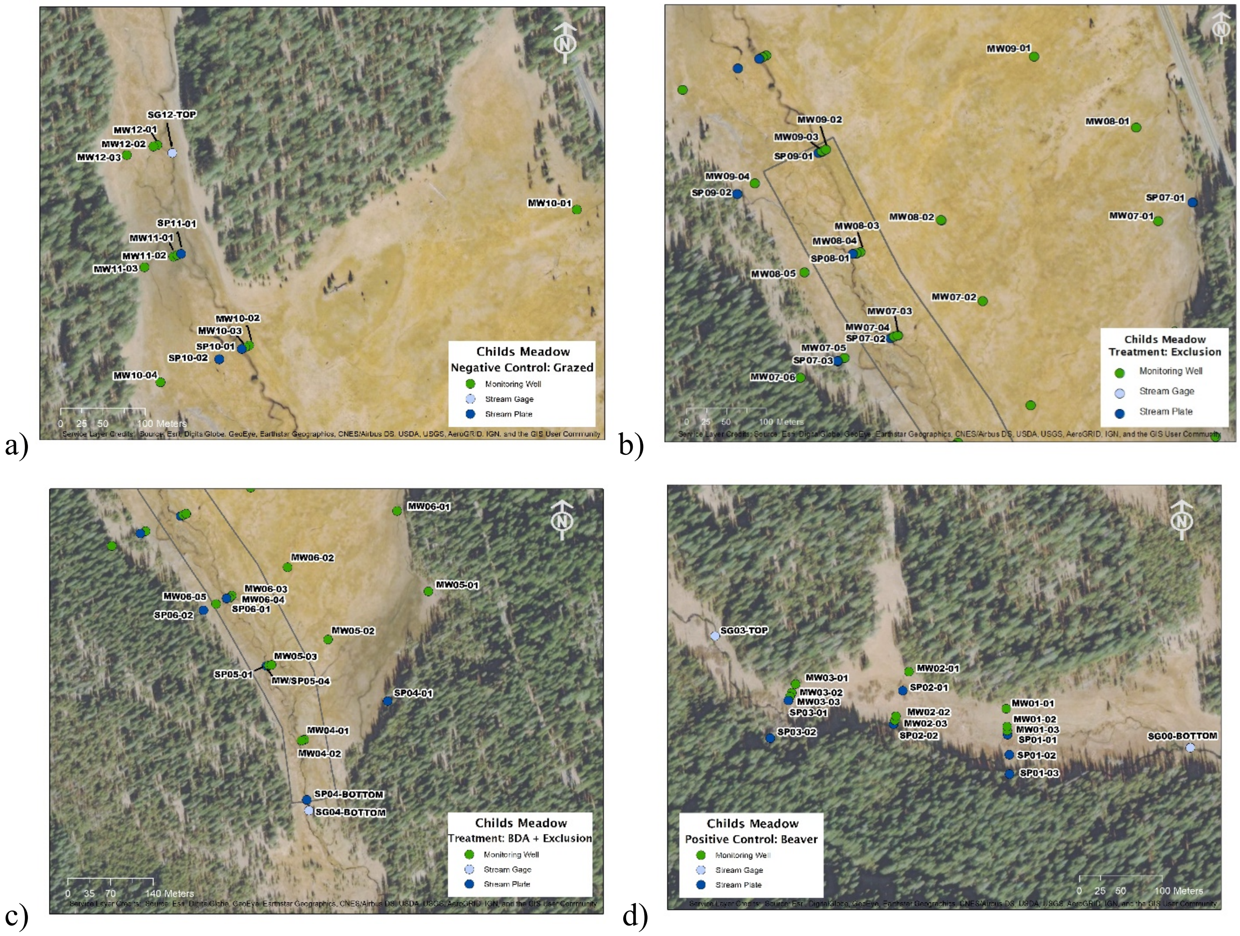


Figure 1. Site maps of each study reach with associated well and staff plate locations and IDs delineated. IDs reflect the location type (monitoring well (MW) or staff plate (SP)), transect number (1-12 from downstream to upstream), and location west of the highway (starting with 01). MW10-01 indicates the monitoring well closest to the highway on transect 10.

Water Elevation

Groundwater and surface water elevations were measured manually at each well and staff plate every 3-4 weeks during the 2015-2017 spring and summer survey seasons, and approximately biweekly during the 2018-2019 seasons. Each sampling season typically began several weeks after snow-off in spring and continued through summer until water elevations began to rise again with fall precipitation. A simple voltage meter attached to a metric measuring tape was used to manually measure depth to water in each well, and well stickup height was measured with a metric tape to determine groundwater depth below the ground surface. Surface water heights were manually measured at each staff plate using a metric tape on the channel-side of the T-post or PVC pipe. Water depth data were recorded on standardized datasheets, then entered and processed in MS Excel. Groundwater elevations were determined by subtracting groundwater depth from the RTK-GPS surveyed elevation of the ground at each well, while surface water elevations were determined by subtracting the height of the staff plate above the water surface from the GPS surveyed elevation of the top of the staff plate.

Differences in groundwater and surface water elevations were visually assessed at each well and staff plate location and collectively along each transect by plotting measured water elevation across the spring and summer season for each year. Water elevations were then statistically compared within study reaches and across years using a one-way analysis of variance (ANOVA) with Tukey post-hoc tests, specifically focusing on potential differences in annual summer groundwater baselevels each year. The summer groundwater baselevel for a well was defined as the average of those groundwater elevations measured between August 15 and September 30, when water elevations were typically lowest. Statistical tests were completed comparing summer groundwater baselevels in near-channel wells (within 10 m of the stream channel) and in wells at the meadow edge (excluding those immediately adjacent to ditches or springs) to assess potential differences across years and near ponds.

To relate water elevations to vegetative conditions, we calculated daily groundwater elevations from the biweekly well survey data using linear interpolation and plotted the duration of groundwater within a variety of depth thresholds at each monitoring well. Locations where depth to groundwater remained less than 30 cm for at least 14 consecutive days during the survey season, per the US ACOE definition of 'wetland', were plotted for each year. Similarly, the number of days groundwater elevations remained within 4 cm of the surface creating near saturated conditions were plotted at each well for each year. Finally, we calculated groundwater elevation thresholds indicative of 'wet', 'moist', or 'dry' adapted vegetation communities per Lowry et al. 2011. Locations where depth to groundwater was less than 20 cm for more than 27 days were designated as 'wet' (tolerant of oxygen stress), while locations where depth to groundwater was greater than 55 cm for at least 120 days were designated as 'dry' (tolerant of water stress). Locations with depth to groundwater between these thresholds were designated as 'moist'. These vegetative community types were plotted at each well for each year, and statistically compared at near-channel wells within each year using t-tests.

Eight water stage and temperature loggers (Solnist Levelogger Edge) were installed throughout the study reaches. Two loggers were placed in slotted PVC pipes secured to the channel bank in the main stream channel at the top of the upper meadow upstream of transect 12 and the bottom of the lower meadow downstream of transect 4 (Figure 1). Two loggers were also placed in slotted PVC pipes secured to bank of the main stream channel in the lower meadow upstream of transect 3 and downstream of transect 1. Four loggers were placed in monitoring wells near the main channel, with one logger in each study reach (Figure 1). A logger (Solnist Barologger) was also installed in the lower meadow in a tree adjacent to the meadow edge to record barometric pressure and air temperature. All loggers were set to 15-minute or 30-minute recording intervals and downloaded each spring and fall. Stage data from each of the eight water level loggers was compensated with the barometric pressure data using the Solnist Levelogger software (v. 4.4.0). Stage data was used to assess trends in hydrologic patterns, while temperature data was used to assess differences in surface water, groundwater, and air conditions over time.

Stream Channel Discharge

To characterize stream channel discharge into and out of the upper and lower meadows, discharge measurements were taken periodically near each stream logger location in 2017 and 2019 at a range of high flows in spring and during low flow in summer. Discharge was determined using the velocity-area method (Harrelson et al. 1994), where depth was measured using a top-set wading rod, depth-averaged velocity was measured with a Marsh-McBirney

Flomate, and cross-sectional width was measured using a standard metric tape. Rating curves were developed between the discharge measurements and the stage data recorded at each stream logger location for those flows within the channel. However, when stream flows were high enough to spill out of the channel and onto the floodplain, discharge measurements were difficult to obtain accurately, and were not included in the rating curves.

Results

Site and Climactic Context

The five years of the study from 2015-2019 represented some of the most variable climate and precipitation conditions typically observed in California. 2015 was the driest year of the 2012-2015 drought with the very low annual precipitation (Figure 2) and the lowest annual snowpack in the Sacramento Basin (cdec.water.ca.gov). Although annual precipitation in 2016 was slightly above average, the increased precipitation was substantial enough to end the drought and improve soil moisture and water conditions across the study area. 2017, in contrast, had the highest precipitation on record for the Sacramento basin (Figure 2), with several 5- to 10-year recurrence interval floods occurring in the study area between December 2016 and March 2017 and extended runoff into early summer. 2018 was below average with regard to annual precipitation, while 2019 had above average annual precipitation. However, unlike the warmer climate conditions in 2017 that resulted in much of the winter precipitation falling as rain, 2019 had relatively cooler winter temperatures with the bulk of the precipitation falling as snow between January and March. Cool spring conditions in April and May 2019 resulted in delayed runoff into early summer.

The varying precipitation conditions contributed to corresponding variable surface and groundwater elevations observed throughout the study area across years, but water elevations in the beaver (positive control) study reach were also highly mediated by the degree of beaver activity. In 2015, at the height of the drought, actively maintained beaver ponds created ponded surface water and locally high groundwater elevations at wells adjacent to the ponds. The beaver appeared to maintain their ponds in 2016, but the high winter precipitation in 2017 resulted in meadow-wide flood flows that breached and scoured away most of the beaver dams. In particular, the two large beaver ponds near transects 2 and 3 were drained, with sediment previously trapped behind the dams redistributing in the channel downstream. In summer 2017, the beavers appeared to shift their location to downstream of the study reach, as the dams at each large pond were not repaired and no signs of activity were noted.

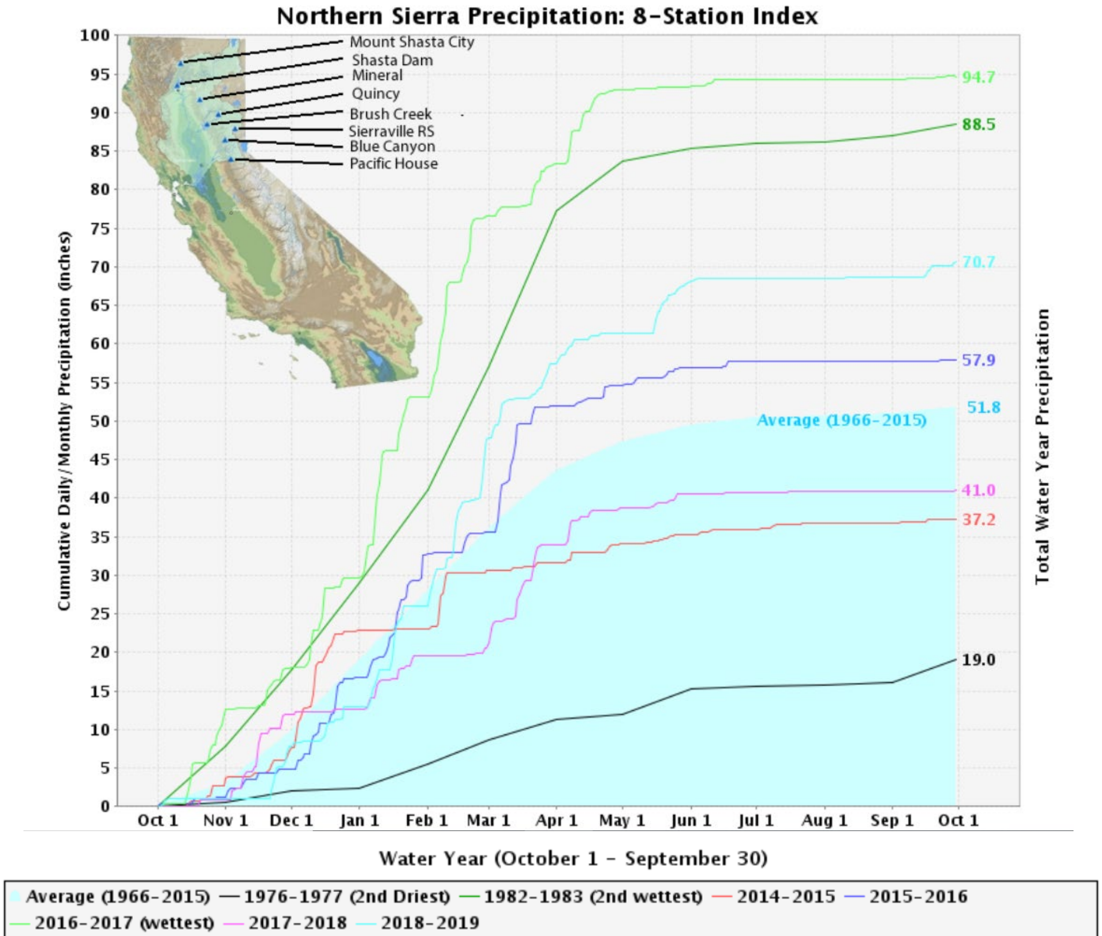


Figure 2. Northern Sierra Precipitation (8-station Index) for the study period (2015-2019), including the second driest and second wettest years for comparison. Data from http://cdec.water.ca.gov.

In early spring 2018, the beavers returned to the lodge adjacent to the large pond just downstream of transect 2, and rebuilt the primary dam. By mid-summer 2018, the beavers had increased the height of the dam at the lodge such that water ponded back to the location of the previous large dam and pond near cross-section 3. They also repaired the dams downstream near transect 1, but did not rebuild the large dam at the upstream end of the study reach near transect 3. In 2019, there was less beaver activity at the large pond with the lodge near transect 2, but the primary dam remained intact and continued to pond water. The downstream dams near transect 1 were actively maintained however, and two new dams were created downstream of transect 1 that extended water laterally out onto the floodplain.

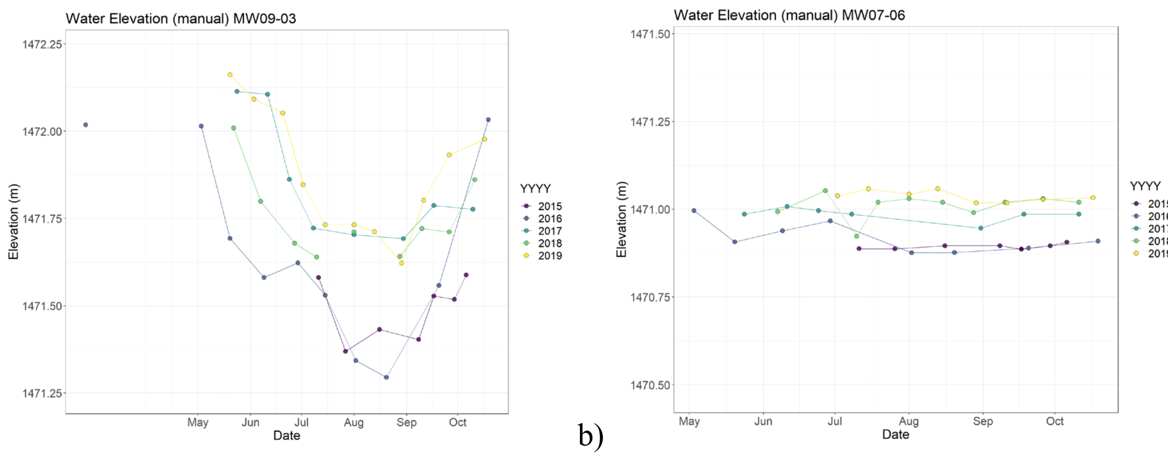
Unlike the natural beaver dams in the beaver reach, the BDAs in the BDA treatment reach remained intact with little damage following the meadow-wide flood flows observed in winter 2017. The BDAs ponded water as expected in spring 2017, but by summer 2017, the BDAs had become leaky and were not ponding water to the top of the BDA structures. The research team decided that some maintenance of the BDAs was needed each spring and summer to maintain full pond capacity, similar to how beavers actively maintain their dams to maximize pond depth. In September 2017, the BDAs were 'resealed' with mud and sedges to maintain their holding capacity, and similar small maintenance activities (plugging holes with rocks, mud and sedges) were required about every 4-6 weeks to maintain full pond elevations over the 2018 and 2019 spring and summer seasons.

Over the course of the study, several equipment repairs and adjustments were needed to facilitate ongoing monitoring. While the PVC monitoring wells were an affordable option compared to the substantially higher cost of stainless steel screened drive-points and well casings, they often required repair or replacement. In the grazed reach and outside the cattle exclosure, many wells were broken during the study period due to damage from cattle. By fall 2018, rebar cages were installed around most wells outside the exclosure in an effort to limit damage. Additionally, because the PVC pipe was not screened, sediment was able to accumulate over time in the bottom of the wells. By 2018 and 2019, several of the wells were re-augered and replaced due to substantial sedimentation. When wells were repaired or replaced, they were resurveyed with the RTK-GPS to determine the new elevation of the top of the well.

The original cattle exclosure was an electric fence installed in fall 2015. But despite some small maintenance of the fence by the cattle managers, the fence repeatedly shorted out on the growing vegetation allowing cattle to enter the exclosure in late summer when vegetation was limited outside the exclosure. In November 2018, TNC funded the installation of a permanent barbed wire fence to better enclose the riparian corridor and keep cows from entering the exclosed treatment areas. This fence worked much better than the previous electric fence in keeping cattle out and allowing vegetation within the exclosure to expand. Although more expensive up front to install, the barbed wire fence did not require any maintenance over the season as the previous electrical fence did, and it successfully kept the cattle out of the treatment areas during the study.

Water Elevation

In general, water elevations across the meadow complex were at the ground surface creating saturated ground conditions in spring following snowmelt and gradually declined as the summer season progressed, until water elevations increased again in fall with the onset of fall precipitation. This seasonal pattern was evident at most wells and stream channel monitoring locations, with the exception of those locations near groundwater discharge at the base of the western hillslope (e.g. MW07-06, MW06-05 on study reach figures in supplemental material) or adjacent to channelized flow along the eastern edge of the treatment reaches (e.g. SP07-01, SP04-01). Figure 3 provides an example of the seasonal variation in water elevation across years at MW09-03 and the consistent water elevations reflecting groundwater discharge near MW07-06.



a) b)

Figure 3. Manual groundwater elevation measurements at monitoring wells a) MW09-03 and b) MW07-06 in the exclosure reach across each sampling season from 2015-2019.

For those sites with seasonal variation in water elevations, the degree to which water elevations changed across each season also varied across years. Some of the wells near the meadow edges of the upper meadow and in the upstream grazed reach varied with water year type, such that they had higher summer groundwater baselevels (average groundwater elevations between August 15-September 30) in the wetter years (2017, 2019), lower groundwater baselevels in the drier years (2016, 2018), and the lowest groundwater baselevels in 2015 during the drought (Figure 4). Similarly, these wells showed a slight delay in water elevation decline in spring of approximately 2-4 weeks in the two wettest years, with declines beginning in early to mid-May in drier years and early June in wetter years. When the summer groundwater baselevels were statistically compared at all meadow edge wells across years within each study reach, 2015 was found to be statistically different with regard to groundwater depth when compared to the other years in the three upper meadow study reaches ($p<0.02$, Table 1). In post-hoc testing in the BDA reach, 2017 and 2019 were significantly different than the other years with higher groundwater baselevels, and 2016 and 2018 were found to have similar groundwater baselevels to each other, but different than either 2015, 2017, or 2019 (Figure 5). There were no statistical differences in groundwater depth at the meadow edge wells across years in the beaver reach ($F=2.37$, $p>0.05$, Table 1).

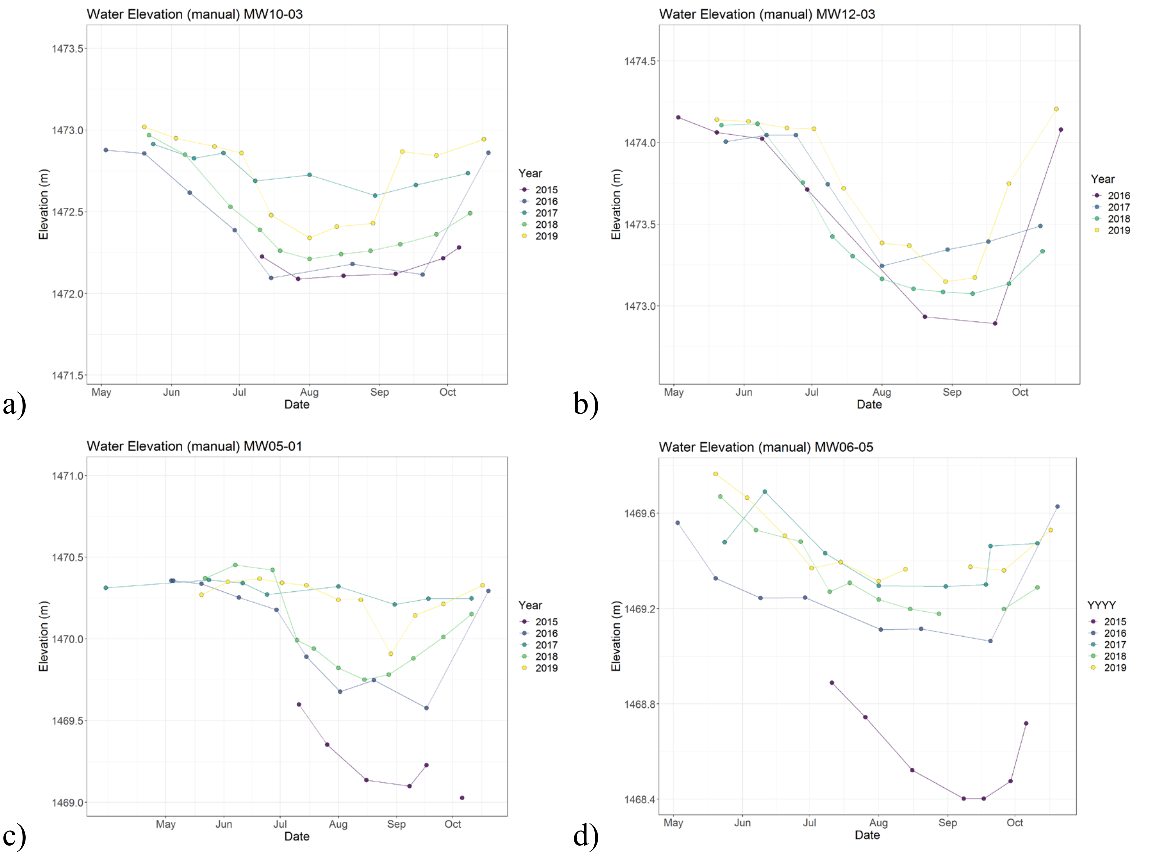


Figure 4. Manual groundwater elevation measurements at monitoring wells a) MW10-03, b) MW12-03, c) MW05-01, and d) MW06-05 located near the meadow edge across each sampling season from 2015-2019.

Table 1. First-order ANOVA results for differences in summer groundwater baselevels across years within each study reach at near-channel and meadow edge locations.

Well Location	Reach	DF	Residuals	F	Pr(>F)
Near-Channel	Grazed	4	70	4.932	0.001
Near- Channel	Exclusion	4	56	3.694	0.01
Near- Channel	BDA	4	49	14.68	<0.001
Near- Channel	Beaver	4	79	3.163	0.018
Edge	Grazed	4	22	6.744	0.001
Edge	Exclusion	4	19	4.146	0.014
Edge	BDA	4	20	40.73	<0.001
Edge	Beaver	4	28	2.37	0.077

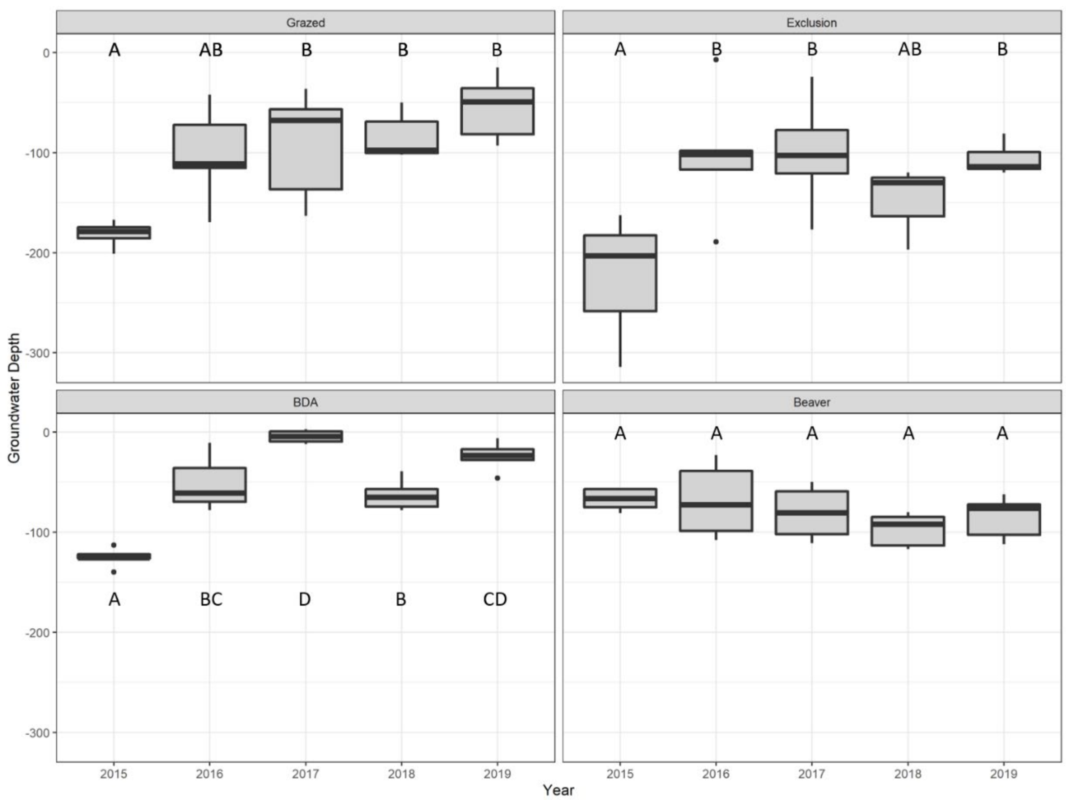


Figure 5. Summer groundwater baselevels (depth to groundwater expressed as a negative number) at all meadow edge wells across years within each study reach. Letters represent statistically significant groupings based on ANOVA post-hoc tests. For example, in the BDA reach groundwater depths were statistically different in 2015 than all other years (A), while 2016 and 2018 were similar to each other (B), but different than 2017 and 2019 (D).

For those wells 5 meters and 10 meters lateral to the main channel, similar patterns of higher groundwater baselevels in wetter years (2017, 2019) versus drier years (2015) were observed at many wells in the grazed and exclusion reaches (e.g. MW09-03 in Figure 3). When data was combined within each study reach and assessed across years, differences in groundwater baselevels between years were significantly different despite high variability ($p<0.02$, Table 1; Figure 6). Interestingly, in the BDA treatment reach, wells near the channels had higher observed groundwater baselevels in 2017-2019 when the BDAs were installed and actively maintained, but when statistically assessed, only 2017 and 2019 were statistically different from the other years, while 2015 had groundwater baselevels significantly lower than the other years ($F=14.68$, $p<0.001$, Table 1). Following installation of the BDAs in 2016, groundwater elevations were 0.25m-0.30m higher at the end of the summer season in 2017 than 2016, while groundwater elevations were similar at the end of the season in 2016 and 2017 in the exclusion reach (see statistical groupings in Figure 6).

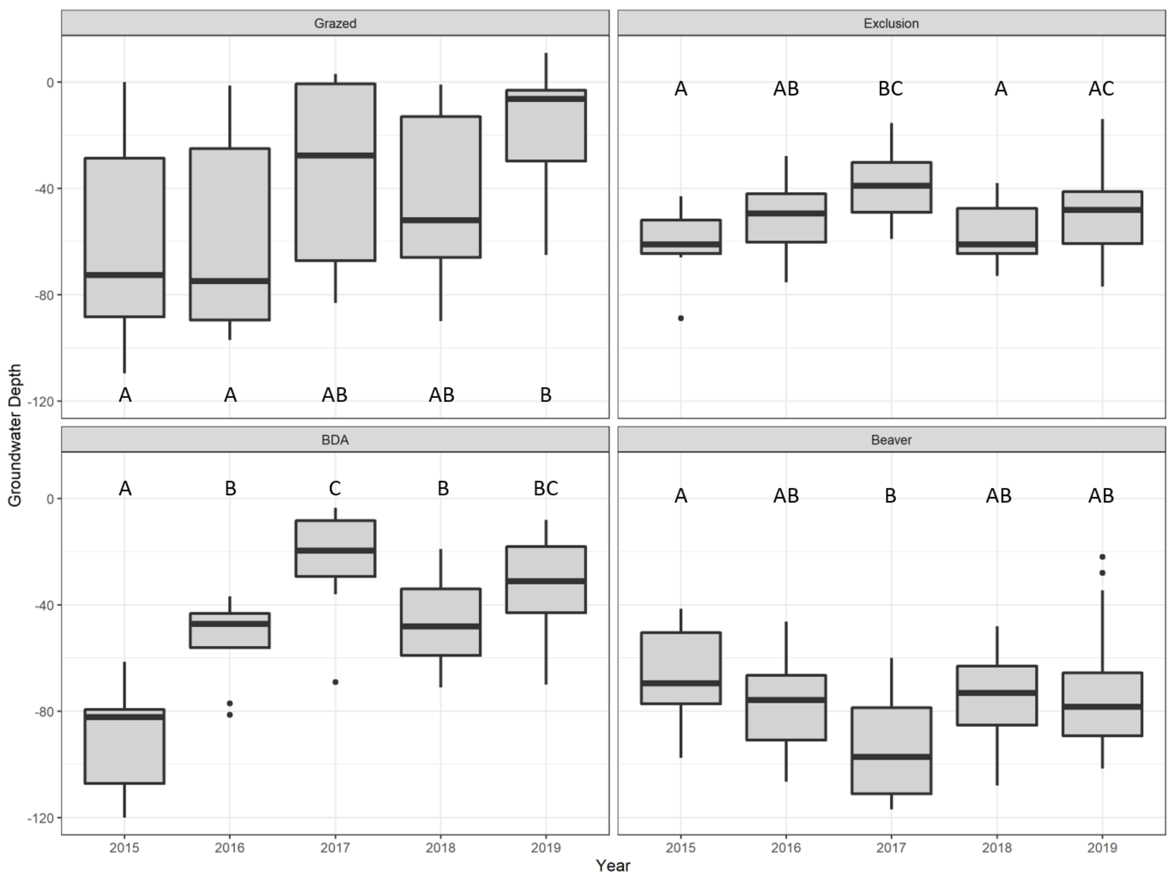
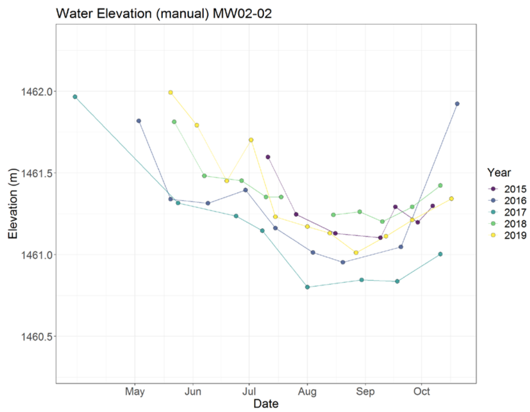
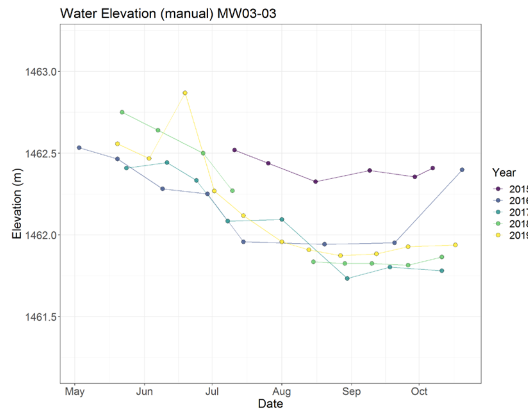


Figure 6. Summer groundwater baselevels (depth to groundwater expressed as a negative number) at all near channel wells across years within each study reach. Letters represent statistically significant groupings based on ANOVA post-hoc tests. For example, in the BDA reach groundwater depths were statistically different in 2015 than all other years (A), while 2016 and 2018 were similar to each other (B), but different than 2017 and 2019 (D).

For those wells near the channel in the beaver reach, groundwater elevations were highest in those years when the beaver dams were actively maintained, including 2015, 2018, and 2019. Most notably, water elevations in 2015 were higher at several wells than in any other year, while water elevations were lowest in 2017 when the dams were breached despite the extremely wet conditions (Figure 7). When statistically compared across the beaver study reach, groundwater baselevels in 2015 were significantly higher than baselevels in 2017 (F=3.163, p=0.018, Table 1), but both years were not significantly different from the other study years due to the high variability between wells (Figure 6).



a)



b)

Figure 7. Manual groundwater elevation measurements at monitoring wells a) MW02-02 and b) MW03-03 in the beaver reach across each sampling season from 2015-2019.

The manual water elevation measurements were also useful for assessing groundwater gradients throughout the study reaches. While groundwater generally flowed down meadow parallel to the main stream channel, groundwater entering from the meadow edges created higher water elevations such that the groundwater gradient was generally north to south across the upper meadow in the widest sections before converging at the upper meadow outlet. In the lower meadow, which was narrower in width, groundwater flowed down meadow parallel to the valley axis, and the groundwater gradient was correspondingly west to east. At the reach scale, lateral groundwater gradients were consistently sloping away from the stream channel, such that losing stream conditions were prevalent at most cross-sections across each season in each year. Figure 8 shows the lateral groundwater gradient sloping away from the main channel at transect 6 when water elevations were below the ground surface across the 2017 season. In the beaver reach, the stream channel showed similar losing conditions such that the ponds were supporting the adjacent meadow when actively maintained, but when the ponds were breached in 2017, adjacent groundwater elevations decreased and the lateral gradient was less pronounced (Figure 9). In each of the study reaches, the influence of the stream channels and ponds on the adjacent groundwater elevations appeared to only extend approximately 10-30 m lateral from the channel.

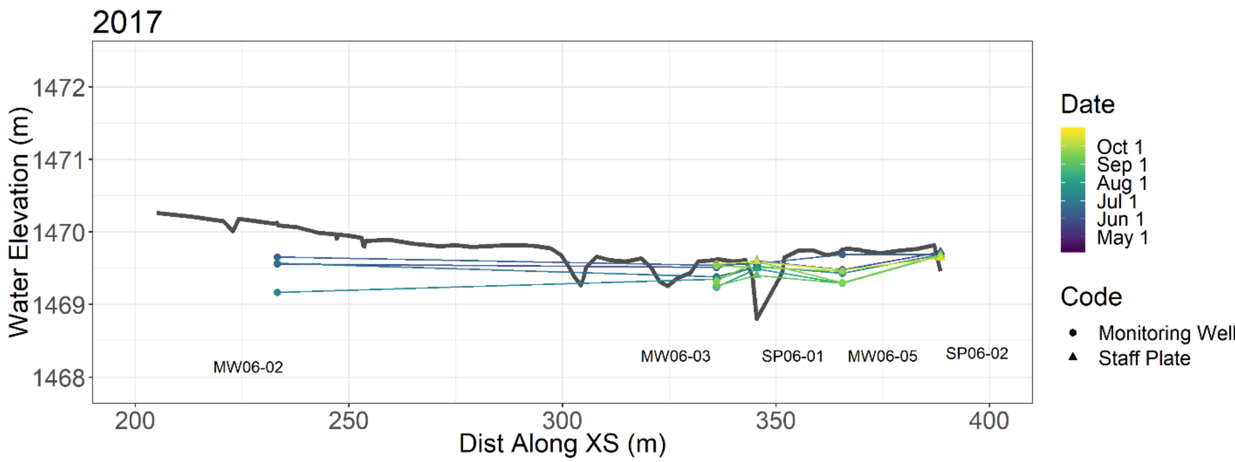


Figure 8. Groundwater elevation along transect 6 across the 2017 sampling season relative to topographic elevation. Solid gray line represents topographic elevation; colored lines represent manually surveyed groundwater elevation at each monitoring well and staff plate on the transect.

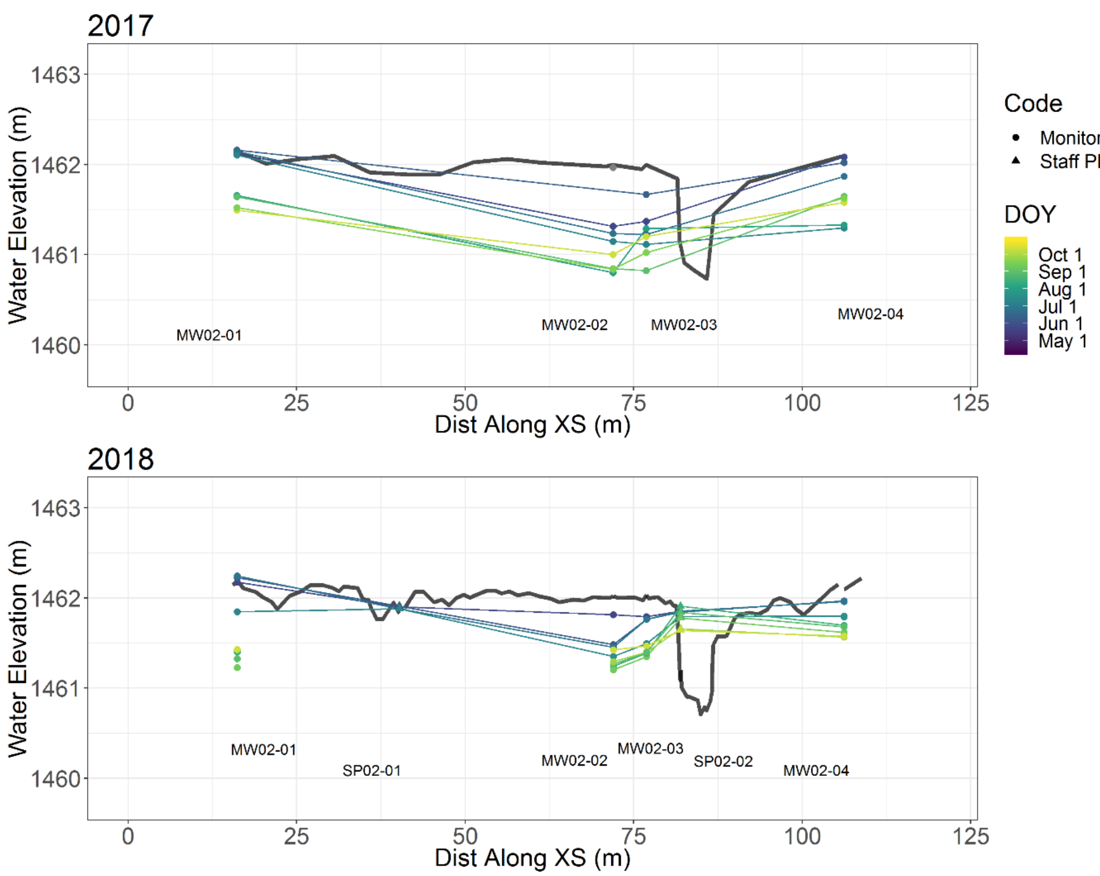
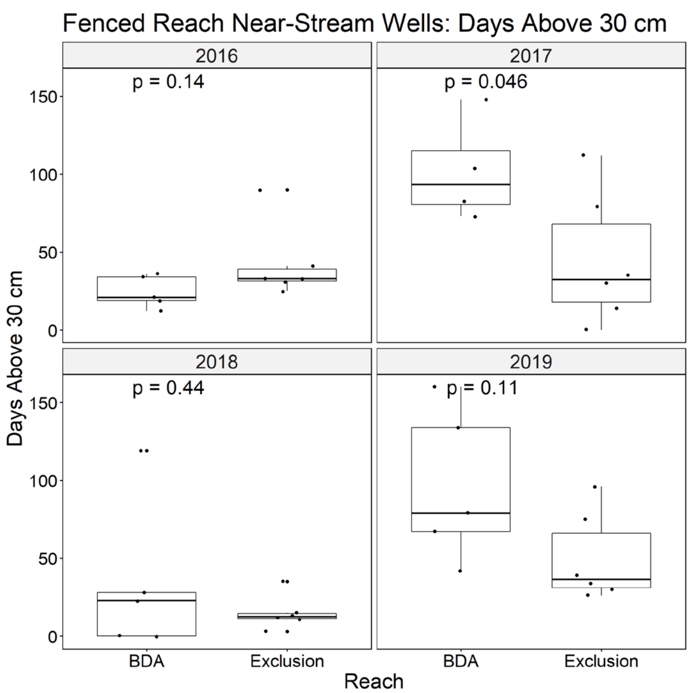


Figure 9. Groundwater elevation along transect 2 across the 2017 and 2018 sampling seasons relative to topographic elevation. Solid gray line represents topographic elevation; colored lines represent manually surveyed groundwater elevation at each monitoring well and staff plate on the transect.

The duration of groundwater elevations within certain thresholds related to vegetative conditions varied across years and between reaches. Similar to comparisons of summer groundwater baselevels across years, wetter years supported higher groundwater elevations for longer durations, and thus were more supportive of wetland and wet vegetation communities. Locations where depth to groundwater was less than 30 cm for at least 14 days, and thus supportive of 'wetland' vegetation, were concentrated around the stream channels, with significantly greater duration of wetland conditions in the BDA reach versus the Exclusion reach in 2017 (Figures 10-11). Water year type also influenced the duration of saturated conditions (depth to groundwater less than 4 cm), with many locations near the channel remaining saturated until early July in 2019 (Figure 12). In the drier years, only wells located near known groundwater discharge locations remained saturated into May.

The variability in water year type greatly influenced the designation of wet, moist, or dry adapted vegetation community type in some meadow edge locations, such as MW09-01 and MW10-01 at the upstream eastern side of the upper meadow (Figure 13). In dry years (2016), groundwater elevations in the northeastern portion of the upper meadow were low sufficiently long enough to create water stress conditions, but in wet years (2019), groundwater elevations were high for sufficiently long enough to create oxygen stress conditions. Conversely, wells near groundwater discharge locations, such as at the upstream end and downstream eastern side of the upper meadow, consistently indicated wet oxygen stress conditions across years. The beaver reach appeared to be the most spatially diverse with regard to vegetation community type but was consistent across years, with most wells remaining one vegetative community type across all years.



a)

Figure 10. Comparison of the number of days depth to groundwater was less than 30 cm at all near-channel wells in the BDA and Exclusion reaches in each year. Statistical significance reflects results from t-tests.

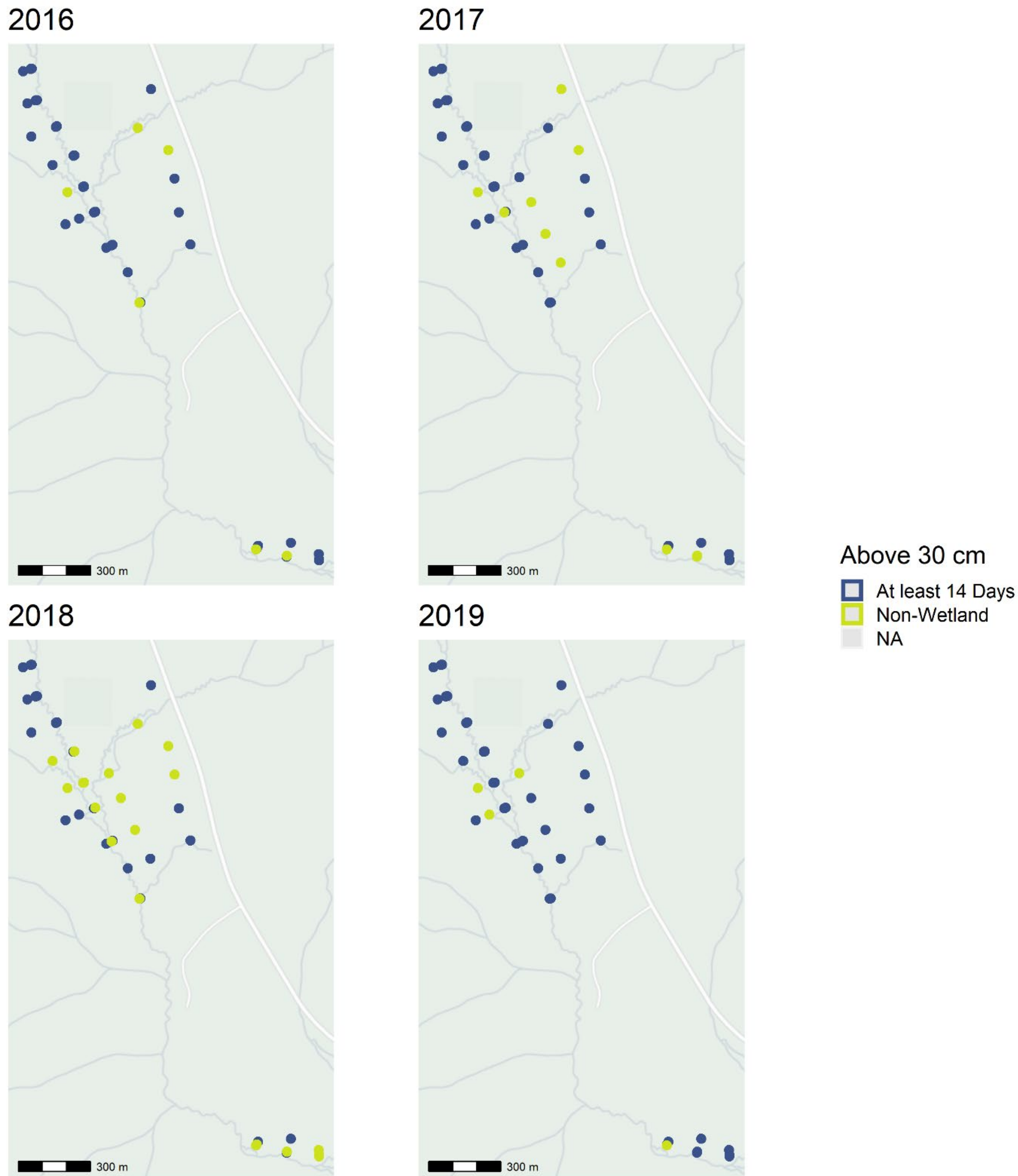


Figure 11. Monitoring well locations in each year with depth to groundwater less than 30 cm for more or less than 14 days indicating 'wetland' or 'non-wetland' vegetation, respectively, per the US Army Corp of Engineers definition.

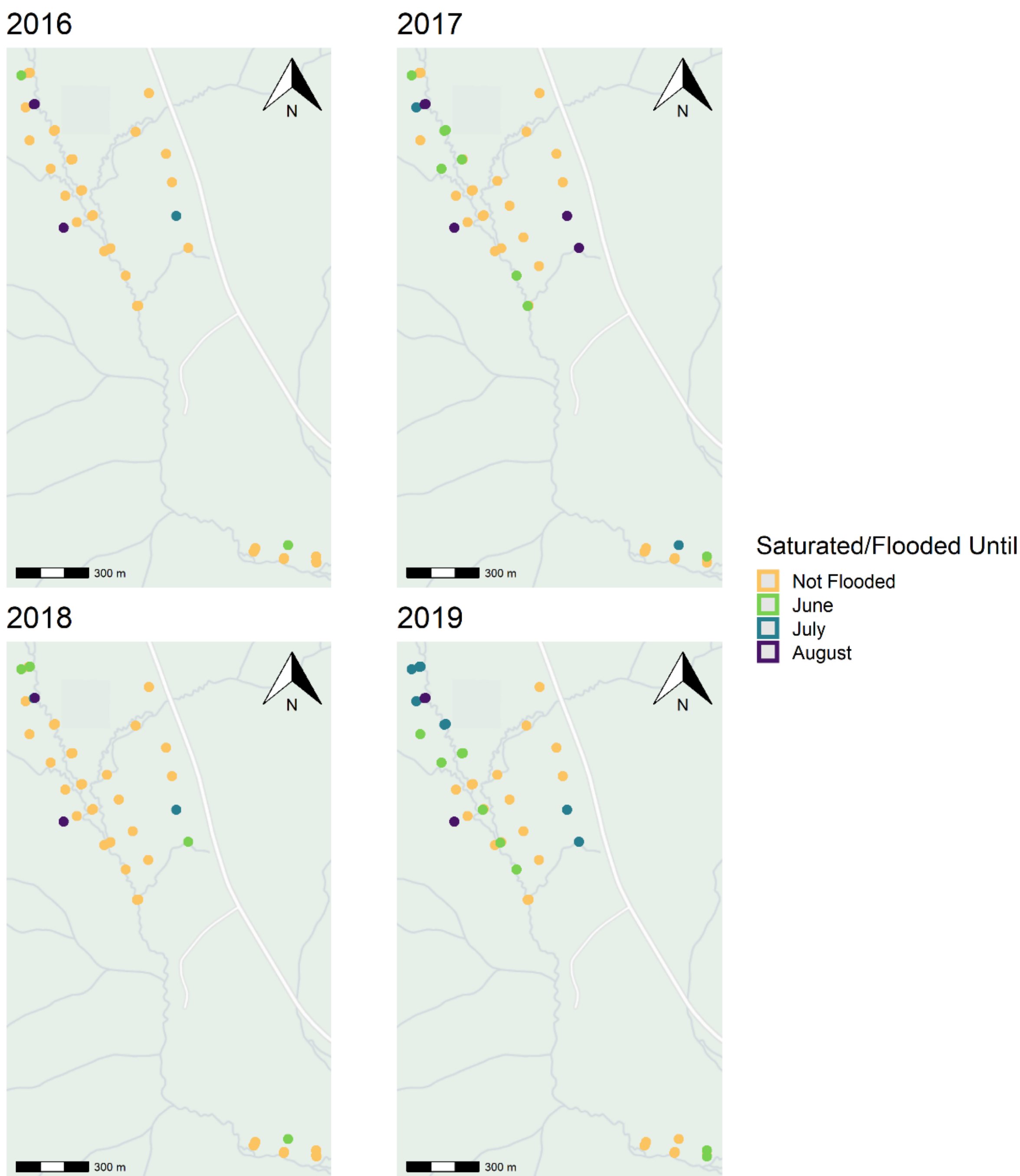


Figure 12. Duration of near saturated water conditions at monitoring wells for each year. Colors represent whether depth to groundwater was less than 4 cm at the beginning of each month (e.g. green represents groundwater saturation through June 1). Locations shown as ‘not flooded’ had depth to groundwater greater than 4 cm prior to June 1.

Figure 13. Monitoring well locations in each year with groundwater elevations indicative of ‘wet’, ‘moist’, or ‘dry’ adapted vegetation communities per Lowry et al. 2011. Locations where depth to groundwater was less than 20 cm for more than 27 days were designated as ‘wet’ (tolerant of oxygen stress), while locations where depth to groundwater was greater than 55 cm for at least 120 days were designated as ‘dry’ (tolerant of water stress). Locations with depth to groundwater between these thresholds were designated as ‘moist’.

The stage data from the water level loggers provided more detail on changes in water elevation across the year. The four loggers that were placed within monitoring wells in each study reach showed generally similar trends across each season and year (Figure 14). Groundwater stage (water level height within well) was highest (closest to the surface) in winter and early spring, and gradually declined across the summer season. Small diurnal fluctuations were observed at each location likely reflecting subtle shifts in evapotranspiration.

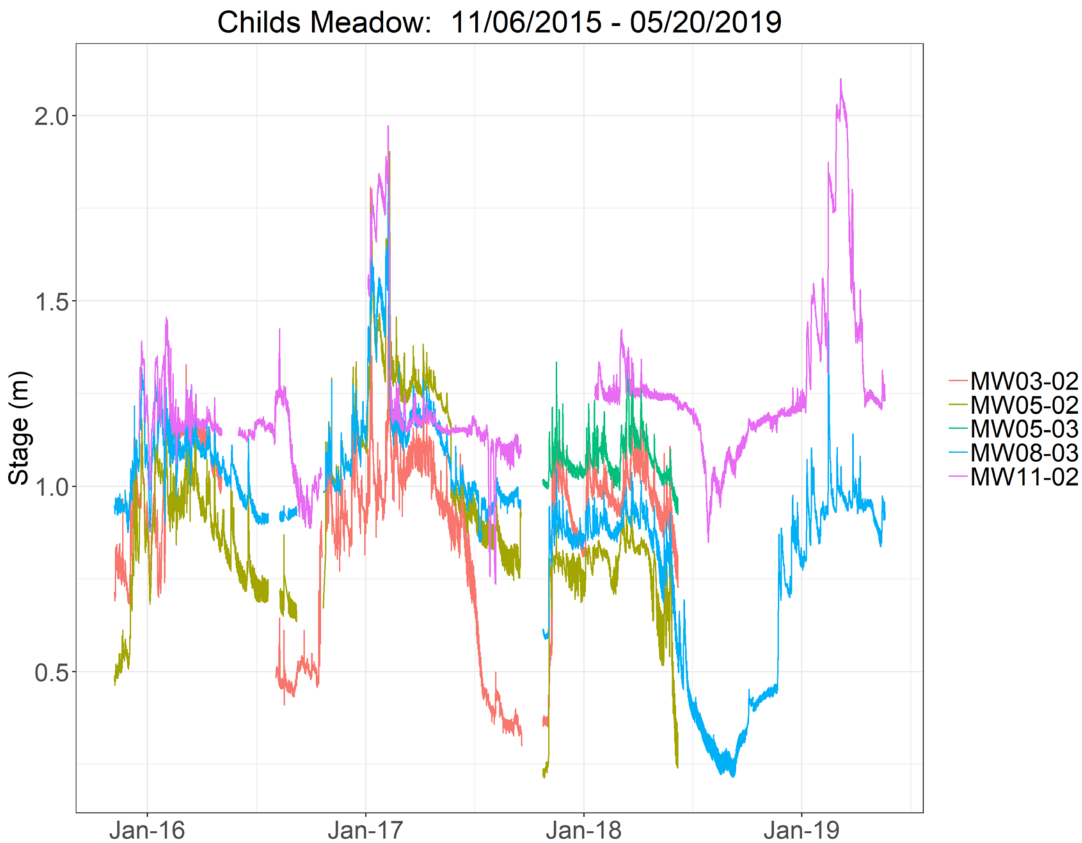


Figure 14. Stage (water level height) of groundwater in a representative monitoring well within each study reach at 15-minute intervals over the course of the study.

Stream Channel Discharge

The water level loggers placed in the main stream channel at the upstream and downstream ends of the upper and lower meadows provided information on the timing and relative magnitude of stream flows across each season. Stage changes corresponded to precipitation inputs and suggested that higher stream flows moved through the meadow system quickly as evidenced by the correlation of high flow event peaks (Figure 15). Summer stream flows were more consistent with relatively stable levels, but also showed small diurnal fluctuations likely related to subtle shifts in evapotranspiration.

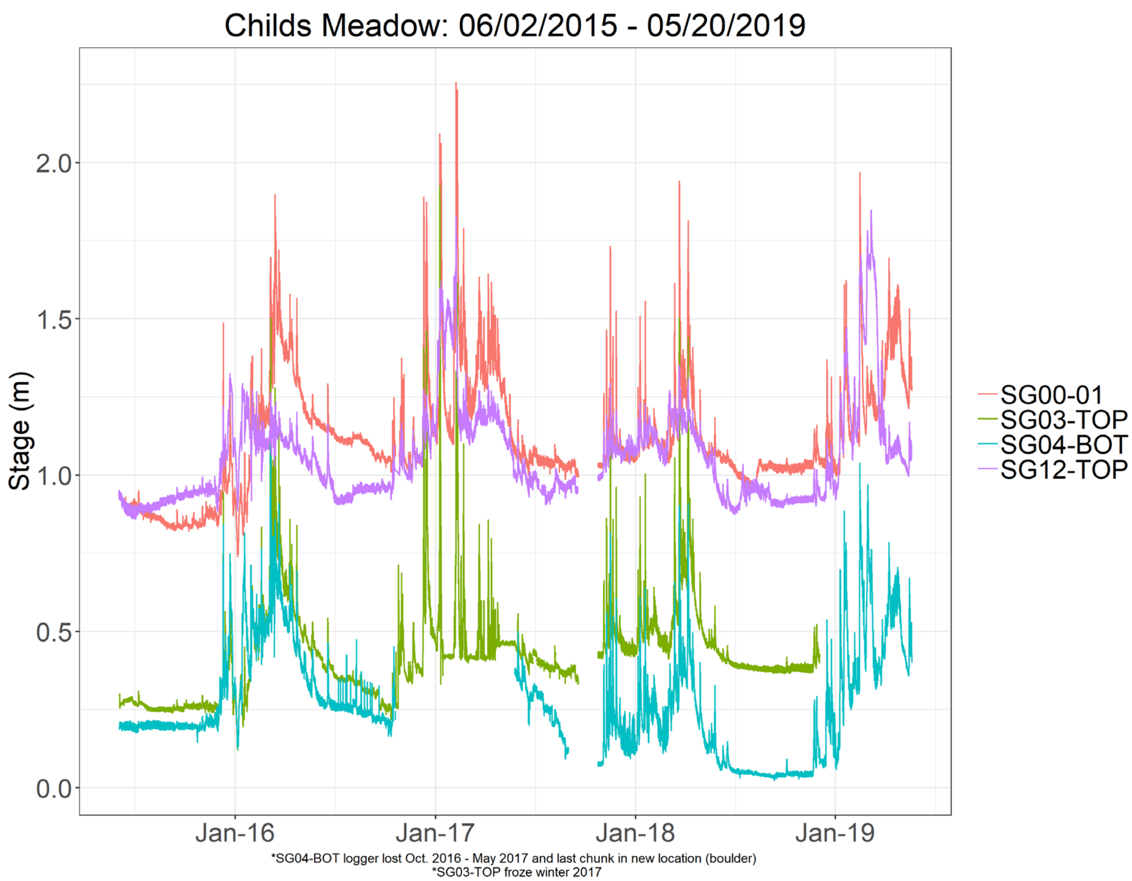


Figure 15. Stage (depth) of surface water in the main stream channel at the top and bottom of the upper and lower meadows. Data reflects measurements taken at 15-minute intervals over the course of the study.

Although discharge measurements were obtained within the stream channel at the upstream and downstream ends of the upper and lower meadows, additional water inputs and outputs to the meadows via shallow subsurface flows could not be accurately measured. Thus, the stream channel discharge data was not sufficient to provide a quantitative assessment of total flow into and out of the upper and lower meadows; however, the patterns in stream channel stage change across each year provide an indication of the relative magnitude of discharge in winter and spring versus summer, and the approximate timing of when water elevations begin to decline in early summer. Stream flows in the channels were 2-5 times deeper in winter and early spring than in summer, and they generally began decreasing in depth in April and stabilizing in early June.

Geomorphology

Methods

To characterize changes in meadow and stream channel topography, each of the twelve permanent transects crossing the full width of the meadow were re-surveyed annually using a Real-Time Kinematic (RTK) GPS system (Topcon HiperLite, Hiper V, and Hiper VR), with the exception of 2016. Topographic surveys of the main channel thalweg were also completed in 2015, 2017, and 2019. In 2018 and 2019, additional surveys were completed in several of the BDA ponds to establish baseline channel conditions of pond topography in order to monitor potential future sedimentation in the ponds. Changes in channel complexity, specifically stream channel length, were analyzed by digitizing visible stream channels in high-resolution unmanned aerial vehicle (UAV) imagery flown in October of 2015 and 2019. These two flights were chosen as they were the comparable with respect to similar meadow-wide extent, degree of resolution, and seasonal timing. Digitized stream layers were compared in ArcGIS (ESRI 2019), and total channel lengths determined in each study reach in each year.

Results

The surveyed cross-sectional and thalweg profiles showed little change across the study, with the exception of the channel thalweg in the beaver reach. Despite the flood flows in winter 2017, the general channel morphology in both the upper and lower meadows remained consistent. Cross-sectional changes were not noted at any transect, including those in the beaver reach where some changes might have been expected due to breaching of the dams (see Figure 16 and supplemental material). Similarly, no changes were observed in the thalweg profiles in the grazed and exclusion reaches (see supplemental material); however, some small erosion and deposition was observed in the BDA reach following the high winter flows in 2017 (Figure 17). In particular, there appeared to be about 10 cm of vertical deposition on the riffles upstream of BDA 6 and in the pool upstream of BDA 2, and approximately 10 cm of vertical erosion downstream of BDA 1 at the downstream end of the upper meadow.

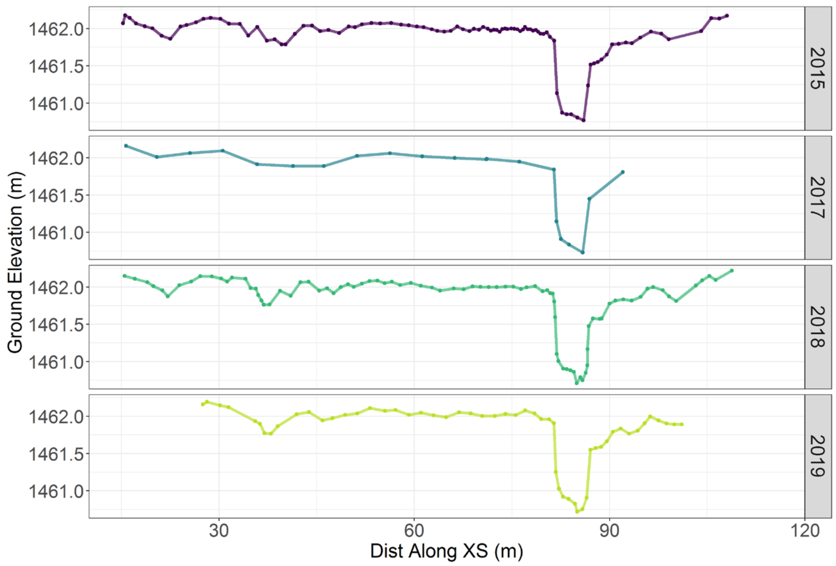


Figure 16. Surveyed cross-sectional topography along transect 2 in the positive control reach from 2015-2019.

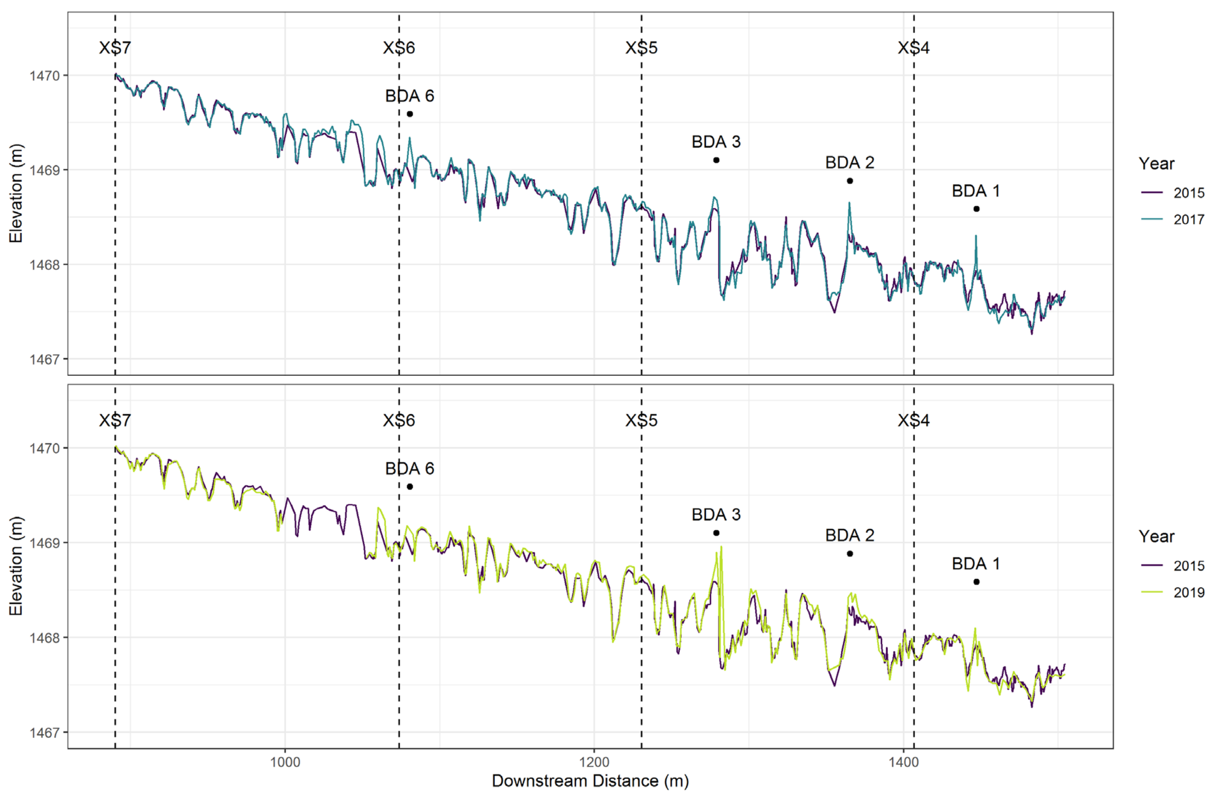


Figure 17. Surveyed longitudinal profile of main channel thalweg through the BDA treatment reach in 2015, 2017, and 2019. Survey points each year were snapped to a channel centerline to allow for direct comparison of thalweg elevation at each transect, which are represented as vertical dashed lines. Transect 4 is approximately 1400 m downstream from the top of the study area.

In the beaver reach, more substantial erosion and deposition was noted in the channel thalweg following the breaching of the dams in winter 2017. Approximately 1 m of vertical erosion occurred downstream of transect 3 after the large beaver dam and pond breached, while 10-40 cm of vertical deposition occurred on the riffles located about 50 m downstream (Figure 18). Similarly, sediment was eroded out of the large pond adjacent to the beaver lodge downstream of transect 2, and deposited throughout much of the main channel downstream through the rest of the study reach. On average, 10-20 cm of vertical deposition occurred in the lower half of the beaver reach following the breaching of the dams.

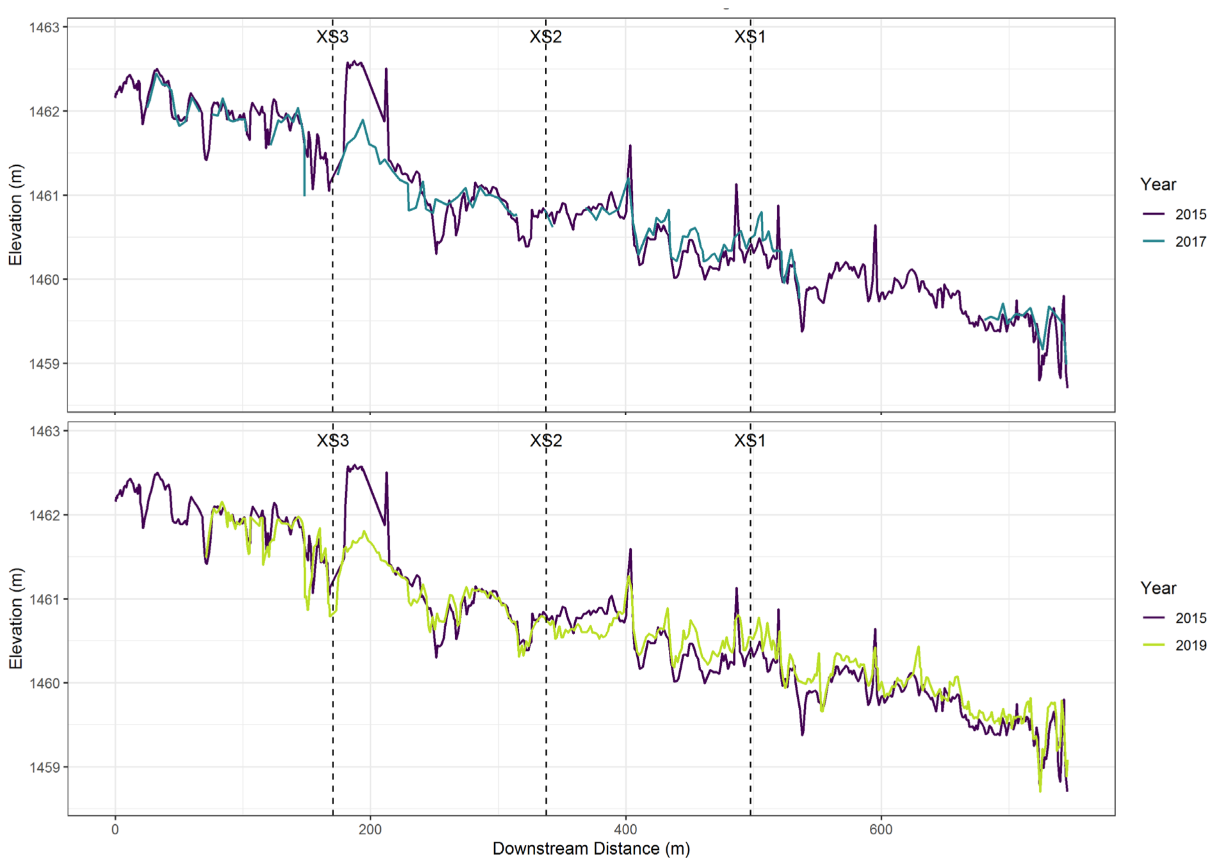
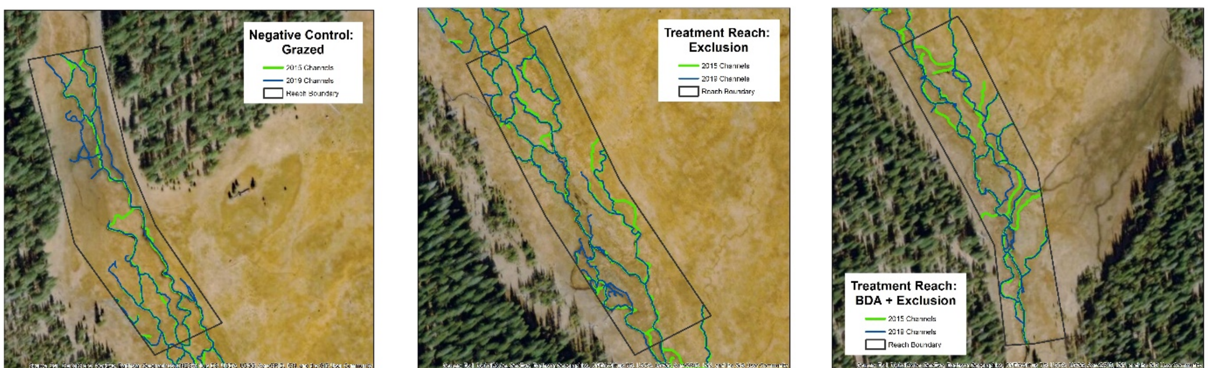


Figure 18. Surveyed longitudinal profile of main channel thalweg through the beaver reach in 2015, 2017, and 2019. Survey points each year were snapped to a channel centerline to allow for direct comparison of thalweg elevation at each transect, which are represented as vertical dashed lines. Transect 1 is approximately 500m downstream from the top of the lower meadow study area. The large beaver dam present at the beginning of the project near 200 m (transect 3) was breached by high flows in winter 2017.

The channel complexity, specifically the length of stream channel as digitized from the UAV imagery, did not change substantially over the length of the study. Figure 19 shows the 2015 and 2019 digitizations for each study reach in the upper meadow. The largest differences between the years occurred in the grazed reach, where a series of side channels west of the main channel were visible and digitized in the 2019 image, but not the 2015 image (Table 2). A few differences were observed in the exclusion reach, both the addition and loss of small channel segments, but together these segments resulted in little net change. In the BDA reach, similar addition and loss of channel segments were observed between 2015 and 2019, but the segments were longer suggesting potentially more change in channel pattern over time. Although both the images were captured in late fall when vegetation senescence had occurred, the degree to which vegetation growth within the exclosure may have obscured remnant or new channels is uncertain. A similar analysis using LiDAR data would provide a more accurate representation of the ground topography and the potential changes in channel complexity.



a b c

Figure 19. Manually digitized stream lines within the a) grazed, b) exclusion, and c) BDA study reaches based on aerial imagery obtained by a high-resolution drone flight in 2015 (green lines) and 2019 (blue lines).

Table 2. Total digitized stream channel lengths within each study reach in the upper meadow as determined from UAV imagery obtained in October of 2015 and 2019.

Upper Meadow Reaches	**Stream Length (meters)**		**Percent Change**
	2015	2019	
Negative Control: Grazed	1653	2104	+27%
Treatment: Exclusion	3021	2934	-3%
Treatment: Exclusion & BDA	2091	2202	+5%
Total	6765	7240	

Water Quality

Methods

Water temperature and electrical conductivity (EC) were manually measured at each well and staff plate every 2-4 weeks during the sampling season concurrent with the water level measurements. A single measurement per location was taken at the time water levels were recorded, thus measurements throughout the study reaches were collected at different times of the day but on the same sampling day. Temperature and conductivity were measured using a YSI Pro30 probe in 2015-2017 and 2019. The probe was unavailable during the 2018 season, so water temperature was measured using a liquid thermometer, and conductivity was not recorded. Due to the single point nature of the manual measurements, these data were broadly representative of seasonal trends in water temperature and EC at each location within the study reaches, but did not reflect potential variation across a day or week.

More detailed sub-hourly data on surface and groundwater temperatures was collected from the stage and temperature loggers (Solnist Levelogger Edge) installed in the main channel upstream and downstream of the upper and lower meadows and in a monitoring well in each study reach. For each logger, the mean daily and maximum daily temperature value was calculated from the sub-hourly data and used to calculate a mean daily value over 7-day moving windows to determine the weekly average temperature (WavgT) and the weekly maximal temperature (WmaxT), respectively. The mean daily temperature values were also assessed over 30-day moving windows to determine the monthly average temperature (MavgT). For the loggers in the stream channels, the maximum weekly average temperature (MWavgT), the maximum weekly maximum temperature (MWmaxT), and the maximum monthly average temperature (MMavgT) were determined for each year to represent the average and maximum values, respectively, during the warmest consecutive seven days of measurements, and the average temperature during the warmest consecutive 30 days of measurements. These metrics are commonly used to assess suitability of stream temperature conditions for various aquatic species (Catenazzi and Kupferberg, 2017; Pyne and Poff, 2017). Although not reflective of surface water temperature differences in each study reach, the temperature data from the stream channels at the top and bottom of the upper and lower meadows provide a general comparison of stream channel temperature conditions across the larger meadow complex.

Results

The water temperature data from the loggers provided information on daily, seasonal, and interannual variation in stream channel temperatures. Loggers at the top and bottom of the upper treatment meadow in the main stream channel showed the most variation in mean daily temperatures ranging from 0-25 ºC annually, while stream temperatures in the lower beaver meadow varied from 0-20 ºC annually (Figure 20). Maximum stream temperatures in summer typically peaked in July, generally mimicking patterns in air temperatures. Summer stream temperatures were notably higher in 2015 than other years, with maximum weekly average temperatures (MWavgT) greater than 19 ºC at all locations (Table 3). In contrast, MWavgT was 18 ºC or less at all locations in 2016 and less than 17 ºC at all locations in 2019. The maximum monthly average temperatures (MMavgT) and maximum monthly maximum temperatures (MMmaxT) showed similar patterns, with 2015 and 2019 the warmest and coolest years at all locations, respectively (Figure 21). Stream temperatures at the upstream and downstream ends of the lower beaver meadow were very similar, with MMavgT slightly lower at the downstream location and MMmaxT slightly higher at the downstream location. In the upper treatment meadow, however, stream channel temperatures varied more widely between the upstream and downstream locations. The upstream location at the top of the upper meadow where groundwater enters the stream channel had the lowest MMmaxT and MWavgT of the four stream channel locations in all years, while the downstream location had the highest MWavgT and MMmaxT of all locations in all years.

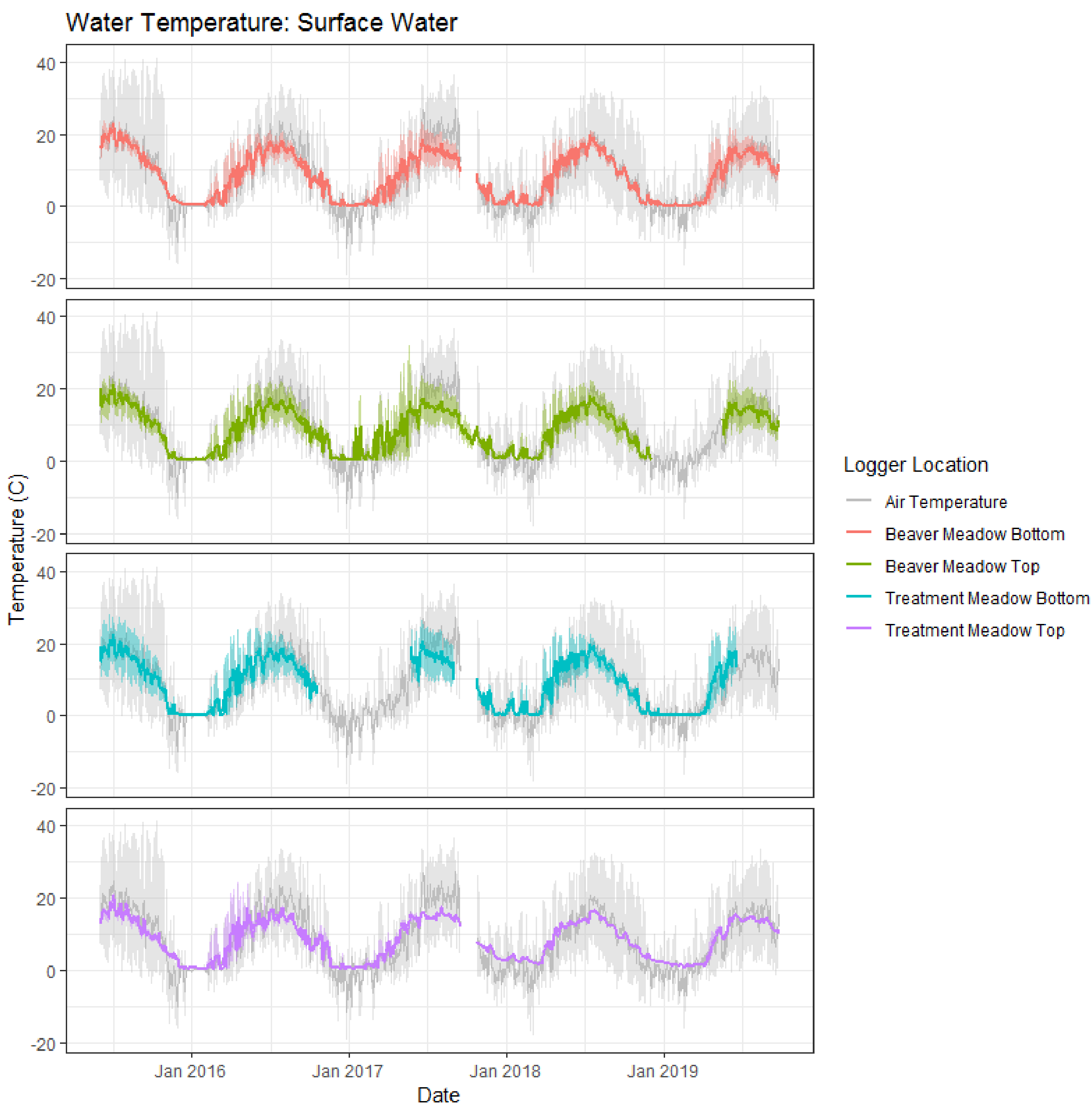


Figure 20. Air and stream channel temperatures at the top and bottom of the upper treatment meadow and lower beaver meadow from 2015-2019. Lines represent average daily temperature, paler ribbons of the same color represent daily minima and maxima.

Table 3. Weekly average, monthly average, and monthly maximum stream temperatures for the warmest week and month, respectively, each year calculated from sub-hourly logger data. Logger locations are shown in Figure 1.

Stream Location	Year	Max Weekly Average Temp (MWavgT)	Max Monthly Average Temp (MMavgT)	Max Monthly Max Temp (MMmaxT)	Date of MMmaxT
SG00_BOT	2015	21.552	20.006	22.815	7/7/2015
SG03_TOP	2015	19.731	18.291	22.190	7/6/2015
SG04_BOT	2015	20.897	19.253	26.297	7/7/2015
SG12_TOP	2015	19.032	17.392	18.447	7/24/2015
SG00_BOT	2016	17.564	16.452	19.482	7/17/2016
SG03_TOP	2016	16.569	15.512	20.863	7/17/2016
SG04_BOT	2016	18.054	16.873	22.253	7/17/2016
SG12_TOP	2016	16.485	15.311	20.003	5/15/2016
SG00_BOT	2017	17.319	16.307	21.397	7/15/2017
SG03_TOP	2017	16.99	15.742	23.503	5/28/2017
SG04_BOT	2017	19.432	17.878	24.488	7/15/2017
SG12_TOP	2017	16.838	15.679	15.950	8/23/2017
SG00_BOT	2018	18.852	17.520	19.682	7/28/2018
SG03_TOP	2018	17.379	16.170	21.137	7/25/2018
SG04_BOT	2018	18.954	17.600	21.724	7/18/2018
SG12_TOP	2018	16.493	15.556	15.683	8/12/2018
SG00_BOT	2019	15.919	15.426	19.488	6/29/2019
SG03_TOP	2019	15.534	14.492	20.280	6/30/2019
SG04_BOT	2019	16.981	14.976	20.961	6/20/2019
SG12_TOP	2019	15.241	14.425	14.655	7/3/2019

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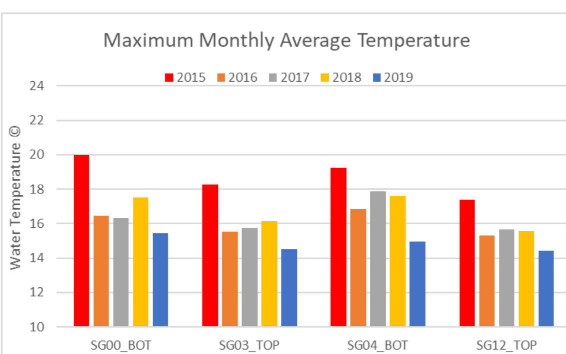

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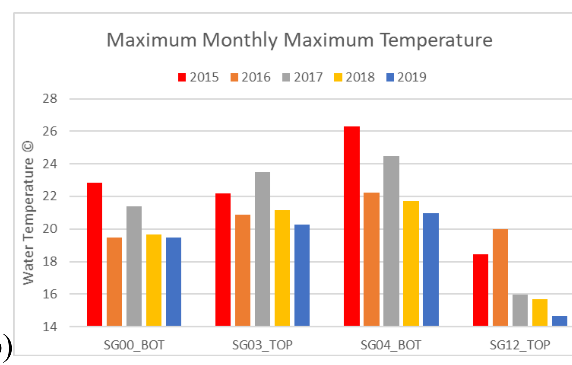


Figure 21. Maximum of the monthly a) average and b) maximum daily temperature in each year from loggers located in the main stream channel. Logger locations are: downstream end of lower beaver meadow (SG00_BOT), upstream end of lower beaver meadow (SG03_TOP), downstream end of upper treatment meadow (SG04_BOT), and upstream end of upper treatment meadow (SG12_TOP).

Groundwater temperatures throughout the meadow complex were fairly consistent across the study reaches and across years varying from about 5-15 ºC annually (Figure 22). Maximum groundwater temperatures were typically observed in early August, while maximum stream temperatures were typically observed in early July. This lag in timing was also observed in winter, with minimum stream temperatures recorded in January, while minimum groundwater temperatures were typically recorded in March.

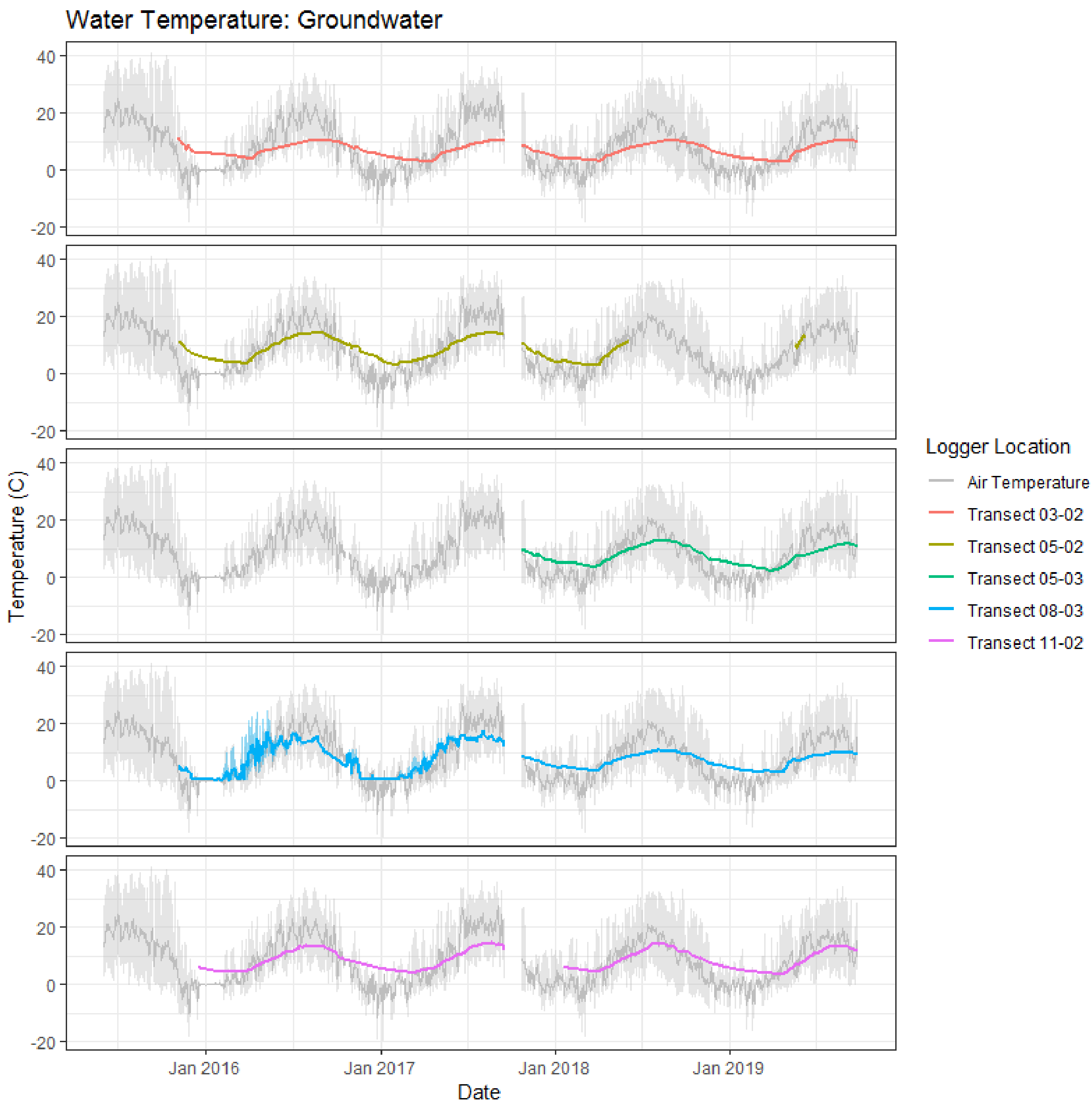
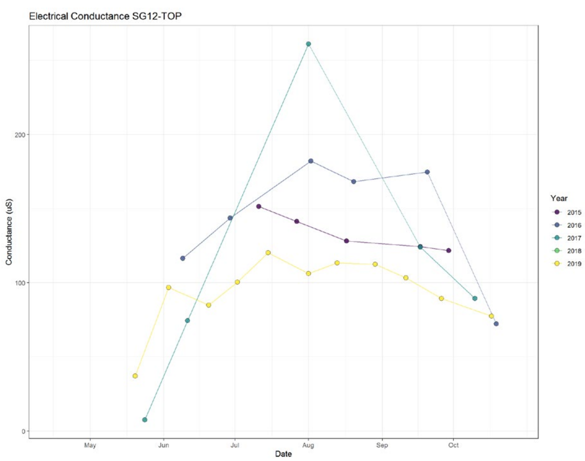


Figure 22. Air and groundwater temperatures at the top and bottom of the upper treatment meadow and lower beaver meadow from 2015-2019. Lines represent average daily temperature, paler ribbons of the same color represent daily minimum and maximum.

The manual water temperature measurements taken concurrent with the water level measurements, while highly variable, did correspond to the broad seasonal trends observed in the logger data. Maximum stream temperatures were typically observed in July, while maximum groundwater temperatures were typically observed in August. Maximum stream temperatures were typically between 20-25 ºC, while maximum groundwater temperatures were typically about 15 ºC. Electrical conductivity (EC) similarly varied widely across the season and between wells, but notable differences were observed between values collected in 2016-2017 versus 2019. A new probe was purchased and used in 2019, and the calibration between the two units appeared to have differed. However, within season trends each year showed that EC values were typically higher in late summer than spring, reflecting the greater relative proportion of groundwater in the meadow. Similarly, EC values in the stream channels were typically lower (less than 100 µs), with the exception of the upstream end of the upper meadow, where groundwater inputs dominate the stream channel and EC was typically greater than 100 µs (Figure 23).



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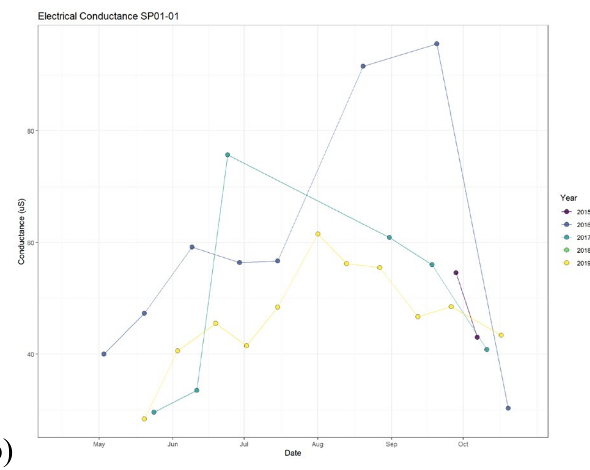


b)

Figure 23. Manually measured electrical conductivity measurements across years at a) SG12-TOP and b) SP01-01.

Aerial Imagery Analysis of Vegetative Conditions

Methods

Within-Season NDVI Trends

Vegetative response to water conditions throughout the growing season was assessed using 3 m resolution 4-band PlanetScope satellite imagery from Planet Labs (Planet Team 2019). Cloud-free images were selected approximately biweekly from snow-off to the end of the growing season (roughly May-October) in 2017, 2018, and 2019, but exact sampling intervals early and late in each season varied due to issues with low-light conditions and image color. Snow-off was determined visually from Planet imagery and was defined as the date when no snow was visible within the meadow complex boundary. Each image was downloaded and processed using R (R Core Team, 2019).

Changes in vegetation greenness over time were characterized by calculating the Normalized Difference Vegetation Index (NDVI = [NIR – red] / [NIR + red]) for each image (Rouse et al. 1974, Tucker 1979). Average NDVI values were compared across the four study reaches plus an additional study reach downstream of the beaver reach where ongoing avian surveys were conducted during the study. Each study reach was approximately 40,000 m^2 and thus roughly comparable in size. Average NDVI values for each study reach were visually and statistically compared across all years, as well as across the growing season. Early, middle, and late growing season was defined by date based on length of time from snow off: early-season was defined as 0-69 days after snow-off, middle-season was defined as 70-129 days after snow-off, and late-season was defined as 130+ days after snow-off. A similar analysis was attempted using the Normalized Difference Water Index (NDWI = [green – NIR] / [green + NIR]) (McFeeters 1996) in order to characterize potential changes in surface water conditions through time. However, surface water could not be uniquely distinguished, as calculations of NDWI did not vary between the shallow, narrow, largely vegetated surface water channels and the surrounding meadow.

Vegetation Extent Over Time

To capture changes in meadow vegetation throughout the project, aerial imagery with centimeter resolution was collected across the entire study extent using unmanned aerial vehicles (UAVs) pre-restoration (October 2015) and post-restoration (October 2019) as well as two-three times per year within the upper and lower meadows between 2017 and 2019. The pre- and post-restoration images were collected across the entire meadow area using a quadcopter carrying a 4-band color infrared camera. The seasonal images were collected during the early and mid-late growing season in the upper and lower meadows individually using a 3DR Solo quadcopter carrying two Canon Powershot S100 cameras, one of which was modified to capture near-infrared instead of visible blue light (camera modification by Llewellyn Data Processing, maxmax.com). The set of images from each seasonal flight was stitched together using Agisoft PhotoScan to create an orthomosaic and a digital elevation model using structure for motion techniques.

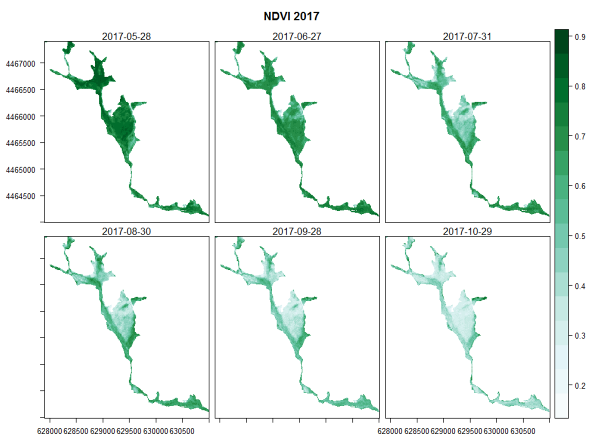
We compared the pre- and post-restoration images visually and quantitatively by calculating indices for vegetation productivity (NDVI) and water content (NDWI). Each metric was summarized for a 1.5 m circular buffer around the near-channel wells (located 5 m and 10 m laterally from the stream channel; 6 wells per reach), and the difference, post-restoration minus pre-restoration value, was calculated at each individual well. The differences in NDVI and NDWI were then analyzed using a one-way Anova with reach as a factor.

In an effort to quantify the aerial extent of willow cover over time from the seasonal UAV imagery, we compared manual digitization of visible willows with two common supervised classification techniques. We explored the techniques using imagery collected in the upper and lower meadow in September, 2017 and the lower meadow in June, 2018. Individual spectral bands (blue, green, red, and near-infrared) from the orthomosaics were combined with three additional spectral indices: Green-Red Vegetation Index (GRVI = [green – red] / [green + red]; Gitelson et al. 2002), NDVI, and NDWI. Together, these seven spectral bands and indices were assessed using the Maximum Likelihood (ML) and Support Vector Machine (SVM) classifiers available in ArcGIS (ESRI, 2019). We manually digitized a set of training polygons for target feature classes (grass/sedge, rock/dead wood, conifers, shadow, soil, water, and willow) for each orthomosaic, and generated 500 random points per class to train each classification. Overall accuracy, Kappa values, and Precision were calculated for each classification to assess classifier performance. Overall accuracy was the proportion of accurately classified training data, Kappa reflected the agreement of training data to classified results adjusted for the possibility that the two agreed by chance, while Precision was defined as the proportion of correctly identified 'willow' out of everything identified as 'willow'. Total willow cover was calculated from the classification results for each reach and compared to the extent of willow cover determined from the manual digitization.

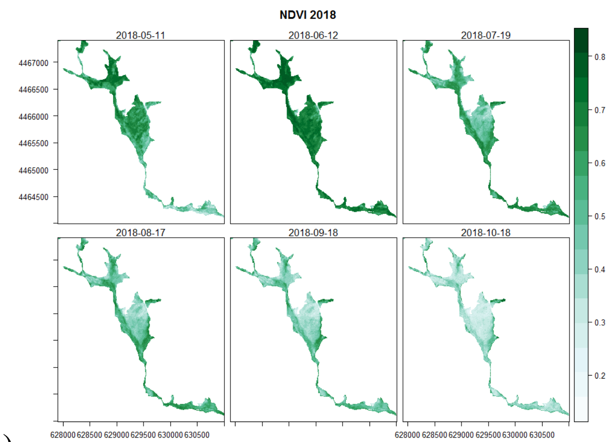
Results

Within-Season NDVI Trends

NDVI trends from the satellite imagery across study reaches were similar from year to year, with some variation in the timing of peak NDVI between water year types (Figure 24). Date of snow-off varied between years, from April 29th in 2017 to April 14th in 2018 to May 9th in 2019. NDVI values decreased at similar rates across the season in each year, and when adjusted for snow-off timing, the date when NDVI values began to decrease in each reach was generally similar across all years (Figure 25). Average annual NDVI values did not vary significantly by year across or within treatments (Figure 26), likely due to the high variation in NDVI seasonally within any given year. In contrast, late-season NDVI values were significantly different from all early- and mid-season values within all reaches (Figure 27). Early and mid-season NDVI values were not significantly different from each other in all reaches, despite lower mean NDVI values mid-season than early-season in the grazed and exclusion reaches. Late-season NDVI values in the beaver reach were also similar to mid-season values in the grazed and exclusion reaches, suggesting greener vegetative conditions persisted later in the growing season in the beaver reach.



a)



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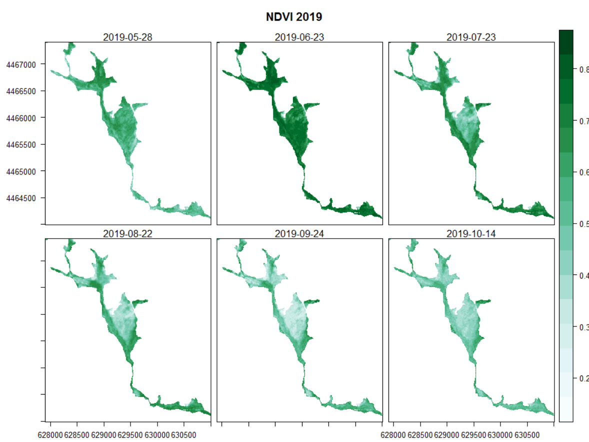

c)

Figure 24. Seasonal NDVI values between May and October in a) 2017, b) 2018, and c) 2019. Darker colors represent higher NDVI values, indicating areas with more green or wet vegetation.

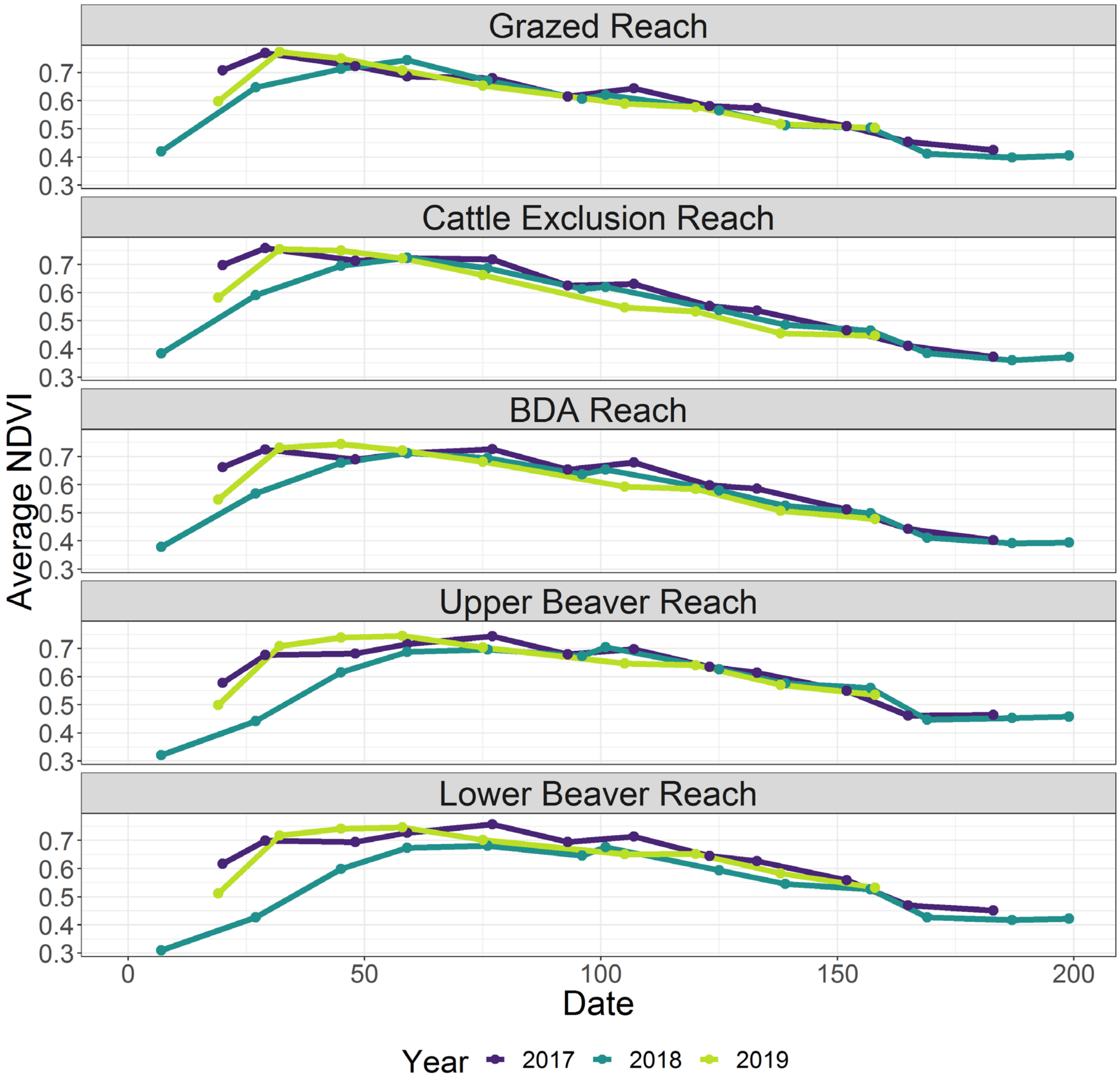

Figure 25. Average NDVI values across the growing season for each year (2017-2019) by study reach, where date is adjusted for the number of days from snow-off (day 0 is first date meadow complex was observed to be snow-free).

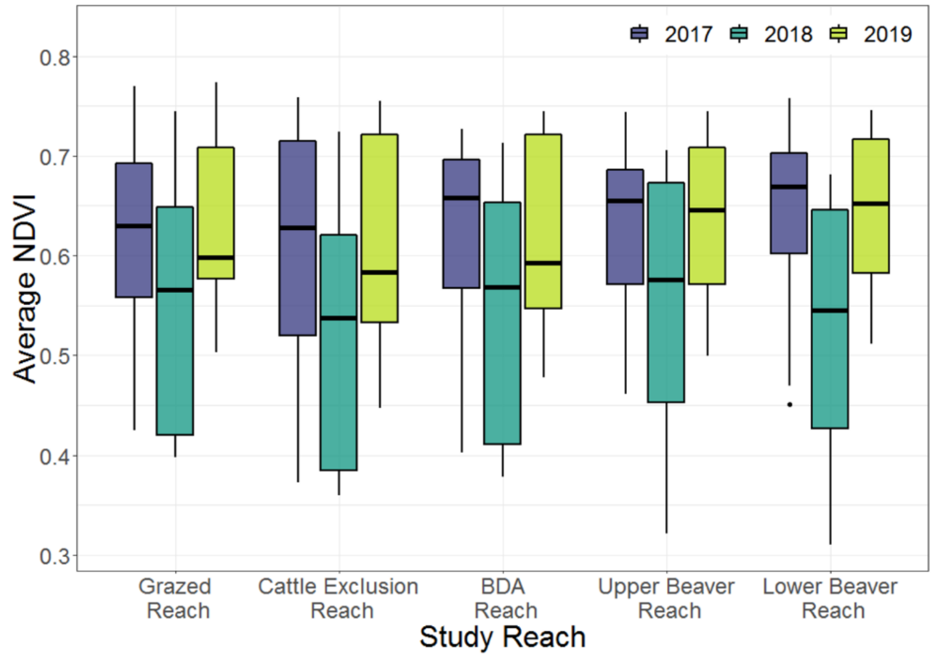

Figure 26. Average annual NDVI scores by year for each treatment reach. No years were significantly different from each other across or within reaches.

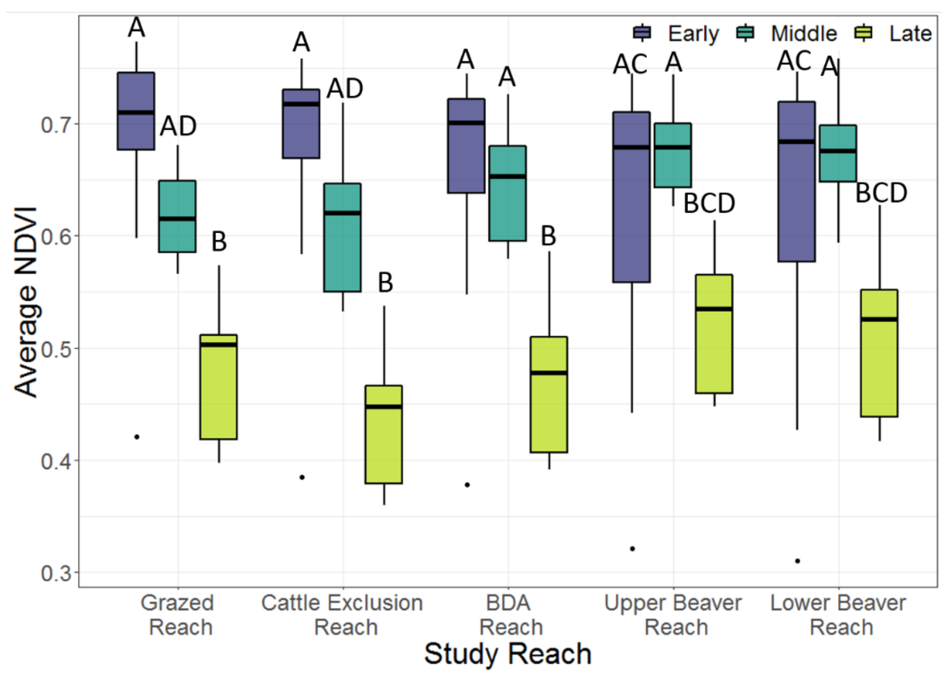

Figure 27. Average seasonal NDVI values across all years for each study reach. Early-season values were defined as 0-69 days after snow-off, middle-season values were defined as 70-129 days after snow-off, and late-season values were defined as 130+ days after snow-off. Boxes that share a letter are not significantly different from one another.

Vegetation Extent Over Time

Vegetation productivity (NDVI) was greater post-restoration than pre-restoration for all near-channel well locations (Table 4), except the two wells close to the beaver dam that washed out in 2017 in the beaver reach which showed a decrease (Figure 28). Similarly, vegetation moisture content (NDWI) was more negative (correlating with higher groundwater elevations) in all reaches in 2019 than in 2015 (Table 4). The least change in both metrics from pre- to post-restoration occurred in the beaver reach, and this reach was significantly different than all other reaches ($P<0.005$). Both vegetation indices are highly correlated with groundwater elevations suggesting the observed differences in index values reflect differences in precipitation and water year type between 2015 (critically dry conditions) and 2019 (wet conditions), rather than differences in restoration treatment.

Table 4. Mean and standard error values for vegetation productivity (NDVI) and vegetation moisture content (NDWI) at near-channel wells within each reach pre- and post-restoration.

Reach	NDVI		NDWI	
	2015	2019	2015	2019
Beaver	0.040 (0.028)	0.071 (0.012)	-0.105 (0.021)	-0.130 (0.012)
BDA	-0.012 (0.016)	0.094 (0.012)	-0.035 (0.014)	-0.142 (0.013)
Exclosure	-0.019 (0.019)	0.119 (0.009)	-0.041 (0.020)	-0.155 (0.012)
Grazed	0.019 (0.037)	0.225 (0.018)	-0.092 (0.047)	-0.243 (0.018)

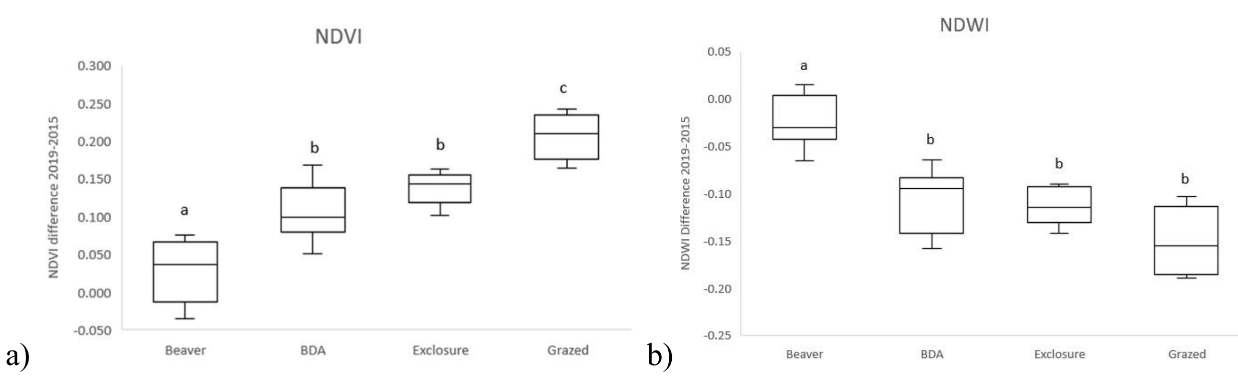

Figure 28. The difference from 2019 to 2015 in a) vegetation productivity (NDVI) and b) vegetation moisture (NDWI) at near-channel wells by study reach.

The supervised classifications of willow features versus other categorized surface features within the seasonal 2017 and 2018 UAV imagery provided highly variable results. When compared to manually digitized willow cover estimates, both supervised classification methods consistently overestimated the extent of willow cover by two-five times the area (Table 5). The Support Vector Machine (SVM) classifier had higher overall accuracy and Kappa scores than the Maximum Likelihood (ML) classifier; however, ML willow cover estimates were consistently more similar to manually digitized willow cover estimate than SVM willow cover estimates. In general, these pixel-based classifications did not effectively differentiate different vegetation types, especially willow. During the growing season (July), willow and pine trees had similar spectral signatures across bands, while at the end of the growing season (October), senesced sedges and willows were not well differentiated. As a result, manually digitizing the extent of willow cover from the UAV images over time was a more accurate method to assessing potential changes in cover, and will be more consistent method for monitoring in the future.

Table 5. Comparison of willow extent estimates from two supervised classifications to willow extent calculated from manual digitization of visible willows. Imagery was collected in September, 2017 and June, 2018. Overall accuracy is the proportion of accurately classified training data; Kappa reflects the agreement of training data to classified results adjusted for the possibility that the two agree by chance; Precision is the proportion of correctly identified willow out of everything identified as willow.

Meadow	**Year**	**Classifier**	**Overall Accuracy**	**Kappa**	**Precision**	**Willow Cover (m^2)**
Upper	2017	Maximum Likelihood	0.600	0.533	0.591	624.8
Upper	2017	Support Vector	0.709	0.660	0.563	9727.3
Upper	2017	Manually Digitized	n/a	n/a	n/a	259.8
Lower	2017	Maximum Likelihood	0.723	0.677	0.459	4788.0
Lower	2017	Support Vector	0.778	0.741	0.544	9252.5
Lower	2017	Manually Digitized	n/a	n/a	n/a	3540.7
Lower	2018	Maximum Likelihood	0.757	0.717	0.794	5110.7
Lower	2018	Support Vector	0.781	0.744	0.760	5652.2
Lower	2018	Manually Digitized	n/a	n/a	n/a	3615.6

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Appendix B - Abundance and Distribution of Cascades Frogs

Native montane amphibians in western North America have experienced precipitous declines due to a range of threats including disease, habitat degradation, and climate change. Functioning wet meadows are important habitats for declining Sierra Nevada amphibians because they provide necessary shallow, protected breeding and rearing conditions throughout the summer. Sierran meadows are complex with spatially and temporally variable habitats that may facilitate amphibian species persistence in the uncertain environments of mountain ecosystems. However, the widespread degradation of wet meadows in the Sierra Nevada has resulted in the deterioration and loss of many of these critical habitats. Meadow restoration is an important tool for recovering wet meadow habitats within degraded systems.

The Childs Meadow demonstration project provided an opportunity to assess the distribution and survival of an at-risk amphibian, the Cascades frog (*Rana cascadae*), in relation to a range of meadow conditions including a cattle excluded and beaver-inhabited reach (positive control, Beaver Reach), a reach where cattle were excluded and six beaver dam analogs (BDAs) were constructed in the channels in the fall of 2016 (BDA Reach), a reach where cattle were excluded (Exclosure Reach) and a reach that was uninhabited by beaver and grazed by cattle (Grazed Reach). The distribution of the four 400 m long reaches and locations of surveyed Cascade frogs is represented in Figure 1. We conducted repeated visual and capture-mark recapture surveys from the fall of 2014 until September 2019 (Table 1).

Throughout the six years, Cascades frogs were predominantly found in the beaver reach and were closely associated with slow or still-water habitats adjacent to the beaver dams. This was most evident in 2015 when beavers maintained near constant water levels across the meadow even during severe drought conditions. 2015 also proved to be the best year for recruitment of juvenile Cascades frogs, and most frogs were found in habitats associated with beaver dams (Figure 2). In 2016, the dams were still intact, but no beaver activity was detected in the reach. Without active maintenance, some of the shallow backwaters that had been used by Cascades frogs for breeding dried before larvae had a chance to metamorphose, and we saw a reduced number of juvenile frogs. When the beaver dams breached in the winter of 2017 and the upper dam stopped backing water, even fewer frogs were found in the reach (Table 2) and locations of frogs moved closer to the remaining surface water associated with the main channel and a few off-channel pools along a remnant channel on the north side of the reach (Figure 3). In 2018 and 2019, beaver began maintaining the lower beaver dam and some frogs were seen nearby, however, Bd loads on frogs spiked during these years and apparently had devastating effects on the Cascades frog population. We recaptured fewer frogs and saw a near complete loss of juveniles in 2019 (Figure 4). Overall numbers of frogs observed and recapture rates for all life stages decreased over the course of the study (Table 2, Figure 5).

In the BDA reach, in all years we only found a few frogs, and none seemed to stay in the reach long. However, after the installation of the BDAs, we began to see juvenile frogs using the shallow backwater habitat caused by the BDAs, and we found two Cascades frog egg masses in a BDA backwater in the spring of 2019.

Table 1. Amphibian survey effort at the study reaches. Most surveys include a double survey and took multiple days to complete. The beaver dam analogs were installed after the surveys in 2016.

2014		2015		2016		2017		2018		2019	
Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
27-Oct	27-Oct	8-May	11-May	1-May	2-May	24-May	25-May	27-May	28-May	5-Jun	6-Jun
		10-Jun	12-Jun	17-May	18-May	1-Jun	1-Jun	21-Jun	22-Jun	1-Jul	1-Jul
		9-Jul	10-Jul	7-Jun	9-Jun	9-Jun	10-Jun	24-Sep	27-Sep	18-Jul	18-Jul
		26-Jul	27-Jul	27-Jun	29-Jun	23-Jun	24-Jun	19-Oct	19-Oct	27-Jul	27-Jul
		16-Aug	17-Aug	13-Jul	14-Jul	7-Jul	8-Jul			20-Aug	20-Aug
		8-Sep	9-Sep	31-Jul	1-Aug	31-Jul	1-Aug			3-Sep	3-Sep
		6-Oct	7-Oct	16-Aug	17-Aug	30-Aug	31-Aug			12-Sep	12-Sep
				16-Sep	17-Sep						

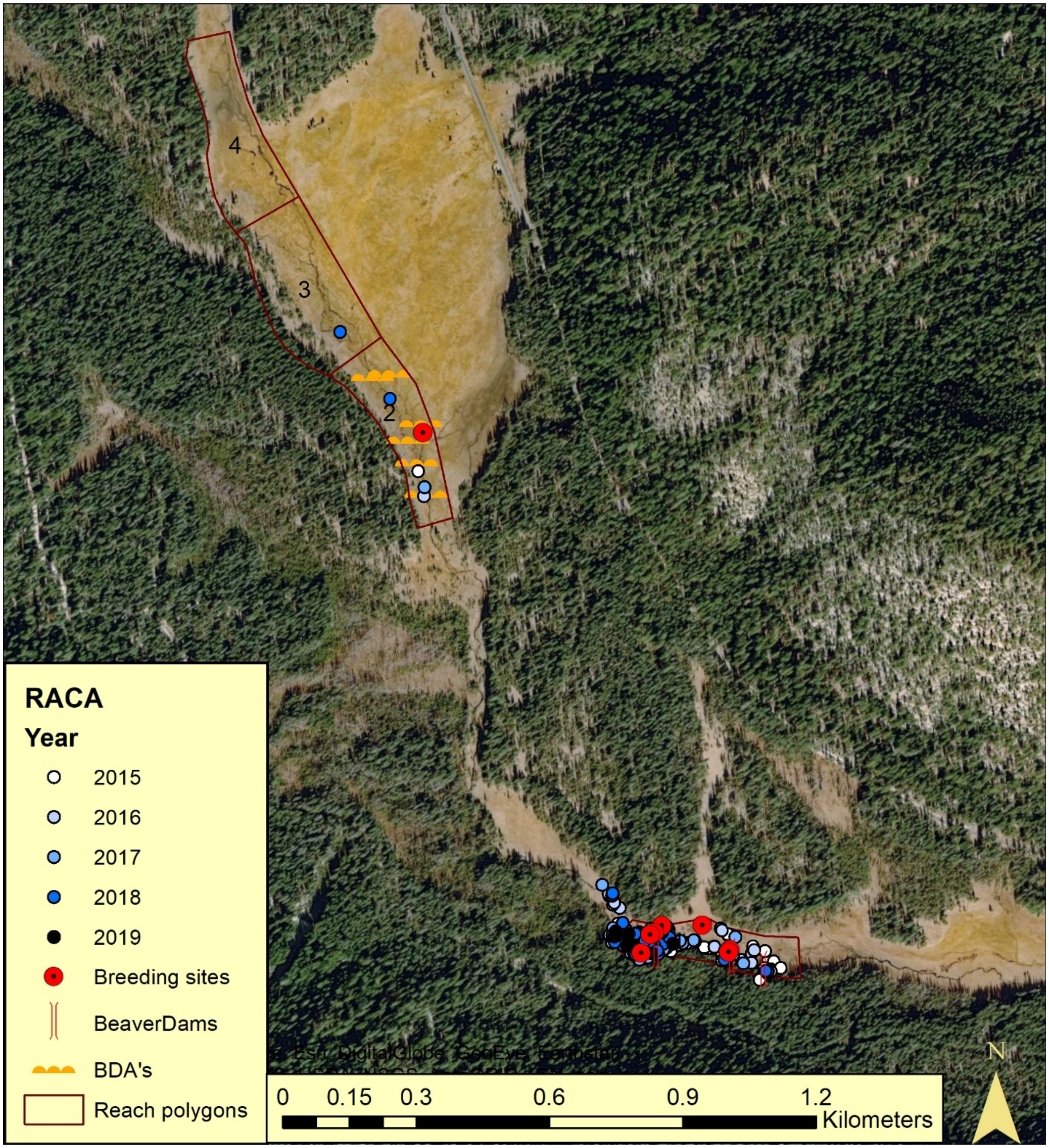

Figure 1. Study reaches and locations of Cascades frogs (*Rana cascadae*) color-coded by the survey year they were found.

Table 2. Annual mean and maximum number of Cascades frogs (*Rana cascadae*) seen in visual encounter surveys for the two control and two treatment reaches.

	2015		2016		2017		2018		2019	
Reach	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
+ Control										
Adult	4	7	7	11	6	8	6	8	6	8
Subadult	6	9	6	9	3	5	5	7	1	1
YOPY	4	5	2	4	2	3	3	3	1	1
Metamorph	29	68	15	21	10	14	43	43	0	0
Egg mass		10		10		6		3		1
BDA, no cattle										
Adult	1	2	0	1	0	1	0	0	0	1
Subadult	0	0	0	1	0	0	0	0	0	0
YOPY	0	0	0	0	0	0	0	0	0	0
Metamorph	0	0	0	0	1	2	1	2	0	0
Egg mass										2
No cattle										
Adult	0	0	0	0	0	0	0	0	0	0
Subadult	0	0	0	0	0	0	0	0	0	0
YOPY	0	0	0	0	0	0	0	1	0	0
Metamorph	0	0	0	0	0	0	0	0	0	0
Egg mass										
- Control										
Adult	0	0	0	0	0	0	0	0	0	0
Subadult	0	0	0	0	0	0	0	0	0	0
YOPY	0	0	0	0	0	0	0	0	0	0
Metamorph	0	0	0	0	0	0	0	0	0	0
Egg mass										

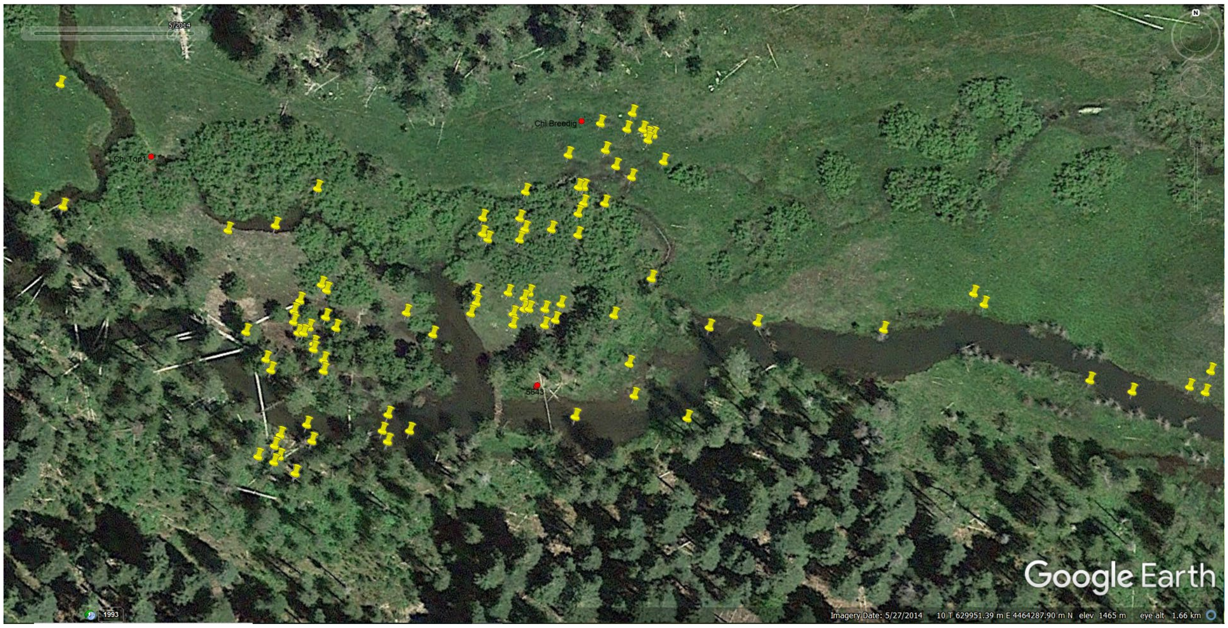

Figure 2. Locations of Cascades frogs (*Rana cascadae*) in the beaver control reach.

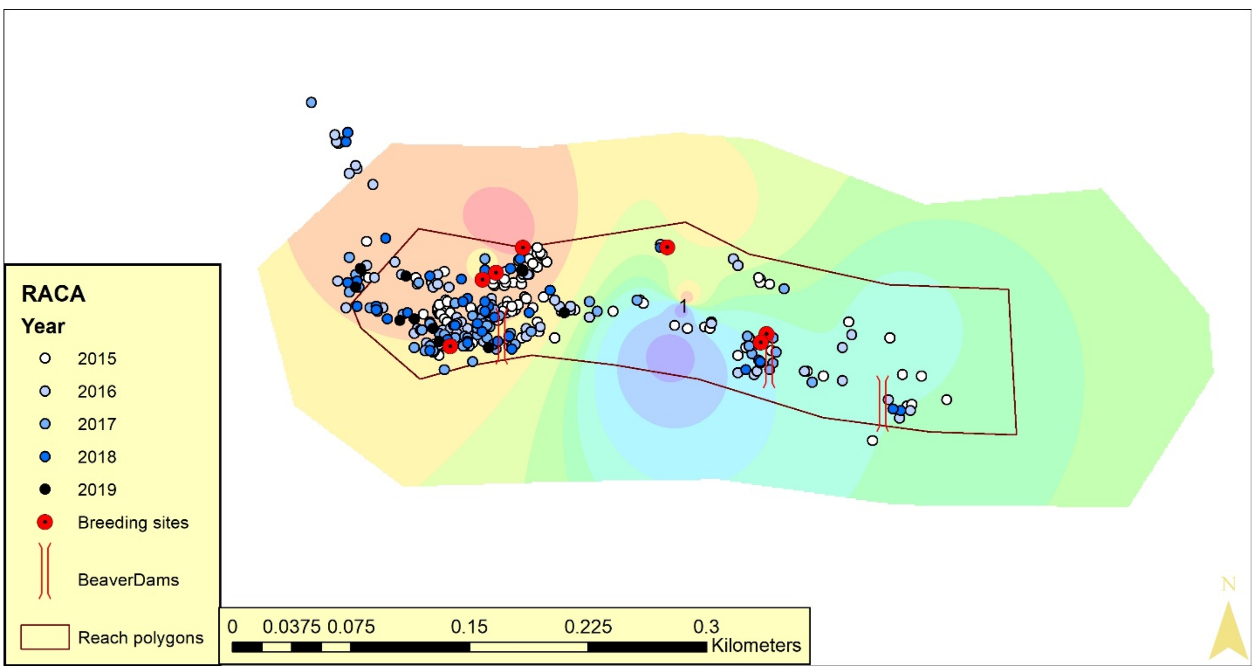

Figure 3. Dots represent locations of Cascades frogs (*Rana cascadae*) color-coded by year in the beaver reach. Background colors show the change in ground water elevation between 2015/2016 and 2018 with red representing the greatest change toward a decreasing water table elevation and blue representing the least change (most stable groundwater elevation between years). The upstream beaver dam on the west side of the reach washed out in the winter of 2017, while the downstream dam remained intact even after the beavers stopped maintaining it.

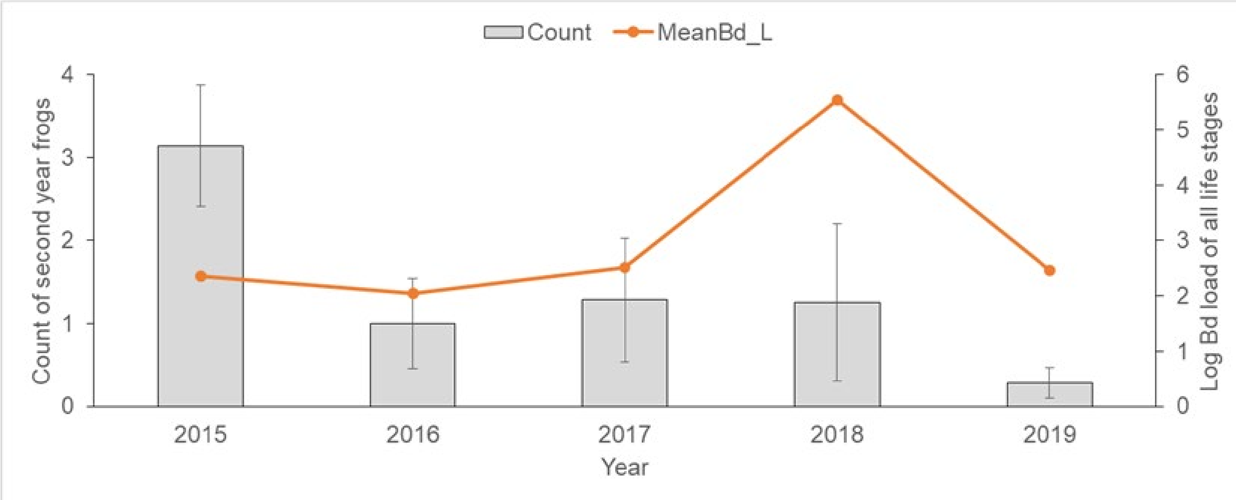

Figure 4. Annual summary of individual second year (juvenile) Cascades frogs observed during surveys. and the mean annual load of *Batrachochytrium dendrobatidis* (Bd), the cause of the amphibian disease chytridiomycosis, quantified from skin swabs of Cascades frogs. The spike in Bd loads in 2018 may have caused reduced over winter survival of young frogs and the reduced number of juvenile frogs found in 2019.

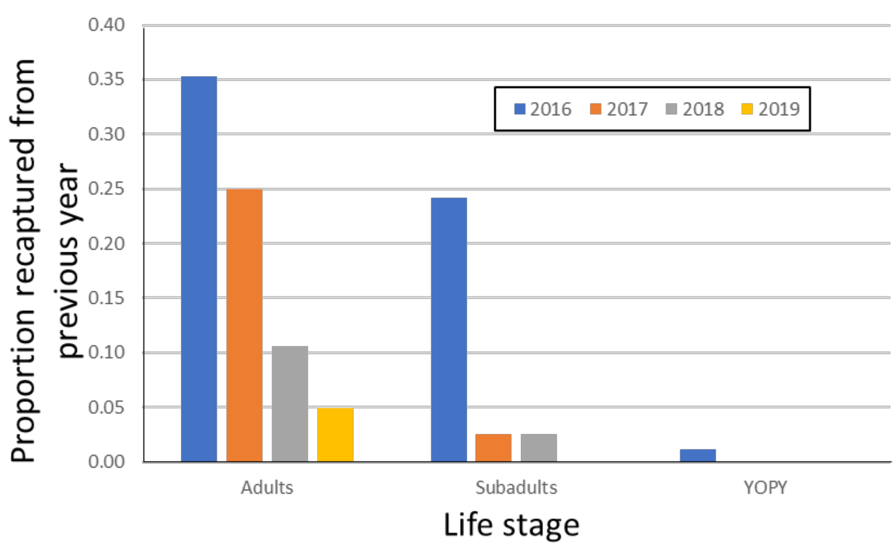

Figure 5. Annual recapture rates of Cascades frogs (*Rana cascadae*) by life stage. Subadult frogs are frogs not yet sexually mature but older than two years, YOPY represents young of previous year, which are frogs that metamorphosed the previous summer.

Appendix C - Avian Monitoring

Avian Monitoring Results

We compared avian diversity and abundance across study reaches in the lower and upper meadows, as well as to historic survey data from Childs Meadow. We sought to quantify bird response to the proposed meadow restoration as a result of beaver, habitat impacts of BDAs, and riparian fencing, as well as to link meadow bird density and health to measured meadow carbon sequestration benefits. We established five meadow bird demographic monitoring study plots along Childs Meadow. Each plot was approximately 10 hectares. Plots covered the range of restoration treatments including: grazing exclusion with recently active beavers (beaver reach), riparian fencing with artificial BDAs and planted willows (BDA reach), riparian fencing with no BDAs and planted willows (exclusion reach), and planted willows with no change in grazing management (grazed reach). Within these study plots, we located and monitored nests and determined territory densities for five meadow focal bird species known to breed in Childs Meadow: Yellow Warbler, Song Sparrow, MacGillivray's Warbler, Wilson's Warbler, and Willow Flycatcher. We monitored these plots from May 15 – July 31 for 4 years, starting in 2015. In July of each year, we conducted vegetation assessments of every nest located as well as a sample of random locations. Response variables included the density of these breeding birds and their nesting success. Nests were checked at least once every four days and followed until their fate was determined. Each breeding male of the five focal species occurring on every plot was followed at least 8 times to map a minimum convex polygon of their territory.

During the peak of willow flycatcher breeding season (May-July) in 2015 and 2016, we completed pre-restoration avian monitoring in seven study plots along Gurnsey Creek established previously by Point Blue surveyors, including a point count transect located within the beaver reach. We conducted at least eight visits in 2015 (twice per week from May 22 – July 10) to map breeding territory densities for seven meadow focal species (Willow Flycatcher, Yellow Warbler, Song Sparrow, Wilson's Warbler, Warbling Vireo, Lincoln's Sparrow, MacGillivray's Warbler). Nest searches were completed on a total of 62 active nests in the study plots until fate of breeding was determined. Following the breeding season (August-September), we created final territory density maps for each of the seven study plots and conducted nest vegetation assessments for the 62 nests. We also conducted similar vegetation assessments at 20 randomly selected locations in each study plot (140 total).

In 2016, we monitored each plot at least 2 days per week from May 15 – August 7, 2016. We located and monitored 90 nests of the six meadow focal bird species across all plots combined. We located 63 Song Sparrow, 9 Yellow Warbler, 7 MacGillivray's Warbler, 5 Wilson's Warbler, and 4 Warbling Vireo nests. There were no Willow Flycatcher territories on any of the plots in 2016, after one territory was tracked in the beaver reach in 2015. We found a total of two focal species nests in the grazed reach, zero nests in the exclusion and BDA treatment reaches, 56 nests in the beaver reach, and 31 nests in the USFS positive control reach downstream. There were no focal species territories in either the BDA or exclusion treatment reaches for the 2nd consecutive year. We collected nest habitat assessments at each nest and 140 randomly selected locations. We mapped every breeding territory for each species on each plot, and we conducted two point count surveys of Gurnsey Creek from the USFS Gurnsey Campground to 1 km upstream of the project area.

In the spring and summer of 2017 and 2018, we completed nest monitoring and territory mapping of seven meadow focal species (Willow Flycatcher, Yellow Warbler, Song Sparrow, Wilson's Warbler, Warbling Vireo, Lincoln's Sparrow, MacGillivray's Warbler). Surveys continued bi-weekly from May 10 through the end of July. Avian field work included surveys to locate nests, map territories, and conduct point counts at seven study plots across all study reaches. In July and August, nest vegetation assessments were conducted for all nest and random sites, and final territory density maps for each of the seven study plots were created. In 2018, we located, monitored to completion, and conducted habitat assessments at 123 nests across all plots combined and 210 random locations. Additional point counts were conducted at the 29 census stations along Gurnsey Creek downstream of the study reaches.

Of note in 2018 was the observation of two Willow Flycatcher nests. One nest was in the USFS positive control reach downstream of the beaver control reach, and one nest was in the grazed negative control reach at the upstream end of our study area. The nest in the USFS positive control reach successfully fledged two young, while the nest in the grazed reach failed after hatching. While meadow focal species use on the two treatment reaches was still far below the positive control reaches, we documented increased presence of Red-winged Blackbirds, Wilson's Snipe, Sora, and Virginia Rail. These species were likely responding to the dramatic increase in herbaceous vegetation vigor, density, and height as a result of excluding cattle from these reaches. Growth of willows planted in the treatment reaches at the start of the study during the drought was slow in the first two years. However, we noticed considerable willow growth in summer 2018 and expected habitat suitable for the remainder of our focal species to manifest over the next 5–10 years.

Herbaceuous Vegetation Height Analysis

We measured herbaceous vegetation at random locations in each study reach in July 16 – August 7 in each year from 2015-2018. We selected 20 random locations within each of the seven study plots using a random point generator in ArcMap version 10.3, yielding 20 points in the three upstream reaches and 40 points in each of the Beaver Positive Control and USFS Positive Control reaches. We sampled the habitat conditions at each random location using a slightly modified version of the Breeding Biology Research and Monitoring Database protocol for vegetation measurements (Martin et al. 1997). We sampled herbaceous vegetation in a 5 m radius plot centered on the random location coordinates. We estimated vegetation cover and height of herbaceous using a 1.2 m measuring stick to take reference measurements. We estimated relative cover of forb, grass, and sedge/rush components of the herbaceous layer and recorded an average height of each component. We calculated average herbaceuous vegetation height using relative cover of each of the herbaceous layer components as weights.

We used linear regression to test for changes in herbaecous vegetation height relative to heights in the USFS Positive Control reach. We chose the USFS Positive Control reach as the reference because it had the least management intervention (e.g. grazing and restoration treatments) in the last 20 years of the two positive control reaches. We included in the model: (1) year as a factor with 2015 as the reference level, (2) reach as a factor with the USFS Positive Control Reach as the reference level, (3) the interaction between year and reach. Analysis was executed using the ‘lm’ function in Program R version 3.5.1.

Figure 1. Average height of herbaceous vegetation within 5 m of random locations across 5 study reaches in the Childs Meadow complex from 2015 through 2018. Measurements were collected from July 16 – August 7 in each year. Each box represents the lower and upper quartiles, with median as horizontal dark line. Whiskers extend from the box no more than 1.5 times the inner-quartile range; values beyond are plotted as open cicrcles.

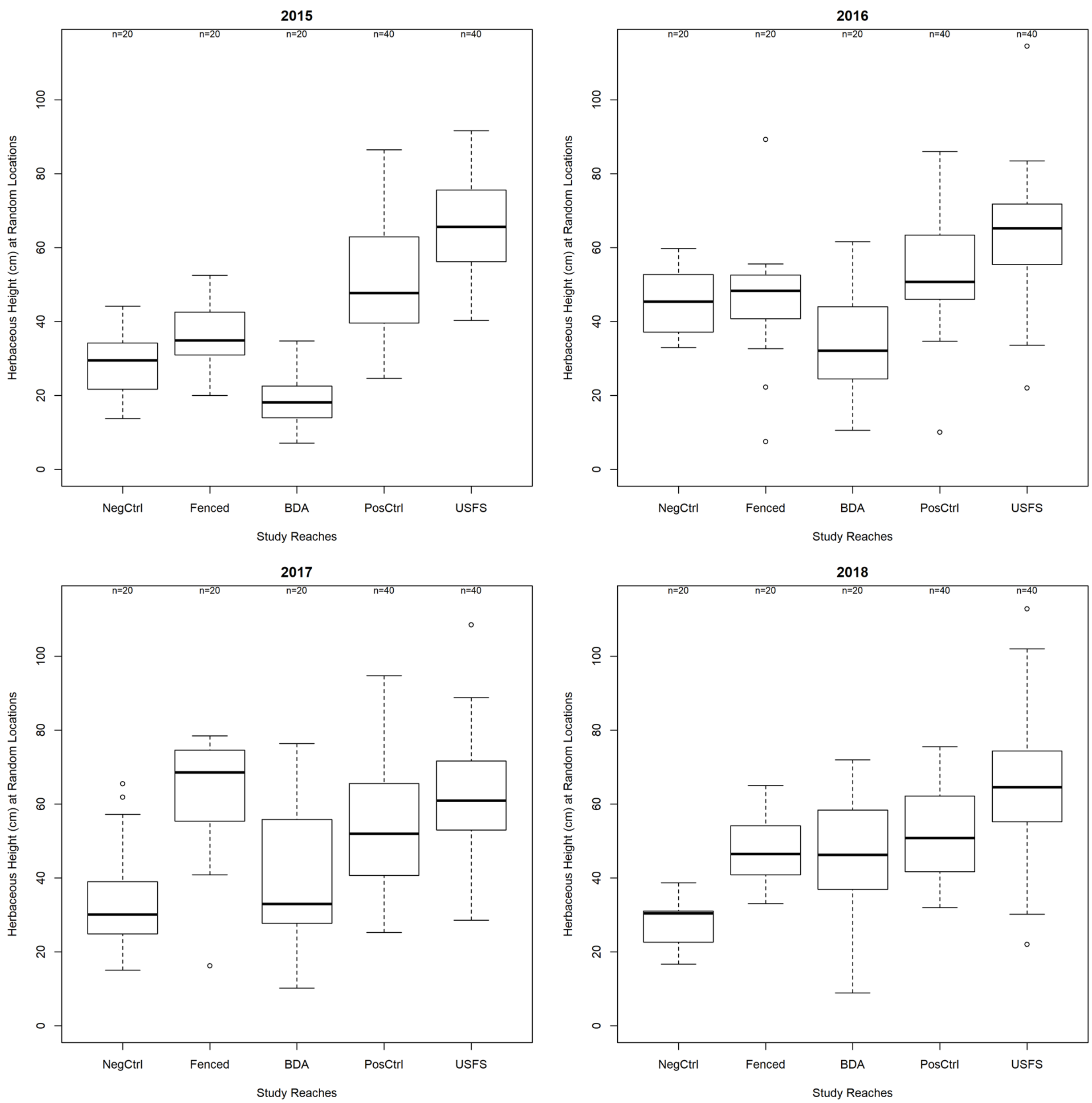

Figure 2. Change in average height of herbaceous vegetation from 2015 across four study reaches, relative to the USFS Positive Control reach, in the Childs Meadow complex from 2015 through 2018. Herbaceous vegetation height was measured within 5 m of random locations across the 5 sutdy reaches from July 16 – August 7, 2015–2018. p values represent the interaction of reach and year from linear regression model, using 2015 and the USFS Positive Control reach as reference factor levels in the analysis. Lower p values indicate stronger evidence of an effect of treatment.