Article

UAV-Supported Biogeomorphic Analysis of Restored Sierra Nevada Montane Meadows

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Abstract: Assessment of meadow restoration benefits from understanding the connection between geomorphology, hydrology and vegetation, and multispectral imagery captured from unpiloted aerial vehicles (UAV) may provide the method most suitable in terms of cost, spatial resolution, support for vegetation indices, and frequency of acquisition. Our field studies of northern Sierra Nevada montane meadows (with <40 km^2 watersheds) in various stages of restoration includes GPS + laser-leveling channel survey, laser-leveled cross section, aerial LiDAR, vegetation sampling, soil measurements, and UAV imaging using a sensor capturing calibrated blue (465-485 nm), green (550-570 nm), red (663-673 nm), near infrared (820-860 nm), and red edge (712-722 nm) bands at 5.5 cm resolution, providing multispectral false-color images and vegetation indices such as normalized difference vegetation index (NDVI) and red-edge Chlorophyll index (Cl$_{re}$). This fine-scale imagery extends our morphometric assessment of post-restoration channel scouring exhibiting bedform patterns and sinuosity related to *Carex*-influenced soil properties and *Salix* copses, but also provided a view of groundwater-related drainage effects including sinuous *Carex*-vegetated zones evident from spring snowmelt images as well as NDVI and Cl$_{re}$ in growing to senescent phenological stages. *Carex* in particular was significantly associated with low bulk density and high soil moisture, NDVI, and Cl$_{re}$ at lower elevations.

Keywords: UAV; meadow; NDVI; geomorphology; restoration; vegetation; hydrophilic; change detection

1. Introduction

The study of alpine and montane meadows lies at the nexus of an array of environmental sciences – hydrology, ecology, edaphology, geomorphology, and micrometeorology – and understanding the interactions among these systems is key to understanding their response to restoration efforts. Wet meadows in particular have attracted increasing attention due to their significance to threatened species, water resources, and the carbon cycle [1,2], and efforts to restore meadow ecosystem services has expanded in recent decades [3,4]. The signal of restoration efforts and the dynamic biogeomorphological systems of meadow channels benefits from the fine resolution afforded by unpiloted aerial systems (UAS) employing multispectral cameras designed for precision agriculture.

In this study, we employ ground measurements and sampling coupled with UAS methods for assessing variables affecting channel development, hydrologic response and vegetation change in montane meadows experiencing various forms of environmental restoration in the northern Sierra Nevada. UAS methods for studying vegetative cover have experienced a dramatic growth in recent years, with technology driven by benefits seen in precision agriculture, where fine-scale multispectral images and vegetative indices provide high-frequency views of moisture and nutrient availability stress [5–7]; and recreational UAS use has greatly expanded the availability, affordability and ease-of-use of remote-piloted and automated platforms. Multispectral cameras employing narrow (10-40 nm width) panel-calibrated spectral bands of blue, green, red, NIR, and the "red edge" near 700 nm provide the ability to create an array of indices useful for interpreting vegetative health, such as normalized difference vegetation index (NDVI) and red-edge chlorophyll (Cl_{re}) [8]:

$$NDVI = \frac{(NIR-Red)}{(NIR+Red)} \qquad (1)$$

$$Cl_{re} = \frac{NIR}{\text{red edge}} - 1 \qquad (2)$$

The deployment of UAV-mounted multispectral cameras has led to an expansion of use in ecological [9] and other environmental science research [10] at low cost compared to conventional methods. The number of applications continues to increase and provide alternatives to more costly approaches (e.g. LiDAR or direct measurement) for estimating vegetation growth rates and biomass [11] or estimates of evapotranspiration [12]. We use UAS and field methods to examine the signal of hydrophilic plants such as sedges (*Carex*) and riparian trees such as willows (Salix) as they relate to meadow groundwater levels and channel bedforms in longitudinal and lateral dimensions.

2. Materials and Methods

While the word "meadow" dates to Germanic origins meaning pastureland, with a root common with "mow," its usage in mountainous landscapes commonly describes herbaceous vegetation patches delimited by forest or bedrock outcrop edges, and typically associated with hydrologic factors such as a high water table. Variations of groundwater which influence vegetation alliances [13] from hydrophilic to xeric interact with soils and biogeomorphic systems, and these systems are significant elements of the biogeochemical carbon cycle [14]. As landscapes with a significant history as grazing lands in the American West, montane meadows have experienced intentional as well as accidental alterations of groundwater levels and related channel developments, and with the added recent attention on their restoration, represent a feedback system with significant human agency [15].

Given their high biodiversity and critical habitat for threatened and endangered species, hydrological significance, and their importance as forage for wildlife and domesticated animals, meadows have received increasing attention as targets for restoration, leading to efforts to better understand and classify meadow types. Classifications vary from efforts that emphasize vegetation and forage types [16] to hydrogeomorphic systems [17], although it is commonly recognized that the vegetation, hydrology, geomorphology, and soils of these systems are interlinked [18,19]. Within the Sierra Nevada, altitudinal zones are commonly used, with montane meadows occupying moderate elevations, as distinct from those in subalpine and alpine zones [19]. However, and perhaps unique to North America, wetland areas such as fens and bogs are also included within the range of meadow classes [16].

The meadows we see today in the Sierra Nevada have been impacted by a history of grazing and timber extraction. Sheep and cattle grazing in the Sierra Nevada was widespread as of the Gold Rush, peaked in 1876, and resulted in meadow degradation with well-documented gullying [19,20]. In the 19th and early 20th centuries, timber extraction was limited to areas in close proximity to settlements or rail access. What later became Tahoe National Forest experienced a significant impact of feeder railway lines built through montane meadows owing to the ability to connect to the Southern Pacific Railroad [20]. Railroad construction was also able to take advantage of easy grades along riparian areas in meadows[21].

A prominent signal of a degraded meadow due to erosion is the lowering of the water table and conversion of plant communities from hydrophilic to more xeric types [19,22], as can be seen in the replacement of sedge (*Carex*) species that mature under seasonal water cover [16] with more mesic grasses and forbs, in many areas extending to xeric plants such as sagebrush (*Artemisia tridentata*). This shift prevents hydrophilic sedge (*Carex*) and rush (*Juncus*) species from creating dense root mats which provide resistance to bank erosion [23–25]**.**

Once initiated, headcuts extend these effects into upstream meadows as gullies. Discontinuous and continuous gullies have been described in relatively steep sites influenced by piping [26] to gradients as low as 1% [27,28]. While many of these systems are in thinly vegetated floors of arroyos [27], processes such as sapping leading to eroding root mats have also been described in Sierran meadows [19].

Meadow protection and restoration efforts have been driven by a combination of factors and diverse stakeholders. Meadow landscapes have more biodiversity than any other habitat type in the Sierra Nevada [21] and thus have great significance for environmental management. Meadow streams provide critical habitat for Lahontan cutthroat trout (*Oncorhynchus clarkii* henshawi), Eagle Lake rainbow trout (*O. mykiss* aquilarum), and California golden trout (*O. mykiss* aguabonita). They also provide critical habitat for wetland indicator species such as Sierra yellow-legged frog (*Rana sierra*) [29] and willow flycatcher (*Empidonax traillii*) [30]. Herbaceous cover (as opposed to sagebrush) is clearly favored by sheep and cattle ranchers as well as wildlife. Healthy meadows can be a carbon sink, and with snowpack in the Sierra projected to decline in the coming years due to climate change [14], meadows are also seen as important for flood storage [4,16] and water quality [31] because healthy meadows maintain large quantities of winter runoff underground and maintain release through summer.

Approaches to protecting meadows from overgrazing have included exclosure fencing to keep cattle away from riparian areas [32], with grade control structures such as check dams commonly used to arrest gully headcuts [33]. These structures however often fail, with erosion laterally bypassing check dams, leading to consideration of other methods such as "pond and plug" installations [3,34]. This design forces surface flow away from formerly incised paths to other parts of the meadow, sometimes old unincised channels, and are intended to raise the water table while minimizing stream power in order to avoid renewed incision. There has also been a recent surge of interest in "employing" beavers or beaver dam analogues in meadow restoration [35,36], since a strong argument can be made that beaver dams were once a major control on limiting channel incision and storing sediment [35,37]. Since both xeric and hydrophilic vegetation respond to groundwater changes, a successfully raised water table can be assessed by looking at changes in vegetation species and seasonal phenology.

The goal of meadow restoration is to raise the water table, but this goal is affected by local conditions related to the interaction between aquifers developed in meadow alluvial sediments and geologic aquifers. Rodriguez et al. [34] observed three conceptual models of post-restoration northern Sierra Nevada meadows based on hydrologic response: (1) sponge models that simply delay runoff through the alluvial aquifer; (2) valve models that are supplemented with springs; and (3) drain models that lose flow while recharging a geologic aquifer via faulting or other structures. Seasonal changes in the distribution and amount of soil moisture and evapotranspiration loss through meadows will largely depend on these conditions in play for a given meadow, and in turn influence vegetation patterns and surface flows.

While the nature of incised channels and their influence on riparian vegetation is generally well understood, post-restoration reoccupied ephemeral channels may have markedly different relationships with vegetation, and are part of the restoration signal requiring ongoing monitoring. Ephemeral channels in wet meadows may differ significantly in their biogeomorphic properties from alluvial streams [38–40] with, for instance, a greater variance in curvature ratio to channel width and a distinct pattern of bedforms resulting from plunge pool development [41].The tendency toward developing discontinuous gullies and their potential for growth into continuous gullies points to the need to carefully assess their change over time. The association of channel bedforms with hydrophilic vegetation, such as sedges, furthermore points to the need to assess vegetation changes. Occupation of old channels and changes to hydrophilic vegetation species are an indication of the success of restoration, and changes in either are a signal of evolutionary changes in the restored system.

Meadows in the northern Sierra Nevada have been the focus of considerable efforts at restoration, with much of this work in the Plumas and Tahoe National Forests involving US Forest Service hydrologists in cooperation with organizations such as the Plumas Corporation [42], American Rivers [43], and local ranchers on private lands or with grazing leases. The Carman Creek system of meadows, including Knuthson Meadow (Figure 1), near the northern boundary of Tahoe National Forest in the Feather River watershed, has been the subject of multiple phases of pond-and-plug restoration [44]. Upstream of Knuthson, especially on West Carman Creek, are several other restoration projects ranging from check dams to pond-and-plug installations. Carman Valley on this west fork exhibits several discontinuous gullies (Figure 2) deemed insufficiently degraded to warrant attention more effective than check dams.

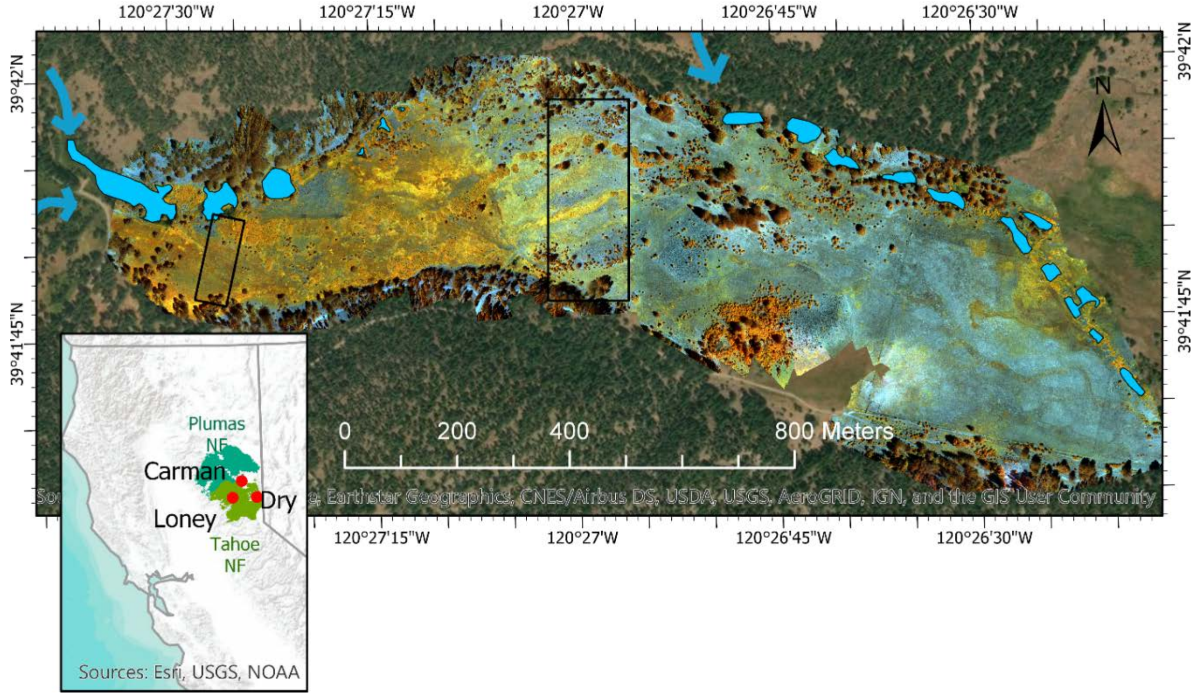

Figure 1. Meadow study sites. Knuthson Meadow, the largest studied on the Carman system, with July and August 2017 UAS-collected multispectral imagery from this project. False color image displays NIR (820-860 nm) as red, red-edge (712-722 nm) as green, and red (663-673 nm) as blue. Ponds from pond & plug restoration follow the pre-restoration incised channel along the northern edge of the meadow. Major surface streamflow inputs are indicated with arrows. Flow is toward the east to southeast, with the west-most pond overflowing into small channels to the south. Locations of cross section Figure 8 (left) and Figures 9-10 (right) are shown as rectangles. The inset map locates the 3 Tahoe National Forest meadow systems that were the focus of this study: Carman (including upper Carman Valley and Knuthson), Dry, and Loney, as well as the adjacent Plumas National Forest where numerous pond-and-plug projects have been built by the Plumas Corporation (accessed 2018).

Figure 2. Pool scour / discontinuous gully in West Fork Carman. Note *Salix* (willow), probably *S. lemmonii*, commonly growing adjacent to scour features. Photograph by Heather Milton, used with permission.

The focus of our study is on meadows in watersheds of limited size (less than 40 km²) that are drained by ephemeral streams. Most meadows of this description have been subject to some form of restoration or protection from ongoing impacts, and the meadows chosen for study (Table 1) have been observed either before, after, or both before and after some form of restoration. Effective restoration should show changes not only in the nature of channelized flow, with reduced incision, but also in an increased cover of hydrophilic as compared with xeric vegetation that should result from raising the water table. Knuthson Meadow (see Figure 1) provides a clear example of a shift in surface drainage away from the formerly incised creek, now occupied with a series of ponds and plugs, into numerous shallow channels along the more southerly parts of the meadow, with most of the flow incorporated into the meadow aquifer. Other meadows that are the focus of this study include another pond-and-plug restoration project – Dry Creek meadow in the Truckee River drainage – and Loney meadow in the Yuba River watershed, which is being restored using a limited (no excavation) pond-and-plug method [45].

Table 1. Meadows in the study. Pond & plug restoration unless specified. Precipitation from PRISM 30-year normal model [46].

Meadow	Watershed Area (km²)	Elevation (m)	Annual Precipitation (mm)	Imaging Related to Pond & Plug (p&p) or Other Restoration
Dry	1	1750	620	before and after p&p
Loney	4	1810	1900	before p&p
Knuthson	37	1520	800	after p&p
Carman Valley	15	1550	800	after check dams

In the meadows studied, pools typically exhibited scouring spaced apart by an intact root mat that may approximate the geomorphic function of riffles in creating roughness and grade control. Observations of flow during the spring snowmelt period demonstrates a system not unlike a pool-riffle system, with wider shallow sheet flows over the high-friction vegetated sections and concentrated flow through scoured pools (Figure 3). Meadows with gully development frequently exhibit degraded root mats that we can assume to be from a pre-incision history of wet-meadow *Carex* cover (Figure 4 and see Figure 2). Discontinuous gullies are frequently found adjacent to *Salix* copses in both Carman and Loney meadows, and commonly are associated with locally greater sinuosity.

Figure 3. Spring snowmelt in upper Knuthson meadow, visited during spring snow-melt 1 May 2011, illustrating a system not unlike a pool-riffle system, with wider shallow sheet flows over the high-friction vegetated sections and concentrated flow through scoured pools, often developed adjacent to willow copses. A scoured pool is visible just to the right of willow copse at left center.

Figure 4. Terrace scarp exposing pre-incision (assumed) *Carex*-dominated root mat. West Fork Carman, upstream of Knuthson. Photograph by Heather Milton, used with permission.

The purpose of our field investigations has been to capture channel development, vegetation/land cover, fine-scale elevation surfaces, seasonal hydrologic condition, and soil properties. During the first phase of this project, Slocombe & Davis [41] employed channel survey methods in five meadows. Plans and profiles of discontinuous ephemeral channels were surveyed using a combination of a 0.1-m accuracy GPS (for horizontal position) and <0.01-m accuracy laser level (for vertical position) in order to optimize field efficiency while maintaining a finer level of vertical accuracy suitable for capturing accurate gradients in the 1-2% range. (The laser level was also used along with a survey tape and GPS end points for a meadow cross section in September 2018.) Planform characteristics differed from alluvial systems and may reflect a unique herbaceous wetland channel habit, with biotic control having major influence relative to fluvial effects [38–40]. Longitudinal pool morphologies exhibit headward plunge pools similar to those described by Hagberg [47] as a dominant erosion process in Sierra meadow streams. Bedform spacing was similar to alluvial systems, exhibiting an average pool to pool spacing of 6.72 channel widths, within published ranges of 5-7 for alluvial streams [48].

As part of a bio-micrometeorological investigation of degraded and restored sections of the Carman Valley system, Maher [49] sampled vegetation and soils from restored and still degraded sections in 2014, with the restored (Knuthson) samples in the vicinity of a flux tower installation used for eddy covariance methods of assessing carbon dioxide, vapor and energy balances [1,49]. The most hydrophilic samples were from channels ~0.5 m in depth similar to the vegetated sections of channels surveyed in this meadow by Slocombe and Davis [41]. Vegetation quadrats (counted by Mike Vasey and Vanessa Stevens) were co-dominated by *Carex utriculata* and *C. nebrascensis* while slightly more elevated adjacent sites had more of a mix of grasses, sedges and rushes (with *Trifolium longipes*, *Deschampsia caespitosa*, *Juncus balticus*, *Phleum alpinum*, and *C. utriculata,* in that order, combining for 84% of quadrat species counts). The top 10 cm of soils from these sites were high in soil organic matter (SOM) and root biomass (RB), with 11.1% SOM and 4,037 g m-2 RB in the lowest elevation samples as compared with 9.9% SOM and 2,438 g m-2 RB at adjacent elevated sites. In comparison, lower

SOM and RB values (4.8% SOM and 488 g m-2 RB) were found at a degraded site further up-valley dominated by *Artemisia tridentata* and other xeric species [49].

This research pointed to the need to understand how extensive these channels and vegetation/soil associations might be by looking at larger areas of such meadows. In the channel study and further observations in a variety of montane meadows, sedge species such as *Carex utriculata* and *C. nebrascensis* have been seen to typify the cover for undisturbed ephemeral channels. Associations of these sedges with ephemeral flow areas at the lowest elevations in the cross section of a meadow suggests that channel development might be assessed by detecting vegetation and scouring signals using low-altitude multispectral imagery.

We employed multiple approaches to capturing elevation surfaces, with the most critical being of the ground terrain below vegetation. While digital surface models (on the vegetation surface) can be captured using either RGB or multispectral imagery and multi-ray photogrammetry methods, the densely vegetated meadows presented challenges for capturing actual ground terrain, with small channels easily obscured. Light Detection and Ranging (LiDAR) data – both conventional aerial and ground-based terrestrial laser scanning (TLS) – were employed, though ultimately the aerial methods proved the only way to reasonably capture sufficient bare ground, given the size of meadows and limited ability to penetrate dense herbaceous vegetation from the limited terrestrial vantage points.

Airborne LiDAR data captured in 2013 and 2014 were provided by Tahoe National Forest. The average point density (under ideal conditions) are 7-8 points per square meter with a point spacing of 0.29 to 0.48 m; reported horizontal and vertical accuracies were 0.02-0.72 m and 0.05-0.35 m, respectively. Collection and processing followed National Center for Airborne Laser Mapping (NCALM) protocols [50]. We then used a 1-m bare-ground digital terrain model (DTM) interpreted from this data set, and employed terrain analysis tools from the System for Automated Geoscientific Analysis (SAGA): Flow Accumulation (settings: Top-Down, Multiple Triangular Flow Direction) on a filled DTM product and Topographic Wetness Index (TWI) [51]. A natural logarithmic function of the flow accumulation result was then derived, which is somewhat similar to TWI but more clearly interpreted. We also derived topographic cross sections of meadows by using the Interpolate Shape tool in ArcGIS.

We experimented with multiple cameras and sensors to capture vegetation and other cover, including small cameras such as the Canon S95 mounted to a hobbyist-grade UAS, a system that was configured to capture either standard RGB color or modified to include near-IR [52,53]. This system when employing standard color also proved highly successful in mapping a hillslope gully with little vegetation cover [53]. The best results in meadows were achieved in 2017 and 2018 using the MicaSense RedEdge, a multispectral sensor designed for precision agriculture, mounted on a 3DR Solo quadcopter (Figure 5), with geolocation RMSE generally below 1m, sufficient for associating with vegetation patches and channels. This 5-camera system captures narrow bands of 465-485, 550-570, 663-673, 820-860 (NIR), and 712-722 (red-edge) nm suitable for processing in Pix4D multi-ray photogrammetry software. The red-edge band combined with NIR has been used to detect seasonal moisture stress and species [54] as well as chlorophyll content of crops [8] which also applies to naturally watered landscapes during the growing season.

Figure 5. MicaSense RedEdge 5-band camera mounted on a 3DR Solo quadcopter, at lower Knuthson Meadow. This small drone (26 cm width) is capable of carrying a small camera such as a GoPro, or the 150-g MicaSense unit as shown here. Photograph by Quentin Clark, and used with permission.

Flight plans were developed and deployed using the 3DR Tower app running on a Nexus 9 tablet, with along- and between-path settings to ensure 75% frontal and lateral image overlap. In the most extensively sampled meadow, Knuthson, 14 soil and vegetation samples were collected immediately after each flight, along with 92 GPS points with linked photographs to aid in image classification, in July and August 2017; partial sections of Knuthson were also flown in September 2018 to capture senescent conditions. Basemap imagery published on Mapbox were used to allow off-line mission planning at the site. Three meadows were mapped, including 72 ha Knuthson Meadow, 13 ha of Loney Meadow, and 10 ha of Dry Creek Meadow, at flight heights of 80 m (Knuthson, Dry) or 120 m (Loney), producing a resolution of 5.6 or 8.3 cm, respectively. Maximum coverage by one flight (1 battery) was approximately 10 ha, at either 80 or 120 m altitude above ground level (at ~1500 m MSL elevation). The five bands were composited to create various false-color image displays, NDVI and CI_{re}, derived from equations 1 and 2.

Vegetation grab samples from the three meadows were assessed in July and August 2017 to use as ground control samples for UAS surveys, with each sample point chosen to be dominated by one species if possible, a characteristic most common with *Carex* sites. Samples from each site were identified to species level. For 29 of these samples, the upper 10 cm of soil at point sample locations were analyzed for soil moisture and bulk density. Bulk density of the upper 10 cm of soil is assumed to be mostly influenced by root density, and this has the closest relationship to soil erosion resistance.

3. Results

The Knuthson Meadow imagery covers one of the sites used in the 2011-12 channel study [41], and one of the sites used in the 2014 micrometeorological study with vegetation and soils sampled [49]. The channel study section is at the headmost 4 ha of Knuthson Meadow (Figure 6), a section that exhibited luxuriant growth of sedges following a wet 2017 snow year. Areas away from the channel flows are also well vegetated until the more elevated Artemisia-covered sites are reached, so channels are not well represented in the imagery. In contrast, the section approximately in the middle of the entire 72-ha Knuthson Meadow sampled for the 2014 micrometeorological study has clear sinuous channel zones with hydrophilic vegetation separated by more mesic to xeric zones (Figure 7).

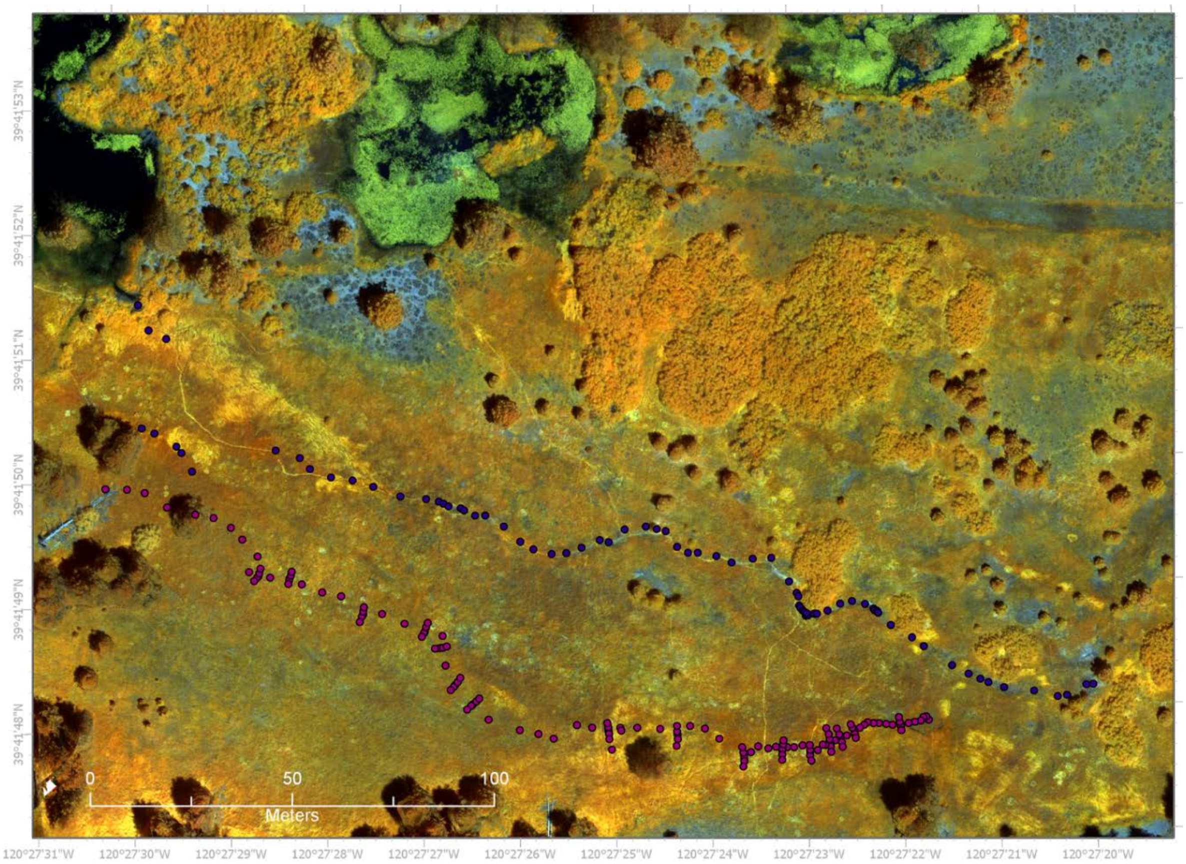

Figure 6. Upper Knuthson Meadow. Channel surveyed by Slocombe and Davis (2014).

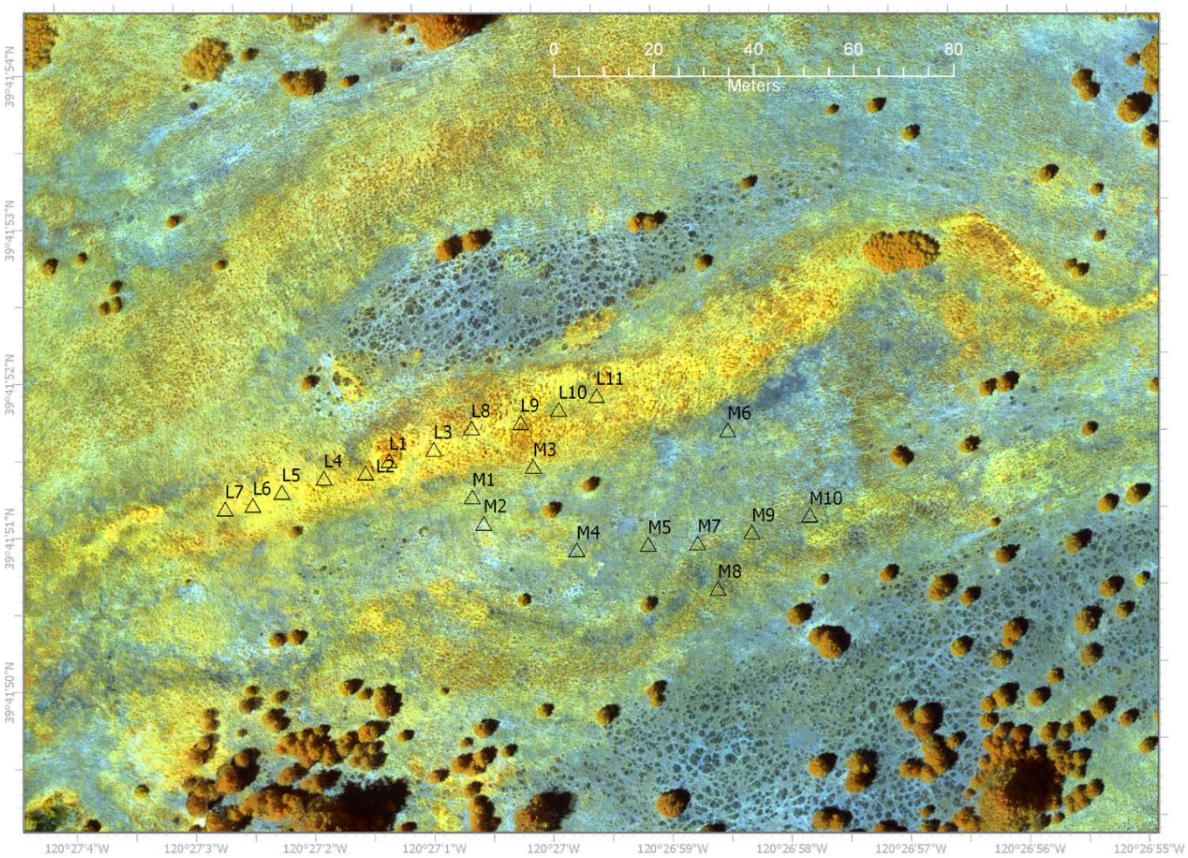

Figure 7. Central Knuthson Meadow. Site of an eddy covariance micrometeorological study by Maher (2016). Vegetation quadrat and soil sample locations used in that study are shown as point symbols, with "L" sites located in lower areas dominated by *Carex* and "M" sites on slightly elevated (+ ~0.5 m) sites with more diverse facultative wetland and upland herbaceous species.

Using multiple views helps us visualize these elusive ephemeral channels. Figure 8 combines four views of a cross-meadow elevation profile in an area with few distinct channels, at the head of a meadow where flow from upstream enters the meadow (see Figure 1), including two channels surveyed in 2012. The four views are (A) false color (R=NIR, G=red edge, B=red); (B) NDVI; (C) 21 April 2013 drone color image mosaic showing surface flow from snowmelt; and (D) natural logarithm of flow accumulation over false color.

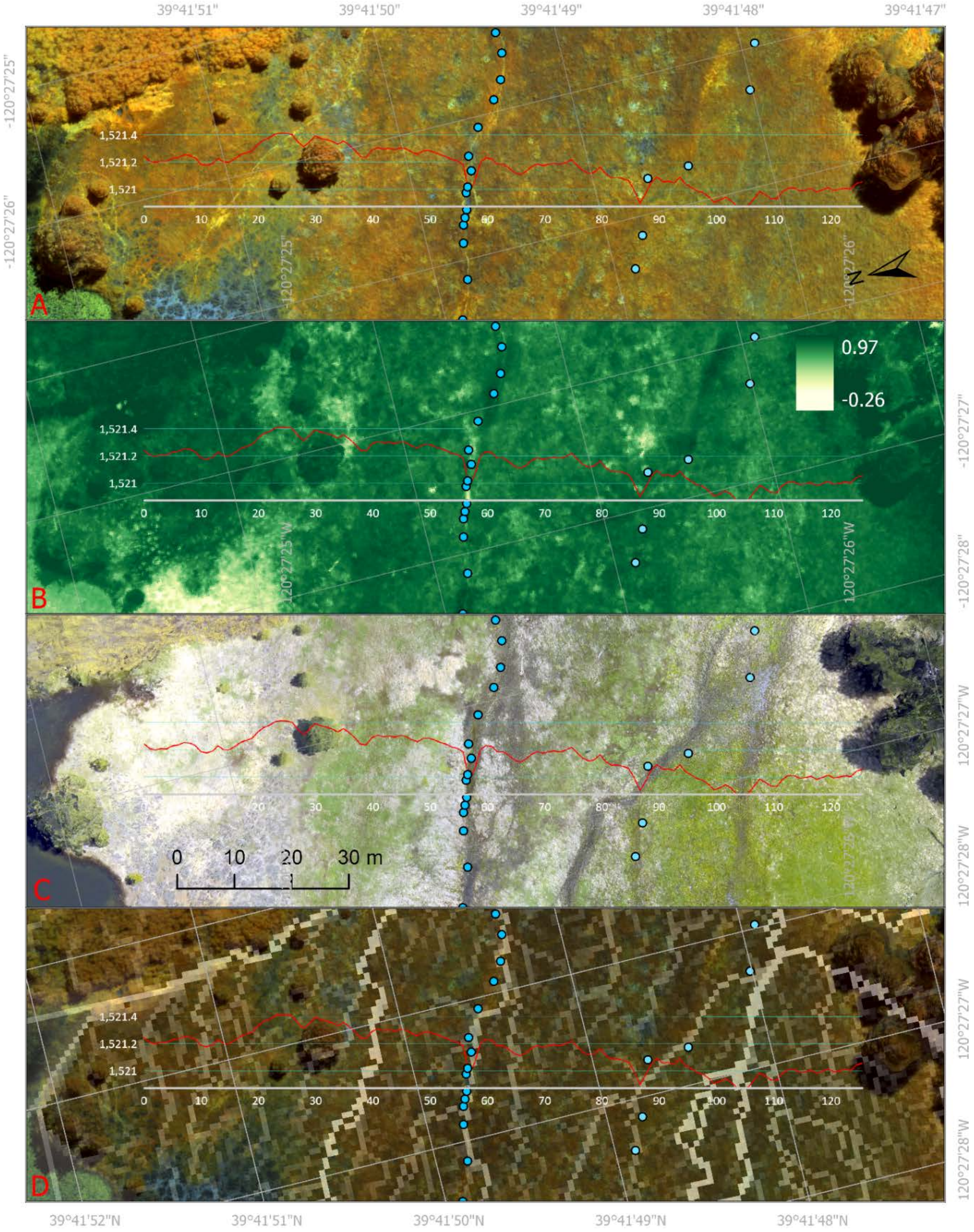

Figure 8. Upper Knuthson cross section. Displayed as (A) false color, (B) NDVI, (C) 21 April 2013 drone color image (GoPro Hero 3) mosaic, and (D) natural logarithm of flow accumulation over false color. The cross section was derived along the white line with distances in meters from Tahoe National Forest LiDAR. The head-most pond of the pond-and-plug restoration is partially visible with the bright green color of aquatic vegetation at the letter A, while a small area of sagebrush is immediately to the south.

Channels detected in Knuthson meadow by either direct observation, survey, flow accumulation, LiDAR cross sections, or vegetation patterns varied from features with periodic pool scouring to no scouring at all. A laser-level cross section was surveyed at the mid-Knuthson site, allowing for a more accurate assessment of the extent and depth of channel development and its vegetation relationship. Figure 9 shows the area of the meadows sampled in 2014 in 3 views: (A) growing season false color (NIR/Red-edge/Red as RGB); (B) senescent-season false color; and (C) flow accumulation. In this area little scouring is apparent along the channel sampled in 2014, however the trend of concentrated flow is clearly seen by comparing the cross section to the bright yellow and orange areas of *Carex* domination, which also follows a high flow-accumulation path. Visible in the imagery is a string of Salix copses at about 30 m in the cross section, to the north (left in the image) of the sampled channel, and a few scour features are evident in the imagery adjacent to copses.

UAS imagery collected 23 September 2018 not surprisingly exhibits highly senescent (and grazed) meadow vegetation (Figure 9B). NDVI and Cl_{re} from both phenological periods provide a view of the likely effect of topographically related soil moisture variations in influencing tendencies ranging from xeric *Artemisia* to hydrophilic *Carex*-dominated sites (Figure 10). During the senescent phenological phase, NDVI and Cl_{re} are greatly reduced, with high values only in trees, though drainage lines such as the *Carex*-dominated area at cross-section distance 150 m has higher NDVI than more elevated mixed graminoid or sagebrush-dominated areas. Leaving out the trees, there is a clear pattern seen in Figure 11 of higher NDVI and Cl_{re} values at lower-lying areas (Table 2), but both indices are not surprisingly significantly lower (NDVI t-test $p = 1.048 \cdot 10^{-11}$; Cl_{re} t-test $p = 7.541 \cdot 10^{-9}$) in the senescent period later in the season. Before sampling for this analysis, in order to reduce noise from vegetation texture and shading effects, NDVI and Cl_{re} rasters were derived as 5x5 focal means of 3x3 aggregate cells from the original 5-cm data.

Table 2. Linear model results of NDVI and Cl_{re} predicted by elevation at vegetation samples along north-south leveling transect in Figure 10. Trees (willow and pine) samples are excluded.

model	slope	r^2	p
lm(NDVIgrowing ~ Elev)	-0.39	57%	0.00012
lm(NDVIsenescent ~ Elev)	-0.20	31%	0.00741
lm(Cl_{re}growing ~ Elev)	-0.46	48%	0.00063
lm(Cl_{re}senescent ~ Elev)	-0.33	29%	0.01019

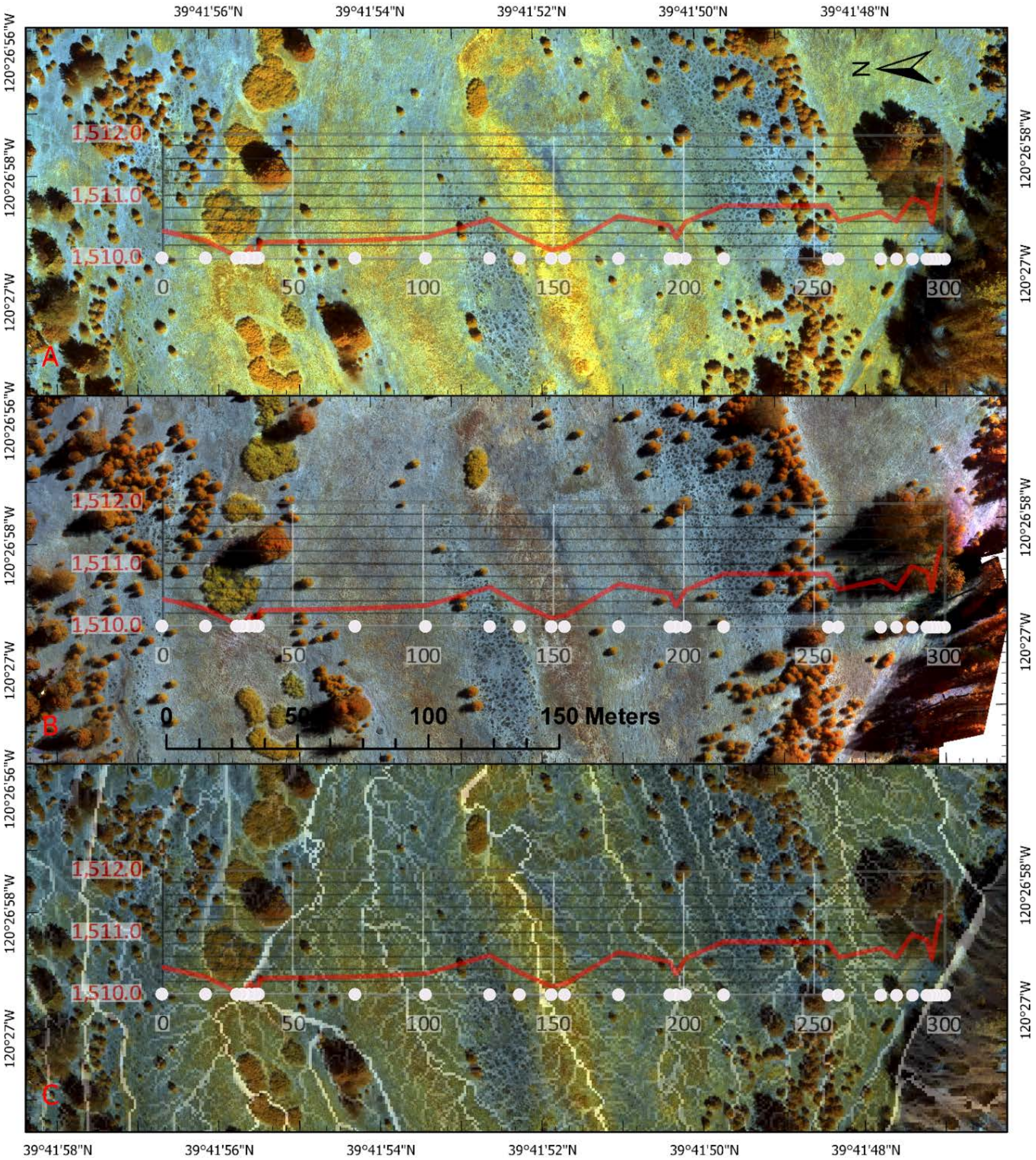

Figure 9. Central Knuthson cross section. Laser-level surveyed cross section superimposed on UAS images from growing and senescent seasons: (A) growing season July 2017; (B) senescent season September 208; (C) natural logarithm of flow accumulation over growing season image. False color image displays NIR (820-860 nm) as red, red-edge (712-722 nm) as green, and red (663-673 nm) as blue. Cross section units are meters horizontally and vertically.

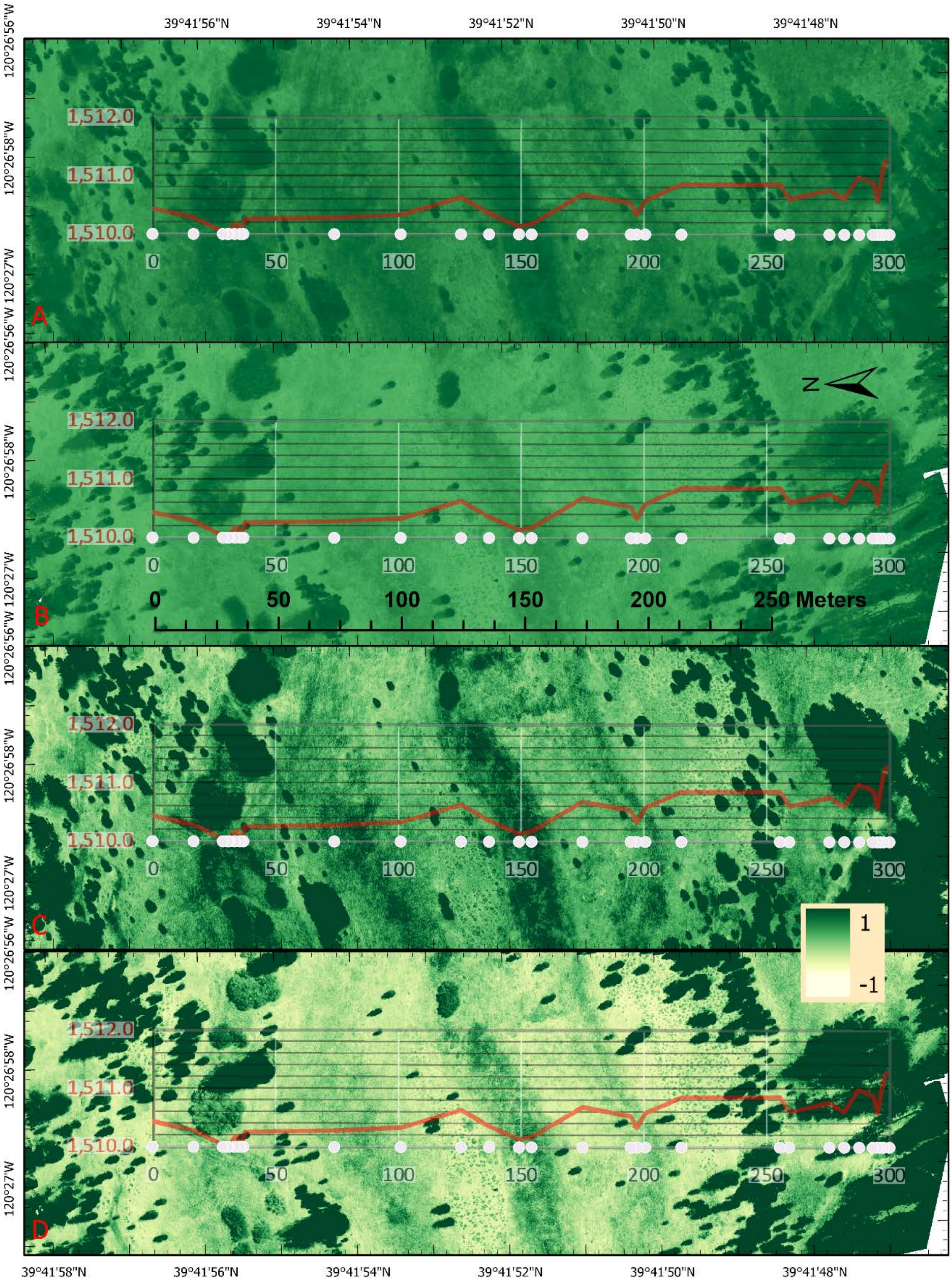

Figure 10. NDVI and CI_{re} indices of central Knuthson cross section. Same cross section as previous figure, with (A) July 2017 NDVI, (B) Sep 2017 NDVI, (C) July 2017 CI_{re}, and (D) Sep 2018 CI_{re}. Legend corresponds to all maps.

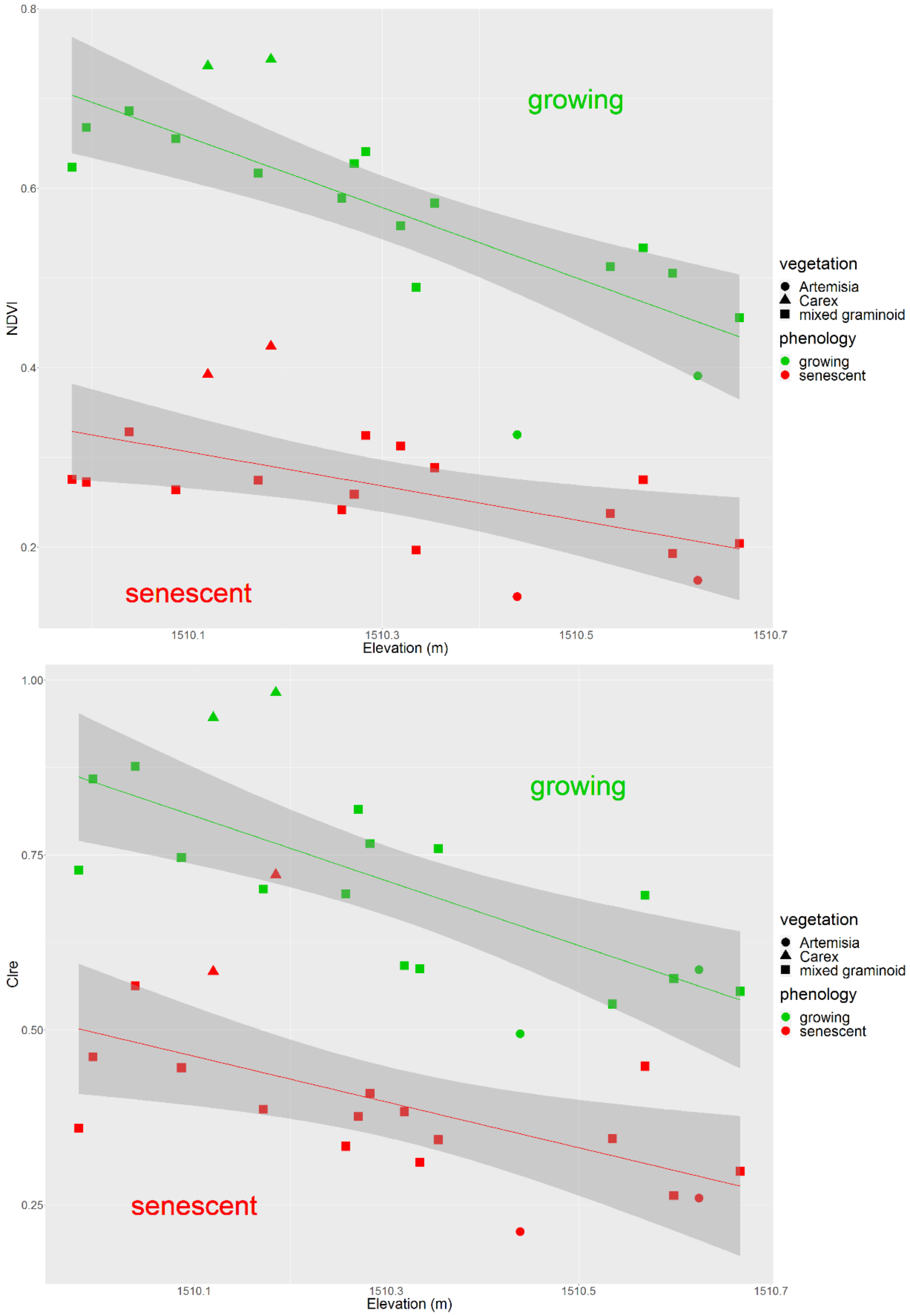

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Figure 11. NDVI and $\mathrm{CI}_{\mathrm{re}}$ during growing and senescent seasons, plotted at elevations of non-tree points along the 23 September 2018 laser-level cross section.

As has been commonly noted in other studies [18,34], groundwater is a significant part of meadow hydrology, and pond-and-plug restoration has had major influence on both seasonal water table fluctuations and evapotranspiration from pond surfaces and vegetation. Knuthson Meadow was classified by Rodriguez et al. [34] as exhibiting properties of a "valve"-type conceptual model since it experiences minimal seasonal pond decline, expected to have resulted from groundwater discharge which maintains pond levels despite seepage and evapotranspiration. While this evidence for additional groundwater sources adds to the picture, we can see evidence for both influx and efflux in Knuthson Meadow. By far the largest flow entering Knuthson Meadow comes from the 30 km^2 basin to the northwest, entering the west-most pond, yet greater surface flow is evident from spring snowmelt from the 3 km^2 basin to the southwest (Figure 12). Recharging the meadow aquifer is in fact a goal of pond-and-plug meadow restoration, with most ponds intended to be groundwater windows and not significantly involved in surface channelized flow; this northwest pond would appear to be a site of significant groundwater influx, by design. In other parts of the meadow, groundwater efflux is evidenced by redox conditions where there are either geologic spring sources or through-meadow resurgences.

Figure 12. West end of Knuthson meadow from a 21 April 2013 color image mosaic. At this time, surface flows can be seen in ephemeral channels. The largest inflow into the meadow is into the pond above B in the image, with a basin area of 30 km^2; at B beavers have frequently built dams to increase the height of the pond. Flow from the southwest (SW) is from a much smaller basin of 3 km^2, yet this contributes more evident surface flows. Channel surveys from 2012 are shown. Imagery was captured using a 3DR Arducopter-mounted GoPro Hero-3 camera and processed with Pix4D. Distorted results in the forest surrounding the meadow is to be expected given limited image coverage, and should be ignored as the focus is on the meadow.

Loney Meadow, in the Yuba River drainage basin, sits at a higher elevation, 1810 m as compared with 1520 m for Knuthson, and is on a more westerly and thus wetter location (see Table 1), so may tend to be a bit more alpine than montane in character, with greater snow accumulations. This meadow has been identified as degraded by the U.S. Forest Service and the National Fish and Wildlife Foundation [54], and a more limited pond-and-plug project was completed in August 2017 after our imagery was captured; we are re-imaging the meadow to detect changes in vegetation cover. As with the mid-Knuthson site, this meadow was the subject of an eddy covariance study [55], and plans are underway to monitor this meadow after restoration.

Loney Meadow also illustrates a complex set of channels. In the cross section (Figure 13) of the meadow relatively near its western (downstream) end, several areas of focused flow can be seen in the flow accumulation view (13D). The deepest channels are not necessarily the wettest predicted by flow accumulation, nor are they are observed in the field or in imagery to have the greatest flows. This likely results in part from the effect of 20th century ditching along the south side of the meadow [44]; however groundwater flow interactions are likely, as seen in the patterns of vegetation and

NDVI and Clre that do not closely match the LiDAR-derived flow accumulation results. Salix copses are evident in the deepest channels and are associated with the greatest local sinuosity.

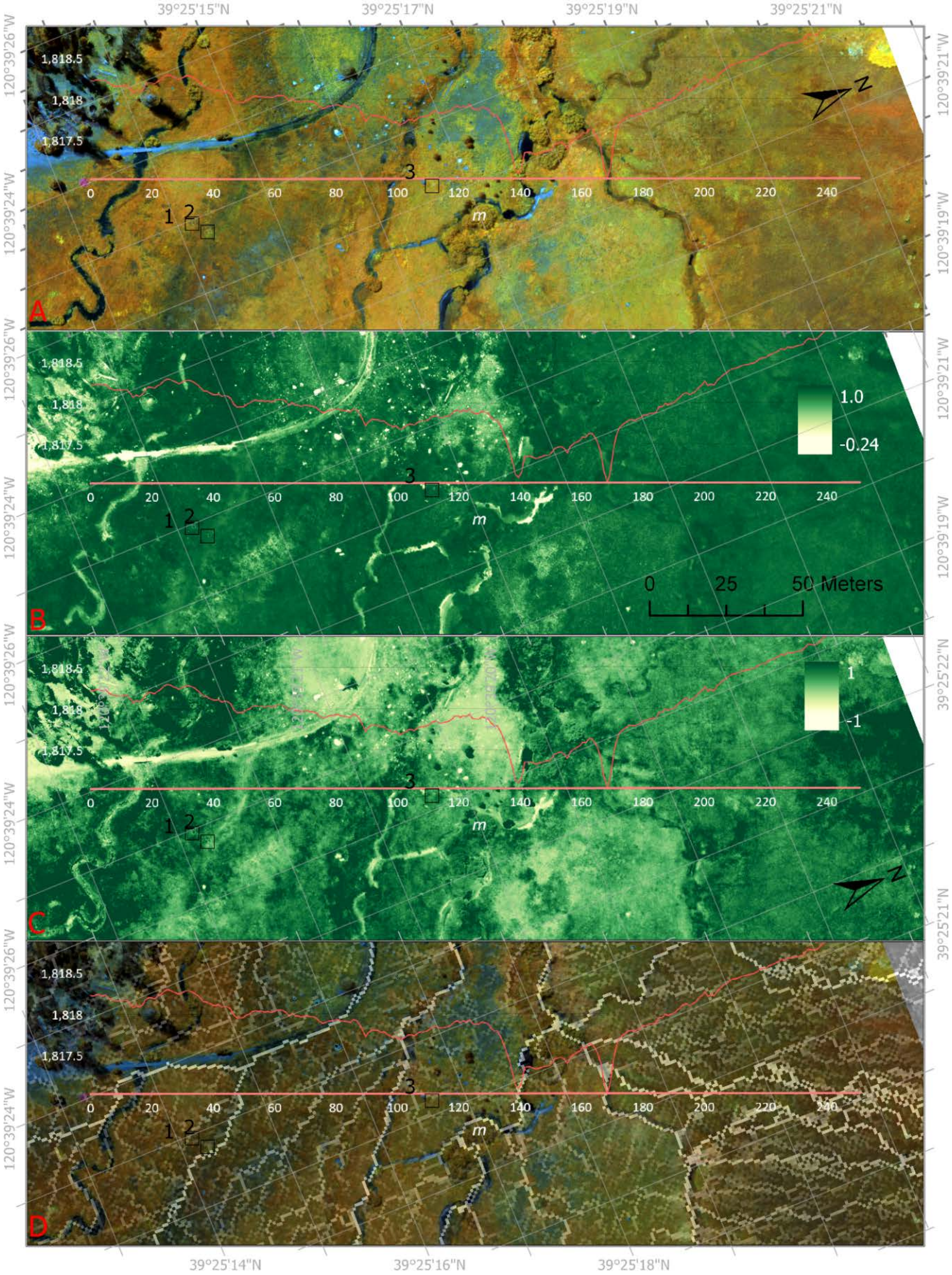

Figure 13. Loney Meadow cross section. Displayed on (A) false color, (B) NDVI, (C) Clre, and (D) natural logarithm of flow accumulation over false color. The cross section was derived along the orange line. Note the main trail and bridge crossing the meadow in the northwest corner of the image.

Dry Creek Meadow was flown before and after pond-and-plug restoration, and exhibits changes from hydrophilic plants only along inset flood plains to more widely distributed patches (Figure 14). The pre-restoration imagery from 2013 employed a 3DR Arducopter with a modified Canon S95 camera attached; the modification consisted of removing the IR blocking filter and adding a Hoya A25 red filter to limit bands to red+IR and IR. While not capable of producing a true NDVI, an approximation was sufficient to clearly detect hydrophilic vegetation growing in a narrow inset flood plain [52] In 2017 imagery using the MicaSense camera, much greater coverage of hydrophilic plants including *Carex* species demonstrated the effectiveness of the restoration project. This tendency was also observed in the field by Tahoe National Forest hydrologist Randy Westmoreland who accompanied the UAS team and helped plan our field data and imagery collection. The extensive distribution away from observed channels supports a hydrologic system with a significant groundwater component, the goal of the restoration. Generalized to the entire meadow, an increase in NDVI can be seen, a result that was observed from Landsat imagery in 30 of 31 restored meadows studied in the Sierra Nevada by Rodriguez et al. [34].

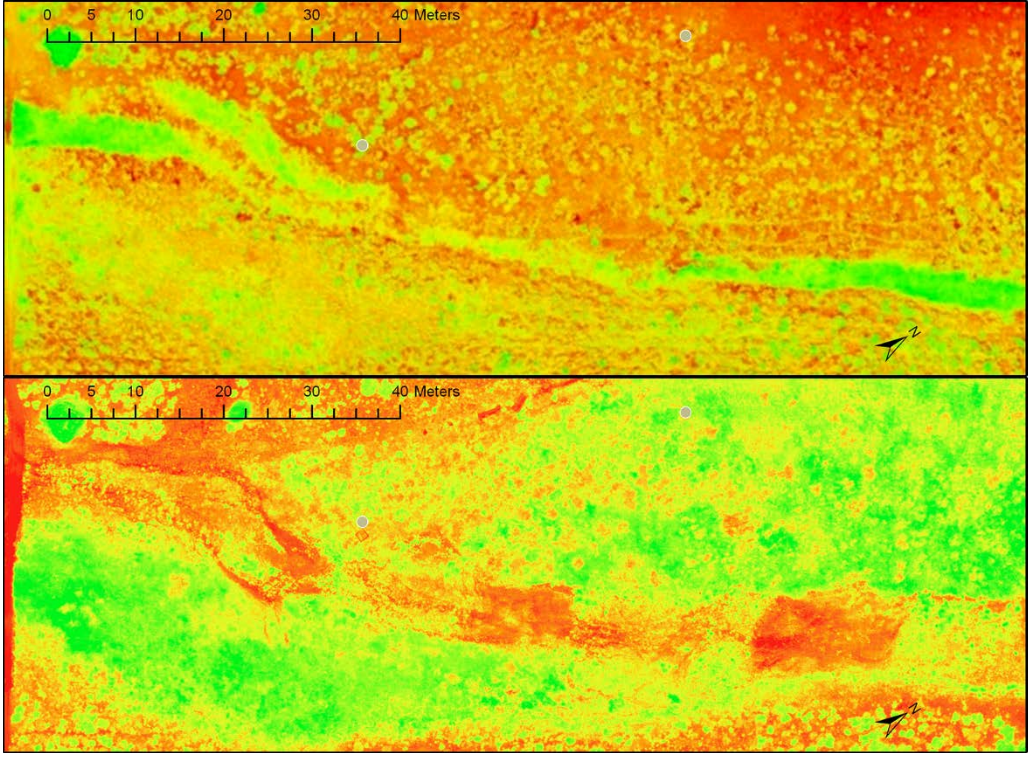

Figure 14. NDVI of part of Dry Creek Meadow. Collected in 2013 (top) and 2017 (bottom), with bright green representing high NDVI values. In 2013, hydrophilic plants producing high NDVI values are only found along an inset channel floodplain. This channel was the focus of pond and plug restoration, which raised the water table sufficiently to create much more extensive hydrophilic growth indicated by high NDVI values in the 2017 map. The 2013 map is modified from Christian [52].

From soil samples of all meadows studied (Table 3), bulk density and soil moisture are the key results, as is NDVI detected in imagery at those point locations. Low bulk density of the upper 10 cm of soil is especially notable in the dense root mats of sedges and rushes. Plant species were grouped into one of four categories, three of which are wetland associated and one upland. The *Carex* group of species include *Carex nebrascensis*, *C. utriculata*, and *C. pellita*, all of which are wetland obligate species characterized by dense root mats. The *Juncus* species are *J. balticus* and *J. nevadensis*. Sites with grasses involved genera such as *Deschampsia* and *Danthonia* as well as meadow flowers such as *Symphiotrichum*. Upland species comprise a range of shrubs including the xeric *Artemisia tridentata*. While all meadows also included scattered willow copses and pines, these were not sampled, though GPS-tagged photographs were used to link these trees with patches in the imagery. For bulk density, while the 4 groups are not significantly distinct in an ANOVA test, *Carex* species vs. all other samples are distinct (p=0.0342). Soil moisture in July samples is significantly distinct for all groups (p=0.0143).

Additional vegetation-only samples were collected as GPS points with captured photographs; 18 observations with vegetation types easily identified in the photographs were used and added to the above vegetation and soil sample locations. For the total of 38 vegetation samples and observations, NDVI values were extracted from the UAS-collected multispectral image data from July 2017 (see Table 2). For NDVI, the four vegetation groups are significantly distinct in an ANOVA test (p = 0.009) and *Carex* is also distinct from all other vegetation types (p = 0.045).

Table 3. Soil and vegetation sample results. Significant grouping variables by ANOVA are given with asterisks: vegetation groups are significantly distinct based on mean soil moisture (p=0.0143) and NDVI (p= 0.009), while only *Carex* is distinct from all other groups based on bulk density (p=0.0342). The *Carex* group is represented only by 3 hydrophilic, wetland obligate species *C. nebrascensis*, *C. utriculata,* and *C. pellita. Juncus* species are also wetland *J. balticus* and *J. nevadensis*.

Vegetation group	bulk density		soil moisture % (July)*		NDVI (July)*	
	mean	s	mean*	s	mean*	s
Carex-dominated	0.629*	0.258	49.7	19.0	0.860	0.052
Juncus - dominated	1.308	0.996	26.2	17.0	0.669	0.146
grasses/mixed	1.250	0.773	19.5	11.9	0.706	0.167
upland	1.422	0.828	11.9	9.3	0.531	0.180

4. Discussion

In this study of three meadows in Tahoe National Forest, the association of wetland-obligate sedges (*Carex* species) with low-lying areas of the meadow agrees with what has been observed in previous studies [16], and an expansion of these hydrophilic plants is a likely contributor to increased NDVI in restored meadows. Results from soil samples demonstrate that for sedges, bulk density and soil moisture are clearly distinct from other vegetation types. Sedge domination in some areas clearly define channelized flow, though this is most apparent in sections of meadows more distant from groundwater source influxes, especially noted in the central Knuthson section. Here greater variability of micro-elevation and possibly piezometric surfaces may occur, creating a more distinct vegetation signal (see Figures 7 and 9). Evidence for a history of wetter meadow conditions can also be seen in relict root mats, though the nature of this phenomenon will require further study.

Aerial LiDAR at a sufficient density such as 7-8 points/m^2 of the Tahoe National Forest acquisition appears to be suitable for detecting surface flow patterns across these meadows, although the contribution of groundwater cannot be detected from elevation, and surface/aquifer interactions are clearly a major component of meadow hydrology and thus channel development.

Capture of vegetation patterns using UAS methods designed for precision agriculture is promising, and should aid in assessing the signal of restoration success. Hydrophilic vegetation depends on a high water table, and xeric vegetation dies back where it gets too wet, and these are readily identified in high-resolution, multispectral imagery captured by UAS. Where vegetation is a prominent signal (see Figures 7 and 9), channel patterns are similar to what had been noted in channel survey studies, with low sinuosity as compared with larger alluvial channels.

Willows (*Salix* species) were noted adjacent to many discontinuous gullies in both the Carman system (upper Carman Valley and Knuthson Meadow) and Loney meadow, and willows are also associated with relatively sharp bends in the channel, producing high local sinuosity (see Figures 6, 7, and 13). In unrestored meadows – Carman Valley and Loney Meadow – willows may grow along channels in inset flood plains (see Figures 2, 4, and 13). Unclear at this stage is whether these shrubs preferably propagate along these sites or if their root systems or shading enhance scouring. Trimble [25] described a creek in Wisconsin that exhibited greater and more variable channel widening associated with riparian trees such as willows, as opposed to grass cover; and Stokes & Cunningham [56] noted that in Australia (invasive) willows spread more rapidly in streams of greater sinuosity where bare soil exposures are more common. Certainly a more incised stream with greater stream power can also more readily distribute willow stems for vegetative reproduction; willows are well known for vegetative propagation along stream courses, a property that makes them a favorite for stream riparian restoration. Sedge growth may also be affected by shading and moisture uptake by willow shrubs that create an environment conducive to root mat disturbance. Positive feedback may be contributing, with willows -- once established and possibly increasing scour -- creating conditions for further propagation; we may be seeing this in a string of willows at 39° 41' 55" N 120° 27' 00" W (see Figure 1), which also exhibits evidence of scour.

5. Conclusions

While UAS color imagery provides clear advantages for visual interpretation of small ephemeral channels on restored meadows, the use of UAV-mounted multispectral cameras adds the important groundwater signal provided by hydrophilic as opposed to mesic or xeric plants. There is a clear association of hydrophilic vegetation with more low-lying areas of meadows that are the sites of greater surface flow, and this vegetation is detectable in UAS multispectral imagery. For a healthy wet meadow, surface flow is likely a minor contributor, so flow accumulations based on elevation data – even fine elevation data provided by LiDAR – is insufficient to explain vegetation patterns. Groundwater is key to vegetation in these meadows, which is why a major goal of restoration is to raise the water table; this is in contrast to degraded meadows where incised channels take a major amount of the flow, and flow in these channels can be easily predicted using elevation-based flow accumulation models. If meadow restoration then leads to sedge growth at the expense of sagebrush (*Artemisia* species) and mesic grasses typifying degraded meadows, root mats will expand and may control incision. The contribution of willow is less clear, though there is an association of willow copses with scours and discontinuous gullies, often associated with an increase in local sinuosity. Capture of vegetation patterns using UAS-mounted multispectral sensors – especially coupled with aerial LiDAR – is promising for detecting vegetation and scour patterns, and should aid in assessing the signal of restoration success, as well as helping us better understand these important biogeomorphic systems.

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