Lake Tahoe Basin Stream Environment Zone (SEZ)

Baseline Condition Assessment

Tahoe Regional Planning Agency

Funded through a United States Environmental Protection Agency Wetland Development Grant

FINAL (December 2020)

Figure 1: Hell Hole meadows

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Executive Summary:
The Stream Environment Zone (SEZ) baseline condition assessment compiles information from a variety of sources to provide a comprehensive assessment of the health of SEZ in the Tahoe Basin. SEZ is a term unique to the Lake Tahoe Region. The Tahoe Regional Planning Agency (TRPA) Code of Ordinances defines an SEZ as, "Generally an area that owes its biological and physical characteristics to the presence of surface or ground water." This definition includes perennial, intermittent, and ephemeral streams; wet meadows, marshes, and other wetlands; riparian areas, beaches, and other areas expressing the presence or influence of surface or ground water. The assessment was made possible through the collaborative contributions of a variety of partners. The project was informed by data collected by United States Forest Service, California State Parks, California Tahoe Conservancy, the Desert Research Institute, TRPA, and other organizations.

A technical advisory committee for this project identified ten indicators to be used to assess the health of SEZ at the regional scale. The project began with the compilation of existing information on SEZ condition. This data came from a variety of high-quality sources including:

- Simon stream sedimentation study (Simon, 2006)
- Pre- and post-restoration project data from USFS, CA State Parks, and CTC
- California Rapid Assessment Methodology (CRAM) data from TRPA and CTC
- Bioassessment and invasive plant data from USFS, NDEP, CA State Parks, and TRPA
- Aquatic organism passage data from USFS

The above data sets were mined for information on the ten priority indicators. Existing data was able to fill in over 50% of needed data. Targeted data collection was conducted by TRPA staff in the summers of 2019 and 2020 to address information gaps in the existing data. Over the summers of 2019 and 2020, TRPA staff:

- Visited and collected data on at least one indicator at 245 meadows
- Collected streambank erosion data on over 20 miles of streams
- Field delineated meadow boundaries for 132 meadows
- Collected benthic macroinvertebrates at 60 stream sites

Through existing data and the new data collected in 2019 and 2020, most SEZ in the Tahoe Basin were assessed and have data for all the indicators. The data provides a nearly complete picture of the current health of SEZ in the Tahoe Basin. It is important to note this is a regional-scale assessment and not project specific in the amount of detail for each SEZ.

After compiling and analyzing the data for the Basin, each SEZ in the Tahoe Basin was given a health rating based on the summary of indicators. All site data can be found in a web map format at https://gis.trpa.org/TahoeSEZViewer/. Twelve key findings were made based on this assessment. More detailed information on these key findings can be found in the Key Findings section.

1. Riverine channels and their associated riparian areas are mostly healthy outside of meadows, but over a third of meadows and their associated stream channels show signs of degradation.
2. Channel incision is evident throughout streams of the Tahoe Basin.
3. Conifer encroachment is prevalent in many meadows in the Tahoe Basin.
4. Remote meadows are not immune to impacts.
5. Although some remote meadows are impacted, most meadows outside urbanized areas are healthy and functioning well.
6. Several degraded meadows and streams are not currently on any restoration priority lists.
7. The Upper Truckee watershed has many of the most impacted meadows and streams in the entire Tahoe Basin.
8. Most past restoration projects are functioning very well.
9. Not all restoration projects are functioning well.
10. Restoration has improved bank stability, but some unstable stream banks can still be found throughout the Tahoe Basin.
11. Around 15% of meadow area in the Tahoe Basin has been lost to development.
12. Meadows in Tahoe overall are increasing in vegetation vigor since 1982.

The SEZ baseline assessment contributes toward several Basin goals including:

- Establishing a baseline from which to track long term condition changes to SEZ
- Identification of restoration opportunities
- Developing a basin-wide goal for SEZ condition (update TRPA SEZ restoration threshold standard)
- Informing the design of a long-term SEZ monitoring plan

SECTION 1: INTRODUCTION AND INDICATORS

Figure 2: Meadows near Mount Tallac

BACKGROUND

TRPA convened a Stream Environment Zone (SEZ) Technical Advisory Committee (TAC) to help guide work performed under a United States EPA wetland development grant. During discussions of which indicators should be included in a long-term monitoring plan, TAC members expressed interest in compiling existing data on SEZ condition to help establish a “baseline” of current SEZ conditions. While a baseline assessment of SEZ was not a deliverable under the grant, the SEZ baseline assessment contributes toward several Basin goals including:

- Establishing a baseline from which to track long term condition changes to SEZ
- Identification of restoration opportunities
- Developing a basin-wide goal for SEZ condition (update SEZ restoration threshold standard)
- Informing the design of a long-term SEZ monitoring plan

This project utilizes all three of the U.S. Environmental Protection Agency’s monitoring levels in an innovative approach. EPA Level 1 is generally a landscape assessment; Level 2 is a rapid site assessment; and Level 3 is a detailed site assessment (United States Environmental Protection Agency, 2006). Because of the development of remote sensing technologies and field-based assessment, this project was able to utilize all three monitoring levels at a Basin-wide scale. Rapid and detailed field assessments were completed in the field and detailed data was collected on each site using remote sensing technologies. This approach allowed somewhat detailed data to be collected at a much larger scale in a shorter amount of time than would be possible using just field-based methods. This draft lays out the assessment framework and the accompanying spatial databases provide an implementation of the assessment. This assessment will be a baseline of current SEZ conditions and will not include any new data past 2020.

SCOPE

The SEZ construct is unique to the Tahoe Basin. The term SEZ includes perennial, intermittent, and ephemeral streams; wet meadows, marshes, and other wetlands; lakes, rivers, riparian areas, beaches, and other areas expressing the presence or influence of surface or ground water. Because the definition of SEZ is broad, it is not possible to develop a single framework that meaningfully assesses condition of all the different SEZ types. While the terms definition is broad, in application the term has primarily been used as a synonym for streams, riparian areas, meadows, wetlands, and marshes in the region.

The baseline assessment focuses on several types of SEZ but combines categories to simplify the assessment. The assessment breaks SEZ into five categories; meadows (channeled and non-channeled) and streams (perennial and non-perennial), as well as forested SEZ (generally riparian zones). However, several more SEZ types are included within these five categories:

- Marshes and fens are different ecosystems than meadows. However, they share enough common attributes that their condition can be measured using similar indicators as meadows. Therefore, this assessment will include marshes and fens under the meadow category.
- Non-perennial streams within urbanized areas were assessed as part of this project under the “forested” SEZ type. These make up a very small percentage of overall SEZ but are important for the nutrient and sediment reduction functions they can provide. Non-perennial streams outside urbanized areas are not assessed to conserve limited monitoring resources.

- Forested SEZ are assessed when they are the riparian area of perennial or urbanized non-perennial streams, or if they are aspen stands within a meadow system.
- Aspen stands outside of meadow areas, lakes, beaches, and forested SEZ that are not the riparian area of perennial streams or urbanized non-perennial streams were not assessed as part of this project.

This project compiles existing data with new data collected specifically for this project to provide a comprehensive assessment of the current condition of SEZ throughout the Lake Tahoe Basin.

IMPORTANT CAVEATS FOR THIS PROJECT

This project compiled data on ten different indicators on SEZ in the Tahoe Basin to give an overall picture of SEZ health. It is important to note that this data gives an overall assessment of the condition of each SEZ assessment unit. However, it is a *regional* assessment and not appropriate for site level restoration design. The data from this project *can* be used to assess the general condition of assessment units, compare assessment units against one another, identify degraded assessment units that may benefit from restoration, and track changes in condition over time. The data from this project *should not* be used as a replacement for site level assessment and monitoring necessary for design, or for detailed assessment of the effectiveness of restoration projects. More detailed monitoring and assessment is needed in these situations.

UTILIZING EXISTING DATA

SEZ restoration projects have been implemented by nearly 20 different Environmental Improvement Program partners in the last 30 years. Monitoring and assessment protocols vary significantly between projects and partners and often depends on project or implementor specific needs. This makes it difficult to get comparable information about SEZ condition across the Basin. Despite more than 30 years of SEZ restoration work, there has never been a basin wide assessment of SEZ condition.

This baseline assessment addresses that challenge by focusing on key indicators of SEZ health and identifying existing sources of information that can be aggregated to inform a more complete picture of the health of the Basin's SEZ. The assessment framework is designed to utilize data from a number of different sources and protocols. For example, both the USFS Stream Condition Inventory (Frazier, et al., 2005) and American Rivers Meadow Scorecard (American Rivers, 2016) collect data on bank stability. Information on bank stability is also often collected as part of more detailed assessments of restoration projects. While these three monitoring protocols may collect different suites of information besides bank stability, by focusing on specific indicators, such as bank stability, and aggregating through a common method, the data can be integrated into a common framework.

The focus on existing data sets enables the assessment to leverage data collected through a variety of methods to the maximum extent possible rather than "re-inventing the wheel." This assessment is not intended to dictate monitoring methods to partners in the Basin. It provides a framework to aggregate monitoring data from different sources and identifies methods to collect additional data that is directly comparable to existing data, and will be used to develop a long term, basin-wide status and trends SEZ monitoring program.

INDICATOR SELECTION

The first step in assessing SEZ condition is selecting indicators of SEZ health. Potential indicators were identified based on several factors. Indicator screening began by reviewing previously completed work and work underway as part of regional initiatives, including the Lake Tahoe West Collaborative, and past work of various SEZ-related groups.

All partners have expressed the importance of using indicators that directly relate to desired SEZ functions such as reducing sediment, groundwater recharge, etc. The important functions SEZ provide in the Tahoe Basin were identified as part of an earlier project and are listed in Table 1 (Roby, et al., 2015). The primary screening factor for choosing indicators was relation to a desired SEZ function.

Issue Category	Desired SEZ Functions
Water Quality	1. Reduce sediment, nutrient, and pollutant loading to surface waters
	2. Moderate water temperature for aquatic species
Water Quantity	3. Flow maintenance and moderation
	4. Allow groundwater recharge
Aquatic Habitats	5. Provide suitable aquatic habitats for native and desirable species and connectivity throughout the stream continuum
Riparian Habitats	6. Contribute to native vegetation community diversity, provide suitable habitat for rare plant species
	7. Contribute to regional native wildlife habitat diversity and provide movement corridors; provide suitable habitat for special interest species
	8. Promote natural soil productivity and nutrient cycling

Table 1: Important SEZ functions derived from SEZ TAC and 2015 SEZ process

In addition to connection to desired SEZ functions, other factors considered in indicator selection include:

- Measurable within given resources (if additional data collection is necessary)
- Robust existing data
- Reliable and repeatable
- Support from the SEZ Technical Advisory Committee (TAC) and other stakeholders

Based on the above five criteria, each potential indicator was evaluated. Indicators that most strongly correlated to the above factors were included. Selected indicators are listed below.

SEZ Type	Indicator	SEZ functions related to (from Table 1)	Existing data?	Existing data sources
Channeled Meadows / Non-channeled Meadows / Perennial Riverine / Non-Perennial Riverine / Forested	Headcuts	1, 2, 3, 4	Yes; limited number of sites	TRPA CRAM meadow data; Meadow Scorecard data; USFS Fire adapted ecosystem monitoring; project-level data

Channeled Meadows / Non-channeled Meadows	Vegetation vigor	1, 2, 3, 4	No	Remotely sensed data
Channeled meadows / Perennial Riverine / Non-Perennial Riverine	Channel incision	1, 2, 3, 4	Yes; 100+ sites	USFS stream condition inventory data; TRPA / CTC CRAM meadow data; Meadow Scorecard data; project-level data; USFS Region 5 meadow monitoring
Channeled Meadows / Non-channeled Meadows	Invasive plant species	6, 7	Yes; 100+ sites	USFS Region 5 meadow monitoring plots; TRPA / CTC CRAM meadow data; CalFlora invasive mapping; USFS invasive plant monitoring; CA State Parks invasive plant monitoring
Channeled Meadows / Non-channeled Meadows / Forested	Presence of ditches / gullies	1, 2, 3, 4	Yes	TRPA / CTC CRAM meadow data; remotely sensed bare-earth LIDAR data
Channeled Meadows / Non-channeled Meadows	Conifer encroachment	6, 7	No	Remotely sensed data
Perennial Riverine / Non-Perennial Riverine / Channeled meadows / Forested	Channel stability	1	Yes; 150+ sites	USFS stream condition inventory data; TRPA / CTC bioassessment data; Trout Unlimited Upper Truckee River Study; project-level data
Perennial Riverine / Channeled meadows	Biotic Integrity (Benthic macroinvertebrates)	7	Yes: 150+ sites	TRPA / CTC / NDEP bioassessment data
Channeled Meadows / Non-channeled Meadows / Perennial Riverine / Non-Perennial Riverine / Forested	Habitat fragmentation	All	Yes; all sites	TRPA impervious cover lidar data
Perennial Riverine / Channeled meadows	Aquatic Organism Passage	7	Yes	USFS Aquatic Organism Passage studies

Table 2: Selected SEZ condition indicators

ASSESSMENT UNITS:

Assessment requires SEZ to be broken down into spatially discreet units. The units are intended to delineate relatively homogenous areas of SEZ condition. The US Forest Service / UC-Davis Sierra Nevada meadows map layer served as the basis for the meadow assessment areas. The base for the stream and associated riparian layers was the Spatial Informatics Group 2015 SEZ map (Roby, et al., 2015). Modifications to the base layer boundaries and delineation into assessment units were guided by the following considerations:

- Pre-existing established assessment areas (Ex. Upper Truckee River Reach 1, 2, 3, etc. and Blackwood Reaches 1, 2, etc.)
- Known breaks in condition (Ex. healthy, degraded, etc.)

- Natural or man-made breaks in SEZ (Ex. development dissecting SEZ, transition from meadow to steep stream channel, etc.)
- Assessment units must be small enough to allow for full assessment of each unit, but large enough to limit the total number of units

There are a few important details in how assessment units were developed:

- In general, SEZ that are partially intact with some development were identified as a single "assessment unit" and the percent of development within the intact SEZ were included in the "assessment unit". If an entire SEZ was lost to the point where few if any indicators are able to be assessed, the entire historic SEZ was given its own "assessment unit" and given a "D" rating.
- Historic SEZ boundaries are shown (regardless of development) to better communicate visually where SEZ have been lost to development.
- Historic SEZ that have since been converted into officially-registered stormwater catchment basin BMP's will be assessed the same as other SEZ, however it will be noted that they are BMP's. Officially-registered stormwater catchment basin serve an important function as stormwater filtration, but they will likely receive a low score in this rating system. That score is not a reflection of their ability to function as stormwater retention basins.

Assessment units for SEZ in undeveloped areas that have experienced less anthropogenic impact are generally larger than assessment units in areas more likely to be degraded based on historic or present land uses. Areas impacted by human activities are more likely to be heterogenous and more likely to be the focus of restoration action. These areas were therefore broken into smaller areas. This will also allow for development of a more accurate compilation of condition and will focus resources in areas where degradation is more likely to be found.

- Stream segments in likely altered areas range from ½ to 1 mile, while stream segments in unaltered areas range from 4-8 miles.
- Meadow segments in likely altered areas range from 10-50 acres, while meadow segments in unaltered areas range from 50-100 acres.

Assessment units are not an exact delineation of the SEZ to be assessed. They are a spatial surrogate used for data compilation and visualization. Each assessment unit will have multiple polygons associated with it depending on the indicator in question. For example, a meadow assessment unit will have one polygon used to assess conifer encroachment, a slightly different polygon used to assess vegetation vigor (NDVI), and a slightly different one used to assess habitat fragmentation. While each assessment unit has multiple polygons associated with it, a single polygon is used for data visualization. The assessment unit that is seen in the maps is the largest of the polygons used and represents the likely historic extent of the SEZ. All other polygons used to analyze different indicators within the assessment unit are either the same size or smaller and totally within the boundaries of the assessment unit.

INDICATORS

This section will go into more detail on the selected indicators. A brief description of the indicator, the types of SEZ they will be assessed in, and how they are related to important SEZ functions are provided. More details on the methods used to measure the indicators can be found in the appendix.

Indicator 1: Headcuts (Channeled Meadows / Non-channeled Meadows / Perennial Riverine / Non-Perennial Riverine / Forested)

Background: Headcuts are an abrupt drop in streambed elevation that can form in meadow and stream systems and may be caused by natural processes or induced by channel or watershed alterations. Headcuts can lead to incised channels and can lower the water table of the surrounding landscape (Bennett, 1999). While channel incision can be the result of headcuts, this indicator was included separately because headcuts can be the beginning of a process of meadow degradation or a result of meadow degradation. They may be a sign of meadow instability, and if caught early, restoration action can prevent further degradation. Alternately, headcuts may remain relatively stable for decades, highlighting the complexities of channel slope, downstream flow accumulation, and the variable erosion resistance of different substrates. Thus, it is important to distinguish between problematic headcuts (actively migrating, introducing large volumes of fine sediment to the channel, disconnecting channels from the floodplain) and benign headcuts (stable, or sufficiently shallow to avoid disrupting meadow or channel functions).

Figure 3: Large headcuts in a non-channeled meadow

Relation to Desired SEZ Functions: The formation and migration of headcuts impairs the hydrologic function of meadows and streams. Therefore, they provide information on the following SEZ functions:

- Reduce sediment, nutrient, and pollutant loading to surface waters
- Moderate water temperature for aquatic species
- Groundwater recharge
- Flow maintenance and moderation

Indicator 2: Vegetation Vigor (Channeled Meadows; Non-channeled Meadows)

Background: Vegetation vigor refers generally to the health of plants. Vegetation vigor is affected by changes in groundwater, climate, and physical conditions (Huntington, et al., 2016). A common objective of many meadow and riverine SEZ restoration projects is to raise shallow groundwater levels in the late summer by increasing channel bed elevations, increasing the duration of floodplain inundation, increasing groundwater storage, and reducing the rate of shallow groundwater loss to the stream. While direct groundwater measurements are an excellent way to assess changes in groundwater depth, they require intensive labor and materials and are therefore not feasible on a basin-wide scale. Vegetation vigor can be measured remotely through indices such as the Normalized Difference Vegetation Index (NDVI) and is a good surrogate for groundwater depth (Huntington, et al., 2016). Very small values (0.1 or less) of the NDVI function correspond to empty areas of rocks, sand or snow. Moderate values (from 0.2 to 0.3) represent shrubs and meadows, while large values (from 0.6 to 0.8) indicate temperate and tropical forests (Huntington, et al., 2016). It can be used as cost-effective indicator of change associated with restoration or land management actions. Plant communities in meadows with shallow groundwater throughout the growing season display higher NDVI values throughout the season. Where groundwater tables have dropped, communities with reduced access to groundwater often display lower NDVI values, reflecting decreased access to shallow groundwater (Huntington, et al., 2016). Further discussion on calculating NDVI values for the Tahoe Basin can be found in appendix 6.

Figure 4: Upper Truckee River at Johnson meadow - Aerial photo taken in late July reveals degraded, dry meadow conditions that will result in low NDVI values.

Figure 5: Trout Creek about Black Bart - Aerial photo taken in late July reveals healthy, wet meadow conditions that will result in high NDVI values.

Relation to Desired SEZ Functions: Vegetation vigor is a way to indirectly evaluate the proximity of groundwater to the ground surface. Because of this, it relates directly to the hydrologic function of a meadow. Therefore, it provides information on the following SEZ functions:

- Reduce sediment, nutrient, and pollutant loading to surface waters
- Moderate water temperature for aquatic species
- Allow groundwater recharge
- Flow maintenance and moderation

Indicator 3: Incision (Channeled Meadows / Perennial Riverine / Non-Perennial Riverine)

Background: Incised channels are associated with impaired riverine and meadow SEZ functions and are often the focus of restoration actions to aggrade or raise the channel bed. Incision ratios are calculated as the maximum bank height divided by the bankfull height and indicate the degree of incision into a floodplain. Incision ratios must be viewed in the context which considers the dynamic nature of the

Figure 6: Upper Truckee River at Reach 5 - Restoration has resulted in a healthy channel and healthy, low incision ratios with good floodplain connection.

Figure 7: Upper Truckee River at Johnson meadow - Extreme degradation has led to unhealthy, high incision ratios with poor floodplain connection.

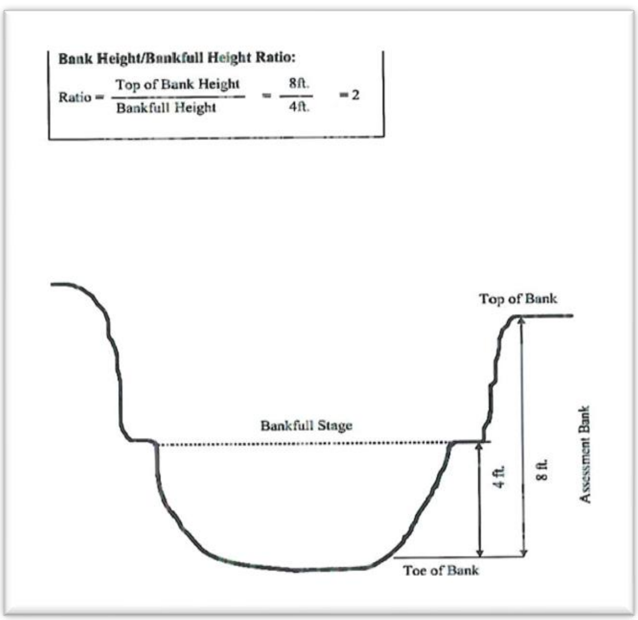

Figure 8: Example of incision measurement (Ratliff, 1985)

system and the degree to which recovery is taking place. Within this context an incised channel does not necessarily indicate ongoing degradation. Watershed change or disturbance often initiate incision. The recovery process then may require decades or even centuries to progress. Equilibrium and stability can be achieved by restoration to a pre-modified, non-incised condition, or by advancing a channel toward quasi equilibrium with the creation of an inset floodplain. Since inset floodplain restoration can be an appropriate restoration strategy, but does not necessarily reduce incision ratios as part of overall system health and the inferred trajectory or equilibrium of a recovering system.

Relation to Desired SEZ Functions: Channel incision directly impairs the hydrologic function of a meadow or stream. Therefore, it provides information on the following SEZ functions:

- Reduce sediment, nutrient, and pollutant loading to surface waters
- Moderate water temperature for aquatic species
- Allow groundwater recharge
- Flow maintenance and moderation

Indicator 4: Ditches / Gullies (Channeled Meadows; Non-channeled Meadows; Forested)

Figure 9: An old ditch in Bijou meadow in South Lake Tahoe.

Background: Much like meadows can be impacted by incised channels, meadows can also be impacted by ditches and gullies. In most cases, depth to groundwater is increased and the meadow is degraded. Ditches and gullies are common in the Lake Tahoe Basin from past agriculture practices and development. Gullies and ditches concentrate water and divert water out of the meadow quicker than natural, thus drying it out.

Relation to Desired SEZ Functions: Ditches and gullies directly impair the hydrologic function of a meadow. Therefore, it relates to the following SEZ functions:

- Reduce sediment, nutrient, and pollutant loading to surface waters
- Moderate water temperature for aquatic species
- Allow groundwater recharge
- Flow maintenance and moderation

Indicator 5: Channel Stability (Channeled Meadows / Perennial Riverine / Non-Perennial Riverine / Forested)

Background: Channel stability is an important indicator of overall system stability, and poor channel stability can indicate increased sediment loading into Lake Tahoe. The indicator is particularly important in the Tahoe Basin where sediment load reduction into Lake Tahoe is one of the primary goals of stream restoration projects. Stream bank stability will be used as the indicator of channel stability. While stream bank erosion does not necessarily mean a channel is unstable, large amounts of stream bank erosion almost always indicates increased sediment loads. Some degree of stream bank erosion is natural and even desirable. Therefore, assessments of channel stability using stream bank erosion should be viewed in the context of the larger system and not assume that bank erosion necessarily means it is a degraded system. Bank erosion may be interpreted as a stage of channel evolution that results in wider channels, slower velocities, and therefore greater channel stability.

Relation to Desired SEZ Functions: Channel stability directly relates to the hydrologic function of a meadow or stream. Unstable systems impair an SEZ's ability to provide the following critical SEZ functions:

- Reduce sediment, nutrient, and pollutant loading to surface waters

Figure 10: Stable stream banks on restored Cold Creek.

Figure 11: Eroded stream banks on the Upper Truckee River.

Indicator 6: Habitat Fragmentation (Channeled Meadows / Non-channeled Meadows / Perennial Riverine / Non-Perennial Riverine / Forested)

There are two different methods for assessing habitat fragmentation. One method is for use in meadows and the other is for use in riverine and forested systems.

Figure 12: (Left) 1940 aerial photo shows no development in meadow. (Right) Same meadow in 2018 shows extensive development in meadow.

Meadows:

Background: It has been estimated that over 50% of meadows in the Tahoe Basin have been lost due to development and therefore continues to represent a large threat to meadow health (Murphy & Knopp, 2000). Habitat fragmentation in meadow systems will be measured through the amount of development in delineated historic meadows.

Relation to desired SEZ functions: Because development in meadows eliminates meadow area, it is related to all SEZ functions that meadows provide.

Streams:

Figure 13: Impervious cover (dark green) overlaid against the riparian corridor (light green) shows extensive development in the riparian corridor in Incline Village.

Background: Development within riparian corridors was commonplace throughout the Tahoe Basin prior to TRPA regulations. Significant resources continue to be invested in removing development from these sensitive areas. Habitat fragmentation in riverine systems will be measured through the amount of development in riparian corridors along perennial streams, as well as non-perennial streams and forested SEZ within urbanized areas.

Relation to desired SEZ functions: Development in riparian corridors impacts many of the functions that riparian corridors provide including:

- Reduce sediment, nutrient, and pollutant loading to surface waters
- Moderate water temperature for aquatic species
- Provide suitable aquatic habitats for native and desirable species and connectivity throughout the stream continuum
- Contribute to native vegetation community diversity, provide suitable habitat for rare plant species
- Contribute to regional native wildlife habitat diversity and provide movement corridors; provide suitable habitat for special interest species

Indicator 7: Conifer Encroachment (Channeled Meadows; Non-channeled Meadows)

Figure 14: Conifer encroachment into a meadow in the Tahoe Basin.

Background: Conifer encroachment into mountain meadows in the Pacific Northwest and the California Sierra Nevada has been reported by many authors (Lubetkin, 2015). Although conifer encroachment into meadows may be induced by natural processes and climate cycles, meadows are more diverse than adjacent forests and therefore replacement of meadow vegetation by conifer forest can reduce local and landscape biodiversity. In the central Sierra Nevada, encroachment occurs most commonly with lodgepole pine and to a lesser amount, red and white fir (Lubetkin, Westerling, & Kueppers, 2017). Conifer encroachment into mountain meadows has been attributed to several (non-exclusive) causes, including climate effects, cessation of grazing, and fire suppression. It is possible that all of these factors allow for increased conifer cover in existing meadows (Lubetkin, 2015).

Relation to desired SEZ functions: Conifer encroachment reduces rare and important meadow habitat. Therefore, conifer encroachment negatively impacts the following SEZ functions:

- Contribute to regional native wildlife habitat diversity and provide movement corridors
- Provide suitable habitat for special interest species
- Contribute to native vegetation community diversity, provide suitable habitat for rare plant species

Indicator 8: Biotic Integrity (Channeled Meadows / Perennial Riverine)

Background: Evaluating the abundance and variety of benthic macroinvertebrates in a waterbody gives an indication of the biological condition of that waterbody. Generally, waterbodies in healthy biological condition support a wide variety and high number of macroinvertebrate taxa, including many that are intolerant of pollution. Samples yielding only pollution–tolerant species or very little diversity or abundance may indicate a less healthy waterbody (Mazor, et al., 2016). Biological condition is the most comprehensive indicator of waterbody health. When the biology of a waterbody is healthy, the chemical and physical components of the waterbody are also typically in good condition. Macroinvertebrates respond reliably to changes in stream condition including water quality pollution and stream habitat degradation.

Figure 15: Macroinvertebrates are a good indicator of a stream's biotic integrity and overall health.

Relation to desired SEZ functions: Macroinvertebrates are an excellent indicator of both water quality and stream habitat. Therefore, it is related to the following SEZ functions:

- Provide suitable habitat for special interest species
- Reduce sediment, nutrient, and pollutant loading to surface waters
- Moderate water temperature for aquatic species
- Provide suitable aquatic habitats for native and desirable species and connectivity throughout the stream continuum

Indicator 9: Invasive Plant Species (Channeled Meadows; Non-channeled Meadows)

Background: Terrestrial invasive plants can significantly alter meadow vegetation communities and degrade wildlife habitat of these rare plant communities.

Figure 16: Invasive Reed Canary Grass taking over a meadow in South Lake Tahoe.

Relation to desired SEZ functions: Terrestrial invasive species threaten the vegetation function of meadow systems. Therefore, they are related to the following SEZ functions:

- Provide suitable habitat for special interest species

- Contribute to native vegetation community diversity, provide suitable habitat for rare plant species

- Contribute to regional native wildlife habitat diversity

Indicator 10: Aquatic Organism Passage (Channeled Meadows / Perennial Riverine)

Background:
Stream crossings by roads can pose serious threats to fishery ecosystems. The cumulative effect of culverts, fords, and other structures throughout a stream channel can significantly change the stream geomorphology and impair fish passage by blocking valuable spawning and rearing habitat (Clarkin, et al., 2005).

Relation to desired SEZ functions:
Several functions relating to aquatic organisms and physical stream structure are related to this indicator:

- Provide suitable habitat for special status species
- Reduce sediment, nutrient, and pollutant loading to surface waters
- Provide suitable aquatic habitats for native and desirable species and connectivity throughout the stream continuum

Figure 17: (Left) impassable culvert at Saxon Creek prior to retrofit. (Right) Fish-passable road crossing at Tallac Creek.

DATA COMPILATION

Once indicators were selected and assessment areas were defined, the next step was compiling existing data that relates directly to the selected indicators. Several existing data sources were drawn upon to inform the assessment. This includes data from USFS Stream Condition Inventory, USFS Aquatic Organism Passage data, USFS Region 5 meadow monitoring, TRPA / CTC CRAM monitoring (meadow CRAM module), TRPA / CTC bioassessment data, Trout Unlimited studies, USFS and CA State Parks invasive species surveys, restoration project-specific data, Simon Tahoe stream sedimentation study for the TMDL, Sierra Nevada Meadow Partnership meadow scorecard assessments, Landsat/Google Earth imagery from 1984-present, and various LIDAR data.

There is an extensive history of data collection in the Tahoe Region. To ensure that the data used in the assessment provide a current picture of SEZ health, current condition will only be utilized if it was collected in the last ten years. It is assumed that without restoration projects, stream and meadow sites are unlikely to have changed drastically in the last ten years. If a restoration project has been completed on a site, only post-restoration data will be used to ensure that only current site conditions are assessed.

RATING SCALE DEFINITION

To enable data aggregation across multiple indicators and multiple methods, a simple rating scale was utilized to standardize scores from each indicator. The scores are also intended to provide a quick snapshot of quality of the indicator. The initial rating will utilize a simple A, B, C, D scale:

- “A” = 12 points and represents excellent conditions
- “B” = 9 points and represents good conditions
- “C” = 6 points and represents moderately degraded conditions
- “D” = 3 points and represents very degraded conditions

Rating scales are derived from established protocols whenever possible, such as the American Rivers meadow scorecard, CRAM, the California Surface Water Ambient Monitoring Program, among others. Rating scales are described in greater detail in the Appendix.

A total score for each site was calculated by summing the individual indicator scores. Because perennial streams, non-perennial streams, channeled meadows, non-channeled meadows, and forested SEZ have a different number of indicators, each also have different total points possible. To allow for greater comparability between different types, a percentage of the total points possible will be used to give the site a final score. For example, if a channeled meadow receives 54 of 108 possible points, this site would be given a final score of 50%. A riverine system receiving a score of 36 out of 48 possible points would be given a final score of 75%. Final scores will be given a rating based on this percentage:

SEZ Final Ratings
• >90% = A (excellent)
• 80% - 89% = B (good)
• 70% – 79% = C (degraded)
• <69% = D (very degraded)

Table 3: SEZ Rating Categories

It is important to note that while the raw data will be scored, the raw data will also remain in the database intact in case the scoring method changes further down the line. Below is a table describing the indicators and rating system proposed for "scoring" SEZ. More details on each of these indicators can be found in the appendix.

INDICATOR SUMMARY

The complete set of indicators provide an overall snapshot of condition. Natural systems are inherently variable and therefore conclusions on condition should not be reached based solely on the score from an individual indicator. Each score should be viewed in the context of the larger system. The selected set of indicators, how they will be measured (methods), and how the associated data will be rated are listed below.

INDICATOR NAME	SEZ TYPES	METRIC	METHODS DERVIED FROM	UNITS	RATING SCALE SOURCE	BIN A - EXCELLENT	BIN B - GOOD	BIN C - DEGRADED	BIN D - VERY DEGRADED
Headcuts	channeled meadows; non-channeled meadows; perennial riverine; non-perennial riverine; forested	Number and size of headcuts	Meadow Scorecard	Number / Size	Meadow Scorecard	0 headcuts	1+ small headcut (0.10 – 0.49m) *and* no other larger headcuts.	1+ medium headcuts (0.50 – 0.99m) *and* no other larger headcuts. There may be small headcuts present as well.	1+ large headcuts (>1m). There may be medium or small headcuts present as well.
Vegetation Vigor	channeled meadows; non-channeled meadows	Climate-adjusted NDVI trend and NDVI percentile rank	Desert Research Institute	Unitless	DRI / TRPA	Climate adjusted NDVI and Percentile Rank trends are positive or stable.	Climate adjusted NDVI is increasing or stable and Percentile Rank trend is declining by less than 0.5% per year.	Climate adjusted NDVI is increasing or stable and Percentile Rank trend is declining by greater than 0.5% per year.	Climate adjusted NDVI is declining and Percentile Rank trend is declining by greater than 0.5% per year.
Conifer Encroachment	channeled meadows; non-channeled meadows	Percent of meadow encroached	TRPA/ USFS / CTC	Percent	TRPA / USFS	0-20% of meadow encroached	21-40% of meadow encroached	41-70% of meadow encroached	71-100% of meadow encroached
Incision	channeled meadows; perennial riverine; non-perennial riverine	Incision ratio	California Rapid Assessment Method	Ratio / percent	California Rapid Assessment Method	Bank height to bankfull depth is ≤ 1.19	Bank height to bankfull depth is 1.2 to 1.5	Bank height to bankfull depth is 1.6 to 2.0	Bank height to bankfull depth is ≥ 2.1
Presence of Ditches / Gullies	channeled meadows; non-channeled meadows; forested	Percent of meadow length	Meadow Scorecard	Percent	Meadow Scorecard	No gullies or ditches or berms	Combined length of all ditches / gullies / berms is 1-10% of total meadow length	Combined length of all ditches / gullies / berms is 10-50% of total meadow length	Combined length of all ditches / gullies / berms is greater than 50% of total meadow length
Channel Stability	channeled meadows; perennial riverine; non-perennial riverine	Percent eroded stream banks	Meadow Scorecard / Multiple Indicator Monitoring	Percent	Meadow Scorecard	<5% of bank is unstable	5-20% of bank is unstable	20-50% of bank is unstable	>50% of bank is unstable
Habitat Fragmentation	channeled meadows; non-channeled	Percent meadow /	TRPA	Percent	TRPA	<1% of historic meadow / riparian habitat	1-10% of historic meadow / riparian habitat	>10% and <20% of historic	>20% of historic meadow / riparian habitat

	meadows; perennial riverine; non-perennial riverine; forested	riparian area developed				has been developed	has been developed	meadow / riparian habitat has been developed	has been developed
Biotic Integrity	channeled meadows; perennial riverine	California Stream Condition Index (CSCI) score	California Surface Water Ambient Monitoring Program	Score	California Surface Water Ambient Monitoring Program	>0.92 CSCI score	0.79 – 0.92 CSCI score	0.62 – 0.79 CSCI score	<0.62 CSCI score
Invasive Species (plants)	channeled meadows; non-channeled meadows	Number of priority invasive plants species	Tahoe Invasive Weeds Coordinating Committee Level 1 and Level 2 Priority Plants	Presence	TRPA	0 invasive plant species	1 Level 2 invasive plant species	2 Level 2 invasive plants species OR 1 Level 1 invasive plant species	3+ Level 2 invasive plant species OR 2+ Level 1 invasive plants species
Aquatic Organism Passage	channeled meadows; perennial riverine	Passage barriers per stream mile	USFS Aquatic Organism Passage study 2010/2011	Number	TRPA	0 barriers per stream mile	>0-1 barriers per stream mile	>1 – 3 barriers per stream mile	>3 barriers per stream mile

Table 4: Indicators, Metrics, and Rating Scales

EXAMPLE PRODUCT

Using existing data, indicators were "scored" and compiled. The preliminary database and map of SEZ condition are included in the accompanying web map https://gis.trpa.org/TahoeSEZViewer/. An example of what this completed database looks like for each SEZ type is included in the table below:

Indicator	Meadow 1 (channeled meadow)	Meadow 2 (non-channeled meadow)	Stream 1 (riverine perennial)	Stream 1 (riverine non-perennial)
Headcuts	"D" very degraded (3)	"C" Degraded (6)	"A" Excellent (12)	"A" Excellent (12)
Vegetation vigor	"D" Very degraded (3)	"C" Degraded (6)	N/A	N/A
Habitat fragmentation	"A" Excellent (12)	"B" Healthy (9)	"C" Degraded (6)	"A" Excellent (12)
Incision	"D" Very degraded (3)	N/A	"A" Excellent (12)	"A" Excellent (12)
Ditches / Gullies	"A" Excellent (12)	"C" Degraded (6)	N/A	N/A
Channel stability	"C" Degraded (6)	N/A	"B" Good (9)	"A" Excellent (12)
Biotic Integrity (macroinvertebrates)	"D" Very degraded (3)	N/A	"B" Good (9)	N/A
Conifer encroachment	"B" Good (9)	"B" Good (9)	N/A	N/A
Invasive species	"B" Good (9)	"D" Very degraded (3)	N/A	N/A
Aquatic Organism Passage	"D" Very degraded (3)	N/A	"A" Excellent (12)	N/A
TOTAL SCORE	**63 out of 120 (53%) = D**	**39 out of 72 (54%) = D**	**60 out of 72 (83%) = B**	**48 out of 48 (100%) = A**

Table 5: Example of final SEZ condition ratings

ADDITIONAL DATA COLLECTION

After filling in the indicator data from existing data sources, data gaps were assessed to determine how much additional data collection is needed. Some data was easy to collect from remote sensing and some required more field intensive methods.

While only existing data that relates to selected indicators was used to "score" indicators, additional data collected only used parts of existing methods that relate to selected indicators. Additional data collection is directly comparable to existing data used to score indicators. For example, if channel incision was scored using existing data where the ratio of bankfull depth to channel height depth (incision ratio), additional data was collected using the same methods. More detail on methods to be used for collecting additional data can be found in the appendix. Data collection methods were taken from existing protocols whenever possible to eliminate "re-inventing the wheel".

Indicator	**Ease of data collection**
Headcuts	Relatively easy to measure in the field / remotely sensed
Vegetation vigor	Easy to obtain with remotely sensed data
Channel incision	Relatively easy to measure in the field
Presence of ditches / gullies	Easy to obtain with remotely sensed data
Channel stability	Relatively easy to measure in the field
Habitat fragmentation	Easy to obtain with remotely sensed data
Conifer encroachment	Easy to obtain with remotely sensed data
Biotic integrity	Somewhat time-consuming measuring in the field
Invasive species	Relatively easy to measure in the field
Aquatic Organism Passage	Somewhat time-consuming measuring in the field

Table 6: SEZ condition indicators and time-intensity of additional data collection

Parts of the following data collection protocols were utilized in this project:

- California Rapid Assessment Method (CRAM) – Slope Wetland Module https://www.cramwetlands.org/sites/default/files/CRAM%20Slope%20Wetland%20Field%20Book%20v6.2_2018-09-05.pdf (San Francisco Estuary Institute, 2017)
- American Rivers Meadow Scorecard https://s3.amazonaws.com/american-rivers-website/wp-content/uploads/2016/06/21173432/MeadowsScorecard-08.25.2014.pdf (American Rivers, 2016)
- BLM / USFS Multiple Indicator Monitoring https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd558332.pdf (Burton, Smith, & Cowley, 2011)
- California Department of Fish and Wildlife / California State Water Boards bioassessment protocol https://www.waterboards.ca.gov/water_issues/programs/swamp/bioassessment/sops.html (Ode, Fetscher, & Busse, 2016)
- USFS San Dimas Aquatic Organism Passage protocol https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5117508.pdf (Clarkin, et al., 2005)

SECTION 2: RESULTS - ASSESSMENT KEY FINDINGS

Figure 18: Restored meadow at High Meadows

Key Findings:

Complete condition assessment scorecards were compiled for 643 SEZ assessments units in the Tahoe Basin including riverine, riparian areas (forested SEZ), meadows, and marshes. This represents a large portion of SEZ in the Tahoe Basin. The SEZ types not assessed were lakes, beaches, and forested SEZ outside of developed areas. For this report, an A or B rating is *generally* (but not always) considered within the range of natural variability in undisturbed systems, while a C or D rating is considered *likely* (but not always) impacted by some sort of degradation. While these final ratings provide a snapshot of each SEZ in the Tahoe Basin, further analysis into individual indicators for each site should always be carefully examined to determine overall condition.

Overall, 11942 acres of SEZ were assessed, with 49% receiving an “A” rating, 23% a “B” rating, 8% receiving a “C” rating, and 17% receiving a “D” rating. 2% of SEZ had incomplete assessments. A much higher percentage of meadows were in the “C” and “D” categories than any other SEZ type, with 39% of meadows receiving these low overall ratings. Overall, 16% of meadows have been completely lost to development (1061 acres out of 6662 acres). Additionally, 6% of riparian areas have been lost to development (270 acres out of 4798 acres). 565 acres of restored SEZ were assessed, with 507 acres receiving high scores (A or B rating) suggesting long-term restoration success. These overall findings and other key themes that emerged through the analysis of the 643 assessment units are discussed below.

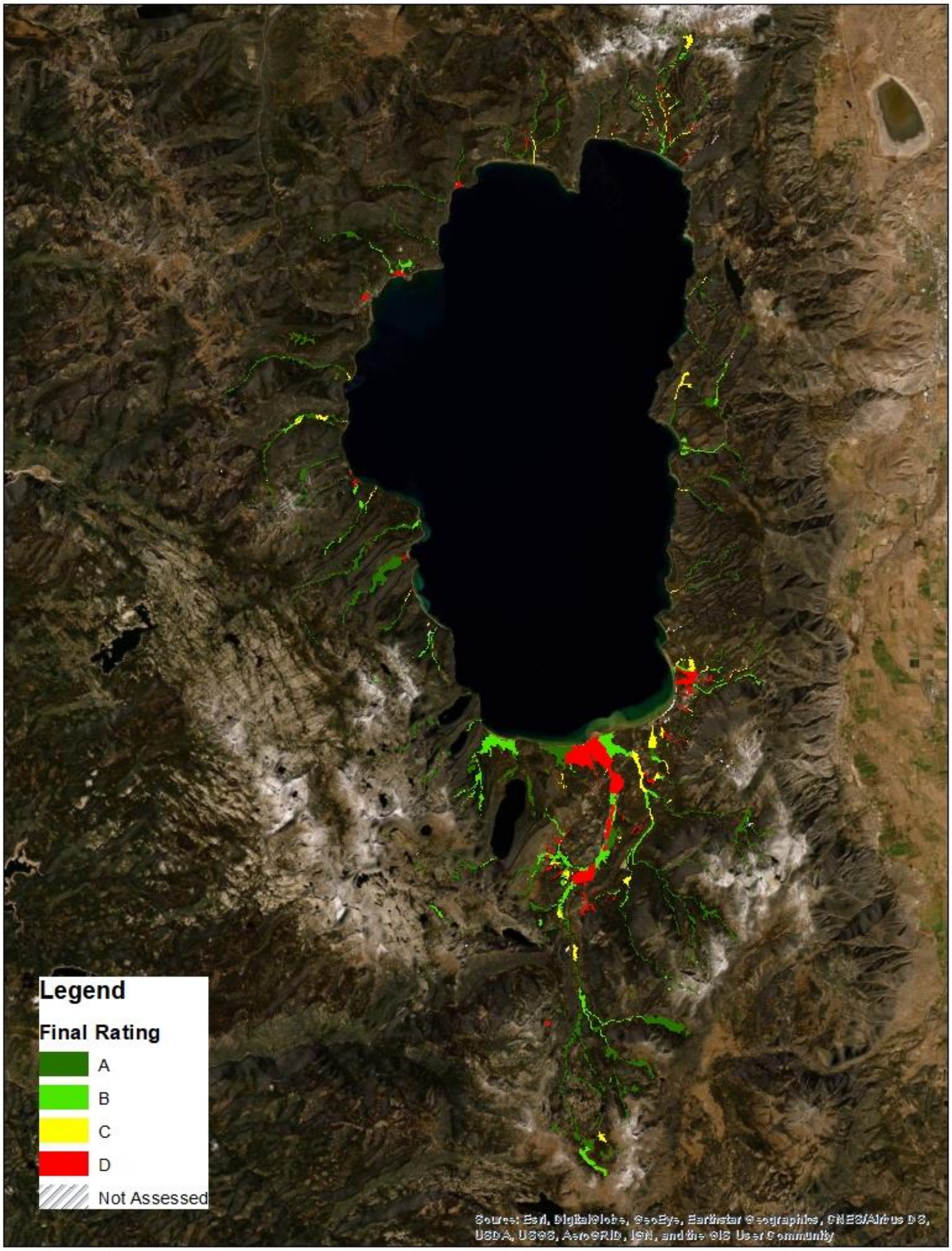

Figure 19: Final SEZ Assessment Unit Ratings - Lake Tahoe Basin

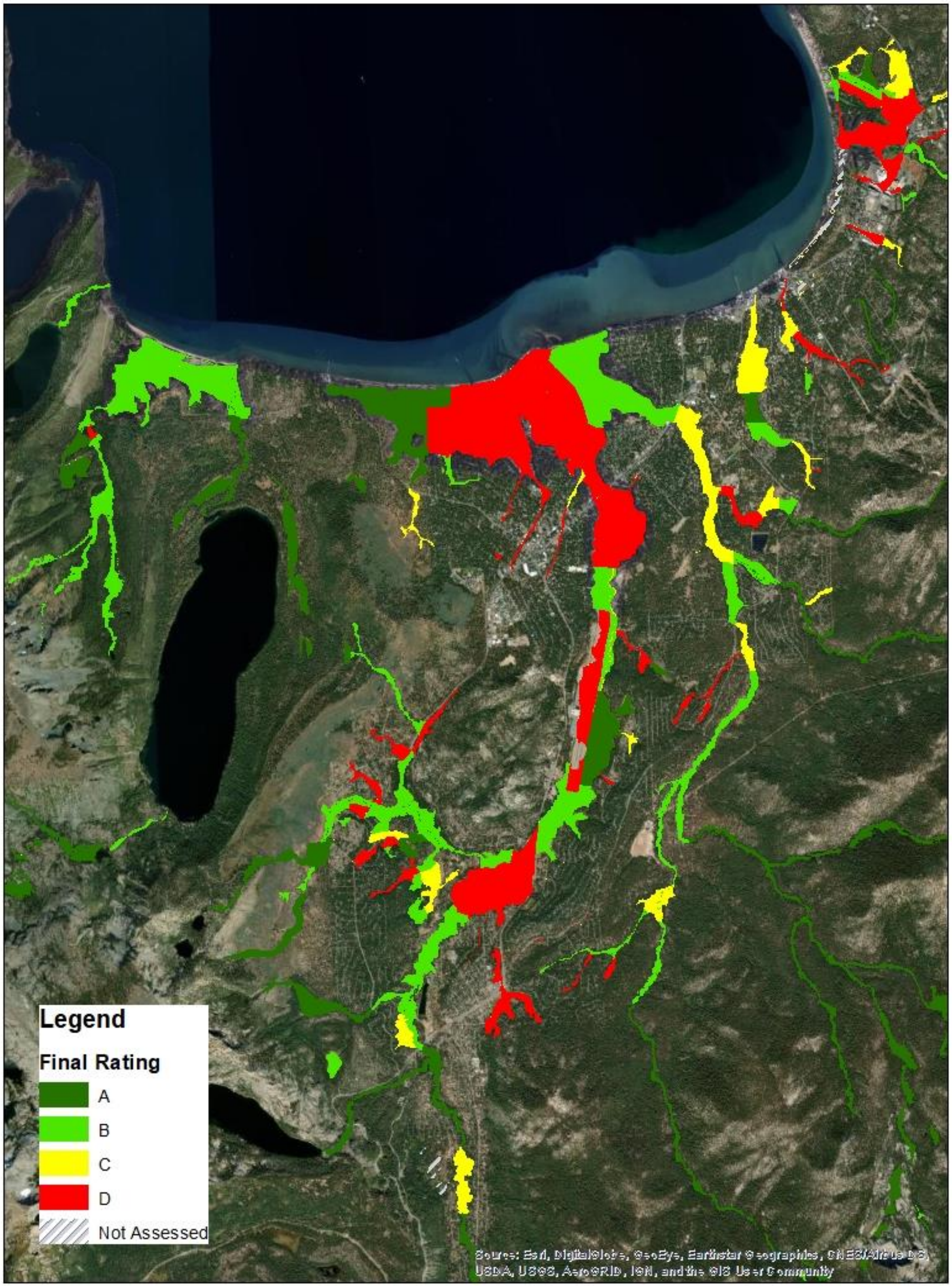

Figure 20: Final SEZ Assessment Unit Ratings - South Shore, Lake Tahoe Basin

Acres	Percent of Total	Category
11942.18	100.00	All SEZ (Total)
5897.11	49.38	All SEZ (A Rating)
2712.74	22.72	All SEZ (B Rating)
1000.34	8.38	All SEZ (C Rating)
2053.25	17.19	All SEZ (D Rating)
278.75	2.33	All SEZ (Not Assessed)
6662.29	100.00	All Meadows (Total)
2140.67	32.13	All Meadows (A Rating)
1766.54	26.52	All Meadows (B Rating)
699.81	10.50	All Meadows (C Rating)
1870.75	28.08	All Meadows (D Rating)
184.51	2.77	All Meadows (Not Assessed)
3780.28	100.00	Channeled Meadows (Total)
988.71	26.15	Channeled Meadows (A Rating)
1468.81	38.85	Channeled Meadows (B Rating)
350.13	9.26	Channeled Meadows (C Rating)
915.46	24.22	Channeled Meadows (D Rating)
57.17	1.51	Channeled Meadows (Not Assessed)
2882.01	100.00	Non-Channeled Meadows (Total)
1151.96	39.97	Non-Channeled Meadows (A Rating)
297.73	10.33	Non-Channeled Meadows (B Rating)
349.68	12.13	Non-Channeled Meadows (C Rating)
955.29	33.15	Non-Channeled Meadows (D Rating)
127.35	4.42	Non-Channeled Meadows (Not Assessed)
482.08	100.00	Riverine (Total)
297.78	61.77	Riverine (A Rating)
94.03	19.51	Riverine (B Rating)
45.63	9.47	Riverine (C Rating)
36.47	7.56	Riverine (D Rating)
7.94	1.65	Riverine (Not Assessed)
4797.81	100.00	Forested - Riparian (Total)
3458.18	72.07	Forested - Riparian (A Rating)
852.16	17.76	Forested - Riparian (B Rating)
254.90	5.31	Forested - Riparian (C Rating)
146.28	3.04	Forested - Riparian (D Rating)
86.29	1.80	Forested - Riparian (Not Assessed)

Table 7: Final SEZ Ratings by SEZ type

Acres Assessed	Percent of Total	Category
8582.00	100.00	Aquatic Organism Passage (Total)
6636.69	77.33	Aquatic Organism Passage (A Rating)
894.36	10.42	Aquatic Organism Passage (B Rating)
609.92	7.11	Aquatic Organism Passage (C Rating)
441.31	5.14	Aquatic Organism Passage (D Rating)
8780.66	100.00	Bank Stability (Total)
6152.70	70.07	Bank Stability (A Rating)
1569.02	17.87	Bank Stability (B Rating)
855.57	9.74	Bank Stability (C Rating)
203.38	2.32	Bank Stability (D Rating)
7337.20	100.00	Biotic Integrity (Total)
4174.79	56.90	Biotic Integrity (A Rating)
1385.45	18.88	Biotic Integrity (B Rating)
1260.90	17.19	Biotic Integrity (C Rating)
516.06	7.03	Biotic Integrity (D Rating)
6164.38	100.00	Conifer Encroachment (Total)
2499.79	40.55	Conifer Encroachment (A Rating)
1157.88	18.78	Conifer Encroachment (B Rating)
1811.48	29.39	Conifer Encroachment (C Rating)
695.22	11.28	Conifer Encroachment (D Rating)
6651.42	100.00	Ditches / Gullies (Total)
5201.64	78.20	Ditches / Gullies (A Rating)
63.45	0.95	Ditches / Gullies (B Rating)
847.82	12.75	Ditches / Gullies (C Rating)
538.50	8.10	Ditches / Gullies (D Rating)
11890.46	100.00	Habitat Fragmentation (Total)
7732.46	65.03	Habitat Fragmentation (A Rating)
2094.37	17.61	Habitat Fragmentation (B Rating)
638.52	5.37	Habitat Fragmentation (C Rating)
1425.11	11.99	Habitat Fragmentation (D Rating)
11384.84	100.00	Headcuts (Total)
10374.53	91.13	Headcuts (A Rating)
169.25	1.49	Headcuts (B Rating)
157.85	1.39	Headcuts (C Rating)
683.21	6.00	Headcuts (D Rating)
5439.58	100.00	Incision (Total)
3135.32	57.64	Incision (A Rating)
645.67	11.87	Incision (B Rating)
530.02	9.74	Incision (C Rating)
1128.58	20.75	Incision (D Rating)
6170.01	100.00	Invasive Plants (Total)
2721.06	44.10	Invasive Plants (A Rating)
1469.53	23.82	Invasive Plants (B Rating)
1776.89	28.80	Invasive Plants (C Rating)
202.53	3.28	Invasive Plants (D Rating)
5073.01	100.00	Vegetation Vigor (Total)
4452.49	87.77	Vegetation Vigor (A Rating)
443.47	8.74	Vegetation Vigor (B Rating)
162.06	3.19	Vegetation Vigor (C Rating)
15.00	0.30	Vegetation Vigor (D Rating)

Table 8: SEZ Assessment Unit Scores by Indicator Type

Key Findings:

Through analysis of the 643 assessment units, several key themes and findings emerged:

1. Riverine channels and their associated riparian areas are mostly healthy outside of meadows, but over a third of meadows and their associated stream channels show signs of degradation.

- 38.5% (2571 of 6662 acres) of meadow areas and their associated channels assessed are likely degraded (C and D categories)
- 9.1% (480 of 5274 acres) of riverine systems and their riparian areas assessed are likely degraded (C and D categories)

Likely due to large percentages of overall meadow area in the Tahoe Basin being in low-lying, developed areas near the Lake, compared to most streams / riparian areas being outside of developed areas, meadows and the stream channels within them are much more degraded overall than streams and their riparian areas outside of meadows. The large prevalence of historic grazing throughout meadows in the Tahoe Basin likely adds to this degradation of meadows. Most degraded meadows and the stream channels within them are in the South Shore of Lake Tahoe, while most degraded streams / riparian areas outside of meadows are near Incline Village, NV. For a full list of degraded SEZ, please see https://gis.trpa.org/TahoeSEZViewer/.

2. Channel incision is evident throughout streams of the Tahoe Basin. Channel incision was measured in all stream channels within meadows and other channels that were formed in alluvial soils. Channel incision is widespread and 1659 acres were in the C and D incision rating categories out of 5440 total acres where incision was assessed (30.4%). Channel incision is evident in a variety of stream channels large and small, and from heavily developed areas to meadows far from any development. Channel incision lowers water tables and can lead to decreased vegetation vigor and encroachment of conifers and other upland plant species. In some of these areas, a stable inset floodplain has formed, and the former floodplain has been abandoned. In other cases, the channel incision is still causing instability as the stream has not yet reached a new equilibrium. This results in streambank erosion in addition to abandonment of the historic floodplain.

Figure 21: An unstable incised channel causing streambank instability and a drying meadow.

Figure 22: Bare ground and drying out vegetation due to an incised channel.

Figure 23: Sagebrush encroaching into a meadow due to an incised channel.

Figure 24: A stable incised channel that has formed an inset floodplain and abandoned its historic meadow floodplain.

3. Conifer encroachment is prevalent in many meadows in the Tahoe Basin. Conifer encroachment has greatly reduced the open meadow area throughout the Basin. Meadows in the lower portions of the Trout Creek and Saxon Creek watershed are especially impacted, with Lodgepole Pine now dominating many formerly open meadow areas. Overall, nearly 40% of meadows assessed received a C or D rating for conifer encroachment. In some cases, 80% of the meadow has been encroached on by conifers.

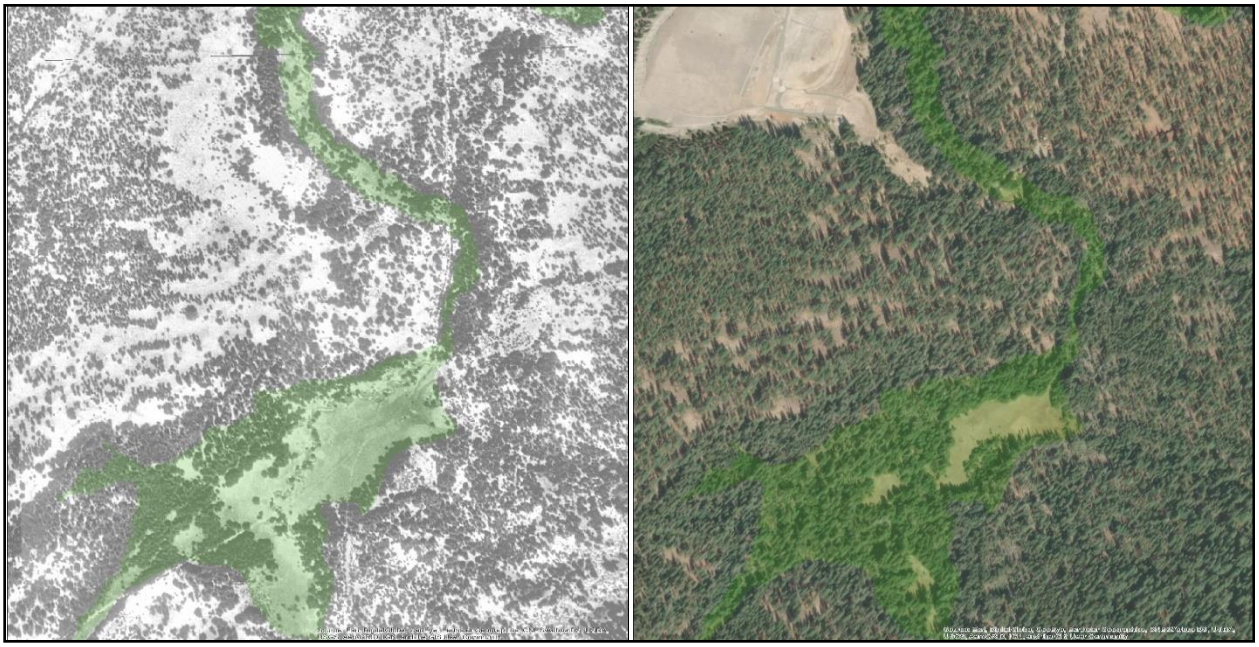

Figure 25: (Left) Saxon Creek meadows in 1940 with expansive open meadow area. (Right) Saxon Creek meadows in 2015 with conifers encroaching into much of the historic open meadow areas.

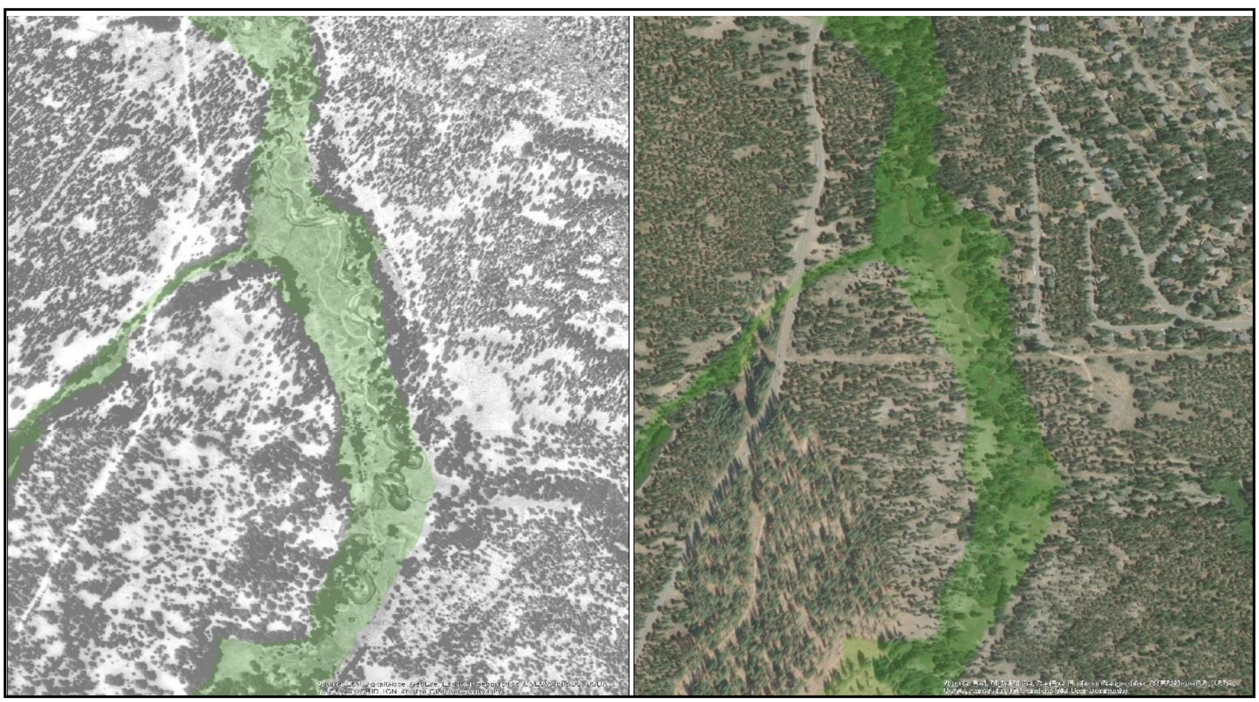

Figure 26 (Left) Trout Creek meadows in 1940 with expansive open meadow area. (Right) Trout Creek meadows in 2015 with conifers encroaching into much of the historic open meadow areas.

4. Remote meadows are not immune to impacts. Urbanization is well known for causing degradation and loss of meadows and wetlands throughout the Tahoe Basin; however, impacts are not limited to urbanized meadows. Headcuts, bank instability, and channel incision were documented at a number of meadows far from the impacts of urbanization. These meadows are most likely impacted by historic grazing (cows or sheep). Analysis of aerial imagery from the 1940s revealed that some of these meadows may have been degraded prior to 1940.

Figure 27: (Meiss Meadows – 3) Despite being in the Meiss meadows area which is treated much like wilderness, this meadow is very degraded. The stream channel is extremely incised with bank instability and multiple headcuts. The meadow is drying out and sagebrush is encroaching into the historic meadow.

Figure 28: (Benwood Meadows – 1) Despite being just off the Pacific Crest Trail in an area that is treated as wilderness, this meadow is very unstable. It is suffering from channel incision, multiple headcuts, streambank instability, and a meadow that is drying out.

5. Most meadows outside urbanized areas are healthy and functioning well. While there are a few exceptions as noted previously, most remote meadows are very healthy. These meadows offer a glimpse of pre-development conditions of meadows in the Tahoe Basin and can serve as “reference” sites for how meadows *should* function and to compare against impacted meadows.

Figure 29: Most meadows outside urbanized areas are healthy with vigorous vegetation, non-incised and stable channels, and are free of headcuts, ditching, and invasive plant species.

6. Several degraded meadows and streams are not currently on any restoration priority lists. There are a number of high-profile projects that have featured prominently on regional restoration lists for years. The importance of many of these projects was reaffirmed in this assessment. The assessment also identified a number of degraded meadows and streams that are currently not on any priority lists. A few examples of possible restoration opportunities are shown below.

Figure 30: (Golden Bear Meadows – 1) This site is mostly unknown because it is partly on private property between the South Lake Tahoe Airport and Pioneer. It was slated for development in the 1960's and land grading was done to prep the site for development. Although the site was never developed, the impacts remain with a large berm built through the middle of the meadow, 10+ headcuts, a large gully, and the meadow drying out with lots of soil cracking and sagebrush encroachment.

Figure 31: (Angora Meadows tributary - 6) This site is located along Lake Tahoe Blvd just upstream of Sawmill pond. This meadow is deeply impacted. Sawmill Pond buried part of the meadow and other parts of the meadow were covered by Lake Tahoe Blvd. The parts of the meadow that remain are plagued by instability in the form of headcuts and deep gullies. Much of the meadow is dewatered.

7. The Upper Truckee watershed has many of the most impacted meadows and streams in the entire Tahoe Basin. The meadow sites along the lower portion of the Upper Truckee River that have not yet been restored remain some of the most impacted and degraded meadows in the Tahoe Basin. While this is not a surprise, it serves to re-enforce the importance of continuing to complete all the Environmental Improvement Program restoration projects along the Upper Truckee River. The sites suffer primarily from historic development, channel incision, streambank instability, reduced vegetation vigor, and conifer encroachment.

Figure 32: Channel incision, bank instability, and reduced vegetation vigor are prevalent along the meadows of the lower portion of the Upper Truckee River.

8. Most restoration projects are functioning well today. Nearly 50 stream and meadow restoration projects have been completed in the last 20 years. Most of these projects are functioning well and received an "A" or "B" final rating. Overall, 507 acres of the 565 acres of restoration project areas assessed were functioning well. These projects display stable channels with healthy stream habitat (riverine), low incision ratios, and vigorous vegetation. A few of the successful projects are highlighted below.

Figure 33: Angora meadows - 2

Figure 34: Angora meadows - 7

Figure 35: High meadows - 1

Figure 36: Third Creek - lower

Figure 37: Incline Creek – middle 1

Figure 38: Cookhouse meadows

Assessment Unit	Assessment Unit Type	Acres	Total Points	Points Possible	Final Percent	Final Rating
Angora meadows - 1	Channeled Meadow	23.00	93	108	86.11	B
Angora meadows - 1	Riverine	0.70	63	72	87.5	B
Angora meadows - 2	Channeled Meadow	51.46	105	120	87.5	B
Angora meadows - 2	Riverine	1.05	69	72	95.83	A
Angora meadows - 6	Channeled Meadow	16.35	105	120	87.5	B
Angora meadows - 6	Riverine	0.47	66	72	91.66	A
Blackwood Creek – lower 2	Riverine + Forested	20.56	57	60	95.00	A
Blackwood Creek – middle 2	Riverine + Forested	23.42	69	72	95.83	A
Blackwood Creek – upper 2	Riverine + Forested	14.94	69	72	95.83	A
Cold Creek - Highland Woods	Channeled Meadow	31.10	96	108	88.88	B
Cold Creek - Highland Woods	Riverine	2.08	54	60	90.00	A
Colony Inn meadows - upper	Non-Channeled Meadow	4.20	51	72	70.8	C
Cookhouse meadow	Channeled Meadow	20.64	120	120	100	A
High meadows - 1	Channeled Meadow	26.22	102	108	94.44	A
High meadows - 1	Riverine	0.92	69	72	95.83	A
Incline Creek - lower	Riverine + Forested	5.74	54	60	90	A
Incline Creek - middle 1	Riverine + Forested	5.94	48	60	80	B
Lake Forest meadows - 1	Non-Channeled Meadow	39.01	60	72	83.33	B
Lake Forest meadows - 4	Channeled Meadow	5.55	78	108	72.22	C
Lake Forest meadows - 4	Riverine	0.09	57	72	79.16	C
Rosewood Creek – lower	Riverine + Forested	10.53	51	60	85	B
Rosewood Creek - middle 1	Riverine + Forested	6.65	63	72	87.5	B
Third Creek - lower	Riverine + Forested	7.53	51	60	85	B
Third Creek - lower 2	Riverine + Forested	5.87	51	60	85	B
Trout Creek - Highland Woods	Channeled Meadow	37.44	102	120	85	B
Trout Creek - Highland Woods	Riverine	2.15	60	72	83.33	B
Trout Creek above Black Bart	Channeled Meadow	42.29	90	120	75.00	C
Trout Creek above Black Bart	Riverine	2.54	51	72	70.83	C
UTR - Airport reach	Channeled Meadow	33.10	99	120	82.5	B
UTR - Airport reach	Riverine	3.18	57	72	79.16	C
UTR - Reach 5	Channeled Meadow	112.99	99	108	91.66	A
UTR - Reach 5	Riverine	6.86	72	72	100	A

Table 9: Scores of completed restoration projects. Most restoration projects are functioning well in the long term with a small number not functioning well.

9. Not all restoration projects succeed. Restoration of complex environmental systems is challenging, and it is common for stream and wetland restoration projects to be unsuccessful. While restoration projects in the Tahoe Basin completed over the past 20 years have been mostly successful, the assessment identified some projects that still shows signs of degradation. For this assessment, success is defined as current, post-restoration conditions getting a final rating of “A” or “B”. Projects that are deemed unsuccessful in the long term are sites that have current conditions in the “C” or “D” rating.

Figure 39: (UTR – airport reach) Nearly half of streambanks are unstable and meadow vegetation has not recovered to vigorous levels since the completion of this project.

Figure 40: (Trout Creek – above Black Bart) The top half of the project is mostly successful while the lower half is showing streambank instability, headcuts, and channel incision following completion of the restoration project.

Figure 41: (Colony Inn meadows) A ditch still runs through the entire project which is dewatering the meadow and leading to loss of vegetation vigor.

10. Restoration has greatly improved bank stability. Addressing streambank stability has been of elevated importance in the Tahoe Basin because of the impacts of bank erosion on lake clarity. As a result of historic logging practices, resources extraction like gravel mining, and urbanization, bank stability and erosion were once common on major streams of the Tahoe Basin (Murphy & Knopp, 2000). Cessation of logging and major resources extraction activities, restrictions on development, BMP implementation, and restoration projects have focused on reducing streambank erosion. Today, streambank instability does not appear to be nearly the problem it once was. Restoration projects have addressed many of the most high-profile cases of streambank erosion.

Figure 42: (Left) Third Creek prior to restoration with bank instability. (Right) Third Creek in the same location following restoration with mostly stable banks.

Figure 43: (Left) Massive bank failures on Blackwood Creek prior to restoration. (Right) A more stable Blackwood Creek following restoration.

11. 16% of meadows are developed. Historic meadows were delineated using a combination of field indicators, historic satellite imagery, and past TRPA SEZ verifications. Due to these delineations, there is high confidence in the boundaries of historic meadows and where current development exists within these meadows. While some large developments are well known such as the Tahoe Keys, this assessment provides a more complete picture of development in historic meadows. According to this assessment, 1061 acres out of 6662 historic meadow acreage has been lost to development (16%). Development comes in the form of buildings, roads, fill, golf courses, ball fields, and other impervious cover.

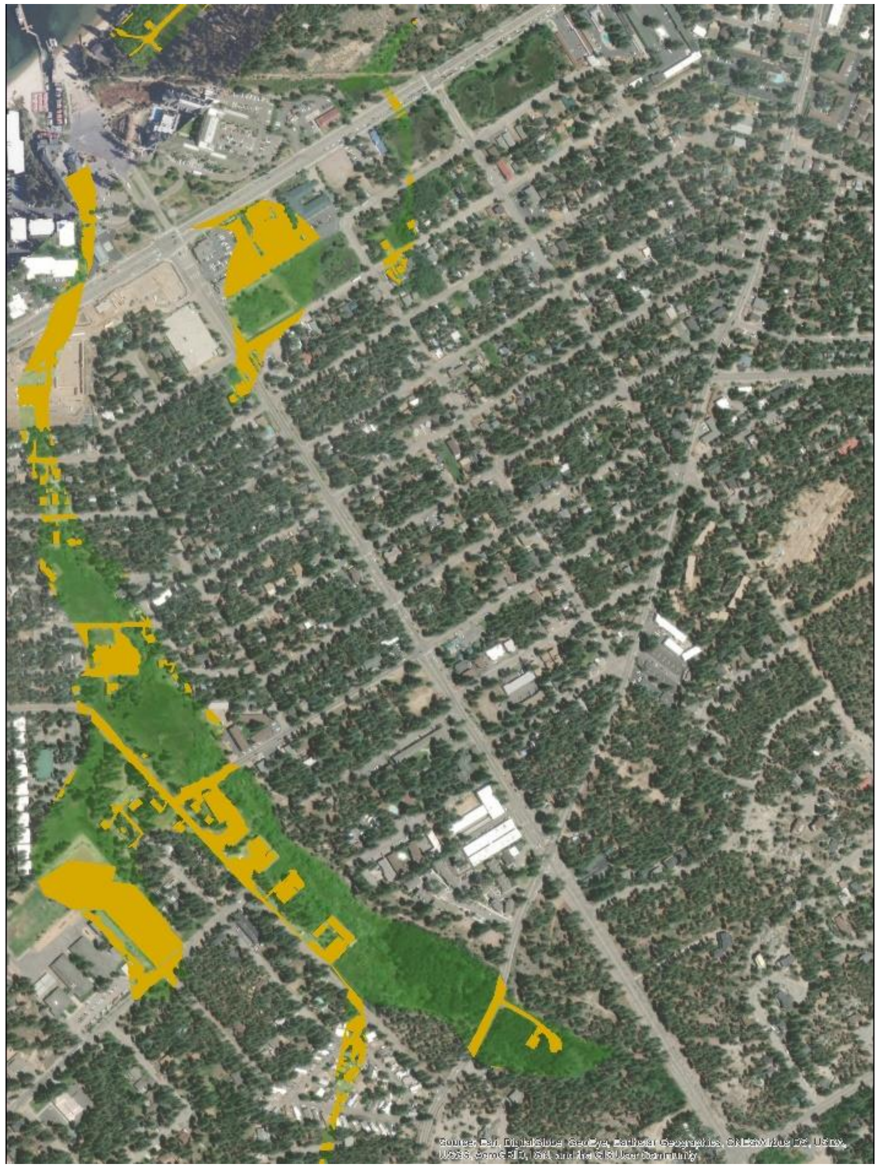

Figure 44: Extensive development (orange) in historic meadow in the Ski Run neighborhood, South Lake Tahoe.

12. ***Meadows in Tahoe overall are increasing in vegetation vigor since 1982.*** Using satellite imagery from 1982 – 2019, DRI was able to assess vegetation vigor using the Normalized Differentiated Vegetation Index (NDVI) for most meadows in the Tahoe Basin (Pearson, Hausner, Morton, & Huntington, 2020). For all meadows combined, late-summer NDVI is increasing across the Basin, and only one meadow in the entire Basin showed an overall decrease in NDVI during the time period, even after adjusting for inter-annual climate variability. DRI concluded that overall increases in NDVI in Tahoe meadows are a likely result of the "global greening" phenomenon, where increased atmospheric CO2 levels and temperature caused by global climate change lead to increased plant photosynthesis and conversion of CO2 to organic matter (Pearson, Hausner, Morton, & Huntington, 2020). Due to this phenomenon, meadows in the Tahoe Basin were also analyzed based on their NDVI values compared to other meadows in the Basin. This allows for the identification of meadows that are showing NDVI values increasing at a lower rate than the rest of the meadows in the Basin, thus showing potential degradation. An additional finding is that successful restoration projects showed large jumps in NDVI values following a project and unsuccessful projects showed little to no change, proving the effectiveness of using remote satellite imagery to track the impact of restoration projects.

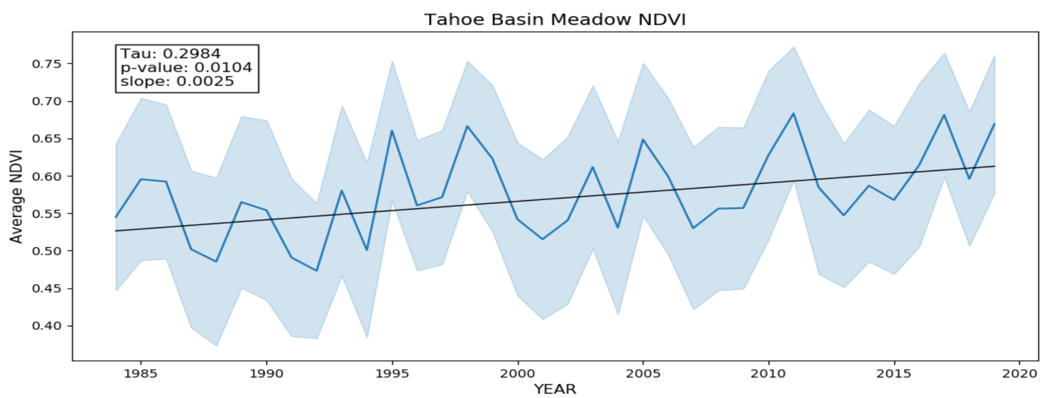

Figure 45: The average NDVI values for all meadows in the Tahoe Basin show significant increases from 1982 - 2019 likely due to the "global greening" phenomenon (Pearson, Hausner, Morton, & Huntington, 2020).

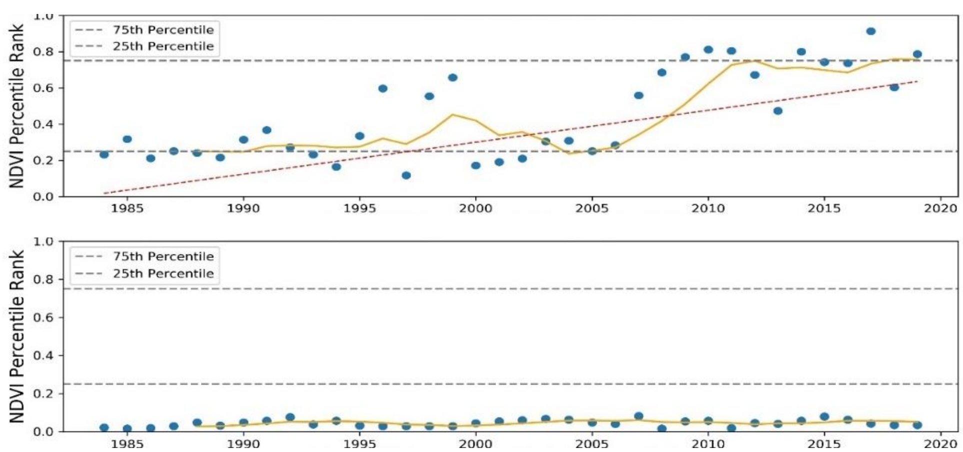

Figure 46: Top - Successful restoration project at Cookhouse Meadows shows a large jump in NDVI following the completion of a restoration project around 2007. Bottom – An unsuccessful restoration project on the UTR Airport Reach shows virtually no change in overall NDVI values following the completion of a restoration project around 2010.

SECTION 3: APPENDICES

Figure 47: Restored Third Creek in Incline Village, NV

APPENDIX 1: Indicator methods

Indicator 1: Headcuts (channeled meadows; non-channeled meadows; perennial riverine; non-perennial riverine; forested)

Relation to existing monitoring programs: Methods and ratings for this indicator were derived from the American Rivers Meadow Scorecard.

Methods: Methods for this indicator were derived directly from the Meadow Scorecard. Please refer to https://meadows.ucdavis.edu/ and here for more details on the protocol. This indicator should only be assessed in streams and meadows with a slope less than 2.5%. To measure presence of headcuts, simply walk around the entire meadow and count the number of headcuts and measure the headcut height. Headcuts should be measured from the bottom of the plunge pool or "base scour" to the knickpoint or "brinkpoint" (see figure below). Bare-earth lidar imagery can help identify potential headcuts from the office before heading out in the field. Headcuts are defined as an erosional feature with an abrupt vertical drop, also known as a knickpoint, in the stream bed. The knickpoint, where a head cut begins, is

Figure 48: A small headcut in a non-channeled meadow.

Figure 49: Large headcuts in a channeled meadow.

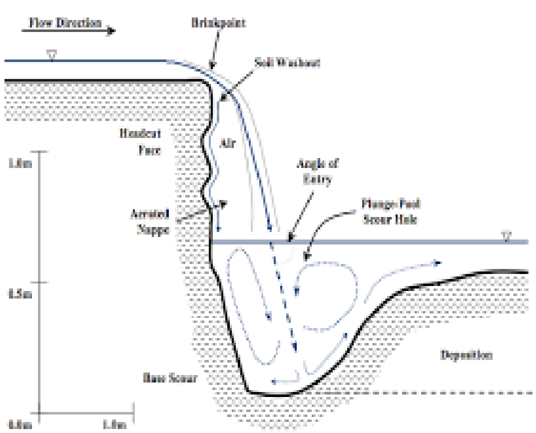

Figure 50: Headcut depth diagram (Parker, 2001)

characterized by a distinct difference in the incision ratio or channel depth. It also can be the point of channel initiation along a drainage, where a drainage goes from having no bed and banks to having bed and banks. When overland flow is not present, the headcut will resemble a very short cliff or bluff. A small plunge pool may be present at the base of the headcut due to the high energy of falling water. As erosion of the knickpoint and the streambed continues, the headcut will migrate upstream.
Groundwater seeps and springs are sometimes found along the face, sides, or base of a head cut. Only headcuts larger than 0.1 meters will be counted. Headcuts will be broken into three size categories as

follows: 0.10 - 0.49 meters = small headcut; 0.50 - 0.99 meters = medium headcut; greater or equal than 1 meter = large headcut.

RATING	**ALTERNATIVE STATES**
A	0 headcuts.
B	1+ small headcut (0.10 – 0.49m) *and* no other larger headcuts.
C	1+ medium headcuts (0.50 – 0.99m) *and* no other larger headcuts. There may be small headcuts present as well.
D	1+ large headcuts (>1m). There may be medium or small headcuts present as well.

Table 10: Headcut Rating

Indicator 2: Vegetation Vigor (channeled meadows; non-channeled meadows)

Relation to existing monitoring programs: Many existing monitoring programs assess vegetation vigor directly or indirectly. The Meadow Scorecard assesses percent bare ground as an indirect measure of vegetation vigor. CRAM measures vegetation vigor indirectly through the assessment of the percent of the meadow that is “dewatered”. Vegetation plots also often seek to establish the vigor of vegetation in post-restoration monitoring. The approach in this project of using remote sensing to assess vegetation vigor is a relatively new science and is therefore somewhat unique in established monitoring programs.

Methods: Full methods for assessing vegetation vigor were developed by DRI in consultations with several partners agencies including TRPA, USFS, CTC, and NDEP (Pearson, Hausner, Morton, & Huntington, 2020). Full methods can be found in Appendix 6. Below is a quick summary of methods:

DRI analyzed 315 meadows delineated as individual management units by TRPA. The analysis focused on the normalized difference vegetation index (NDVI), a measure of vegetation greenness and vigor. Spatially and temporally integrated values of late summer NDVI were obtained for each meadow for each year of the Landsat record (1984-2019) and were examined using multiple statistical approaches. End of summer meadow imagery captures key interannual vegetation variability related to water supply and growth dynamics and has been used to track vegetation health in groundwater dependent ecosystems (Huntington, et al., 2016) and vegetation change in response to restoration work (Hausner, et al., 2018). Statistical analyses followed non-parametric methods that can be confidently applied to data from a wide variety of distributions. NDVI was calculated for all pixels in each Landsat image. Composite end-of-season reflectance images were calculated by taking the median August-September pixel value for each year from 1984-2019. Summary zonal statistics for each meadow were calculated on the yearly median composite images.

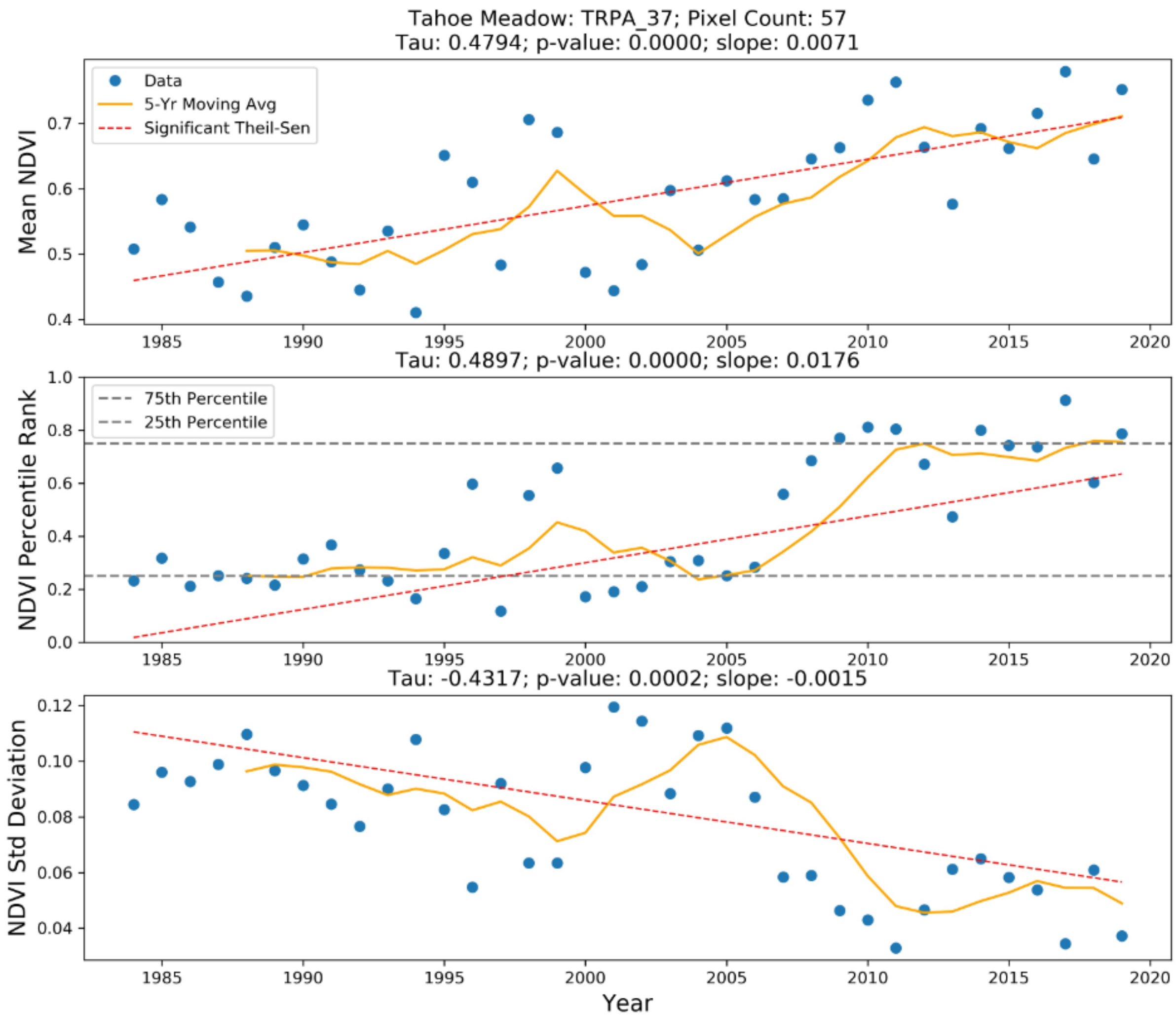

Figure 51: Cookhouse Meadow, restored 2007. Summary time series of mean NDVI, NDVI rank, and NDVI StdDev. Kendall Tau statistics are included for each subplot. Theil-Sen trend lines are shown in red for trends significant at the 95% confidence level.

In order to overcome bias due to natural spectral differences, temporal trend and temporal variability statistics were utilized to assess all meadows throughout the Basin. Temporal trend represents the overall activity and direction of meadow vegetation greenness in time (i.e. stable, increasing, or decreasing). Temporal variability (i.e. volatility) represents the range of values in time and is related to the meadow's sensitivity to interannual climate variability. Analyzing trends and anomalies gives temporal context to current conditions and provides a relative measure of state.

Trends were assessed using the Mann Kendall non-parametric trend test to determine significantly increasing, decreasing, and stable systems. When applied to temporal datasets, the Mann Kendall trend test measures monotonically increasing and decreasing patterns with no assumption about the underlying distribution (Mann, 1945). Mann Kendall significance levels were adjusted for temporal autocorrelation using techniques proposed by Hamed and Rao (Hamed & Rao, 1998). All autocorrelation adjustments were implemented at the 95% confidence threshold. The non-parametric Theil-Sen slope estimator was utilized to determine the rate of change for each significant trend. Analyzing trends and anomalies gives temporal context to current conditions and provides a relative measure of state and variability (Theil, 1950).

Individual meadows were examined using the annual observed values of NDVI using two main analyses, climate-adjusted NDVI and the percentile-rank trend of meadows.

- Climate-adjusted NDVI: NDVI values were adjusted for climate to remove the impacts of interannual climate variability. To accomplish this, NDVI values were adjusted using the standardized precipitation evaporation index (SPEI). SPEI is a drought index that considers the difference between precipitation (PPT) and potential evapotranspiration (PET) at different timescales. SPEI is determined by summing the cumulative difference between PPT and PET over that time period for each water year and applying a non-parametric standardization to the time series. The SPEI time series was calculated individually for each meadow and regressed against the NDVI percent difference from mean, where NDVI is the observed annual value in a meadow and NDVI is the mean of the annual NDVI values for that meadow over the period of record.
- Percentile-rank trend of meadows: Meadows were compared to one another using basin-wide percentile rankings. The ranking was applied to yearly end of season mean NDVI to consider long-term trends in meadow vegetation relative to other meadows and to remove longer-term synoptic climate signals common to the entire basin (i.e. declimatize). Percentile ranking effectively normalizes the dataset allowing for identification of anomalous patterns relative to the average basin benchmark signal.

RATING	ALTERNATIVE STATES
A	Climate adjusted NDVI and Percentile Rank trends are positive or stable.
B	Climate adjusted NDVI is increasing or stable and Percentile Rank trend is declining by less than 0.5% per year.
C	Climate adjusted NDVI is increasing or stable and Percentile Rank trend is declining by greater than 0.5% per year.
D	Climate adjusted NDVI is declining and Percentile Rank trend is declining by greater than 0.5% per year.

Table 11: Vegetation Vigor Rating

Indicator 3: Incision (channeled meadows; perennial riverine; non-perennial riverine)

Relation to existing monitoring programs: Methods and ratings for this indicator were derived from the USFS Region 5 meadow monitoring protocol (Roche, et al., 2015) and the California Rapid Assessment Method Slope Wetland Module.

Methods: More detailed methods can be found in the California Rapid Assessment Method Slope Wetland module which can be found here.

Incision ratios are established in the field by an experienced practitioner. Because incision ratios depend on accurate identification of bankfull stage and bankfull stage is notoriously difficult to identify, a few extra steps need to be taken to reduce uncertainty:

1) Before going into the field, a relative elevation model (REM) is created by generating a sloping surface equal to the channel bed elevation over the entire width of a meadow and subtracting that surface from the digital elevation model (DEM) for the meadow topography. The resulting REM shows all heights in the meadow as elevations above the river bed (referenced to the nearest point perpendicular along the channel). Wherever a cross-section is established in the field to measure channel incision, a corresponding line will be created in ArcGIS. This line will be overlaid across a DEM to give a graph of the channel morphology. While bankfull depth cannot be determined from a DEM, the difference between the highest bank height and the bottom of the stream can be determined. If any field-measured values are vastly different from the DEM, more field measurements will be required to get an accurate estimate.

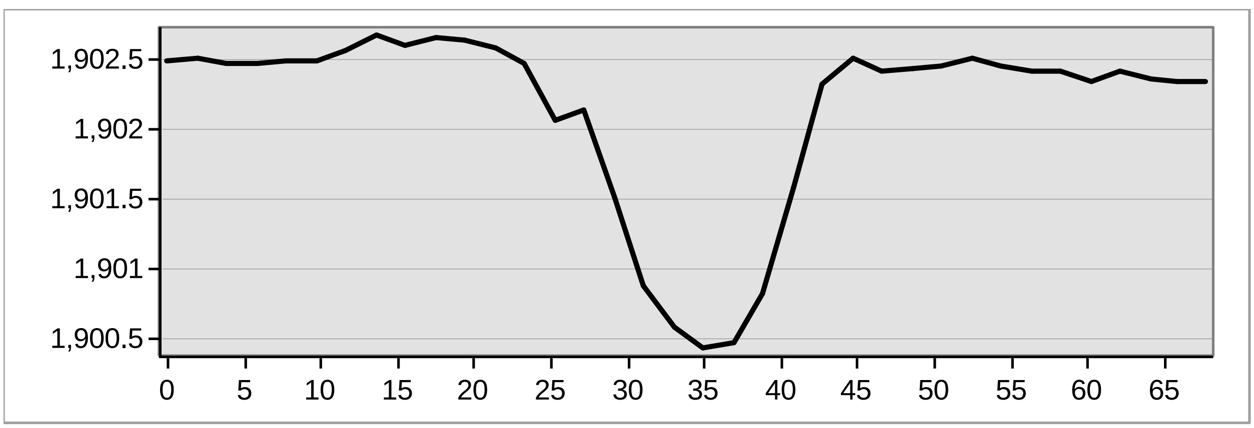

Figure 52: Examples of LiDAR-derived channel morphology measurements at the Upper Truckee River in Johnson Meadow. These graphs will be used to help verify field measurements of channel incision.

2) All field practitioners calculating incision ratios should be properly trained in identifying bankfull geometry. All practitioners should at the least be very familiar with the methods described in “A Field Guide for Identifying Bankfull in the Western United States” (U.S. Department of Agriculture Forest Service, 2010).

In the field, channel incision will be calculated in all channeled meadows, as well as riverine systems formed in alluvial soils. Steps for identifying riverine systems formed in alluvial soils are detailed in Appendix 7. To measure channel incision, make two in-channel measurements in at least three representative locations in the assessment unit (upstream, middle, downstream). Make more measurements if there are large variations or if the result is close to a break point in scoring. Bank height is measured as the maximum height between the thalweg (the deepest point along the channel bed) and the top of the channel bank. For meadows, the top of the channel bank is the break in slope between the channel bank slope and the near horizontal meadow surface. The meadow surface is measured at the level of the primary horizontal meadow, or valley floor surface, and not at the height of a small inset floodplain that may be forming in an entrenched or incising system. For non-meadow riverine systems, the top of the channel bank is the elevation of the first terrace of the valley floodplain as seen in the figure above. Bankfull depth is measured as the height between the thalweg and the projected water surface at the level of bankfull flow. It is probable that a single riverine or meadow SEZ will exhibit a range of incision ratios. Where this is the case, the channel will be divided into multiple assessment units and incision ratios are measured at 3 locations and averaged within each newly delineated assessment unit. Ratings will be assigned as per the table below.

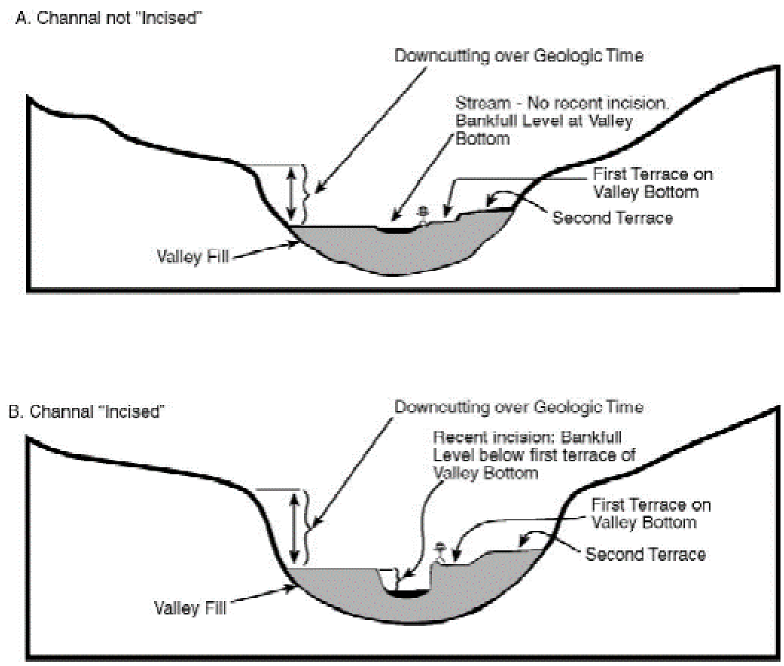

Figure 53:Bankfull and top-of-bank features in a riverine system (Washington State Department of Natural Resources, 2004).

RATING	ALTERNATIVE STATES
A	Bank height to bankfull depth is ≤ 1.19
B	Bank height to bankfull depth is 1.2 to 1.5
C	Bank height to bankfull depth is 1.6 to 2.0
D	Bank height to bankfull depth is ≥ 2.1

Table 12: Incision Ratio Rating

Figure 54: Examples of incised meadow systems: The photos above show meadows with varying degrees of channel incision where the bankfull height is much lower than the meadow surface.

Figure 55: Examples of non-incised meadow systems: The photos above show meadows with no channel incision where the bankfull height is very similar to the meadow surface.

Indicator 4: Ditches / Gullies (channeled meadows; non-channeled meadows; forested)

Relation to existing monitoring programs: The general idea and indicator ratings for this indicator were derived from the American Rivers Meadows Scorecard. The remote-sensing approach to collection of data from this indicator is novel.

Methods: Methods for this indicator were derived from the Meadows Scorecard and more details on the methods can be found here.

To assess this indicator, bare-earth lidar will be used to identify ditches and gullies and will be verified in the field. These ditches and gullies are very apparent in bare-earth lidar. The percentage of the total assessment unit length that the ditch /gully covers will be used to rate the degree to which it is impacting the meadow.

Figure 56: Examples of LiDAR-derived bare-earth imagery: The photo on the right shows the bare-earth lidar of the meadow on the left in Meyers, Lake Tahoe, CA. The artificial ditch running through the meadow is obvious in the bare-earth lidar image on the right.

RATING	ALTERNATIVE STATES
A	No ditches / gullies
B	Combined length of all ditches / gullies is less than 10% of total meadow length
C	Combined length of all ditches / gullies is between 10%-50% of total meadow length
D	Combined length of all ditches / gullies is greater than 50% of total meadow length

Table 13: Ditches / Gullies Rating

Indicator 5: Channel Stability (channeled meadows; perennial riverine; non-perennial riverine; forested)

Relation to existing monitoring programs: Methods and ratings for this indicator were derived from the American Rivers Meadows Scorecard and the BLM's Multiple Indicator Monitoring method.

Methods: Methods for this indicator were derived from the Meadows Scorecard and more details on the methods can be found here; methods were also taken from the BLM's Multiple Indicator Monitoring method that can be found here.

To assess channel stability, a practitioner will walk the length of the channel and collect information on bank stability. Because of how the observations are made, streambank stability can only be assessed when the stream is flowing below the scour line, usually well after the seasonal peak flow event. The percentage of total banks that are unstable within the assessment unit will then be used to "score" the entire assessment unit. For this method, unstable banks must contain the following: 1) a fracture in the bank (a crack is obvious along the top or on the face of the bank; 2) a slump (a portion of the bank has slipped down as a separate block of soil or sod); 3) a bank slough (soil broken away or crumbled and accumulated at the base of the bank); 4) or if the bank is steep (within 10 degrees of vertical) and/or bare and eroding (including bare depositional bars).

Because this is a time-intensive method, priority will be given to urbanized systems or systems with a history of human impact. These systems are most likely to be impacted by channel instability. Channel instability is likely to be impacted in these areas due to the following sources:

- Urbanized areas: stormwater runoff; past development
- Meadows: all meadows likely used for past grazing
- Certain riverine systems: Large riverine systems outside of urbanized areas like Ward Creek and Blackwood Creek were impacted by gravel mining and other resource extraction activities

For systems that are outside of human influence and unlikely to be impacted by channel instability, channel stability data collected from Simon's Estimates of Fine-Sediment Loadings to Lake Tahoe from Channel and Watershed Sources (Simon, 2006) or TRPA's bioassessment program will be substituted for field data collection in order to conserve resources. If a channel was identified in the Simon report as Stage 1 or 6 (stable systems), the stream segment will be given an "A" rating. For stream segments identified as Stage 4 and 5 (unstable and degrading), resources will be focused on streambank stability surveys to obtain a calculation of unstable banks. Bioassessment surveys take 22 stream stability measurements over a 150-meter stream reach and will be used in situations where the stream is outside human influence and other data does not exist for the stream segment.

RATING	ALTERNATIVE STATES
A	<5% of bank length is unstable
B	5-20% of bank length is unstable
C	20-50% of bank length is unstable
D	>50% of bank length is unstable

Table 14: Channel Stability Rating

Indicator 6: Habitat Fragmentation (channeled meadows; non-channeled meadows; perennial riverine; non-perennial riverine; forested)

Two different methods for assessing habitat fragmentation are used; one method for use in meadows and the other for use in riverine and forested systems.

Meadows:

Methods: For meadow systems, habitat fragmentation will be assessed based on the amount of development (impervious cover, fill, golf courses, etc.) in historic meadow habitat. Historic meadow extent was delineated based on a variety of historic aerial imagery, SEZ field verifications, and field delineations. More information on meadow delineation can be found in Appendix 5 on conifer encroachment. Development in historic meadows will then be assessed using LIDAR-derived impervious cover. Only hard coverage (as opposed to soft coverage) will be assessed for impervious coverage in order to avoid penalizing trails through meadows. Golf courses and ball-fields were manually drawn in based off satellite photos. Because historic meadows were delineated and LIDAR-derived impervious coverage is highly accurate, there is very high confidence in the location of development in historic meadows.

In general, meadows that are partially intact with some development were listed as a single “assessment unit” and the percent of development within the intact meadow was included in the “assessment unit”. If an entire meadow was lost, or an entire large area of a meadow were lost that is somewhat disconnected from surrounding meadows, the entire former meadow was counted as its own “assessment unit” and marked as 100% developed.

RATING	ALTERNATIVE STATES
A	<1% of historic meadow habitat has been developed
B	>1% and <10% of historic meadow habitat has been developed
C	>10% and <20% of historic meadow habitat has been developed
D	>20% of historic meadow habitat has been developed

Table 15: Habitat Fragmentation Rating (Meadows)

Streams:

Relation to existing monitoring programs: The methods for assessing habitat fragmentation for riverine and forested systems were derived from the California Rapid Assessment Method (CRAM).

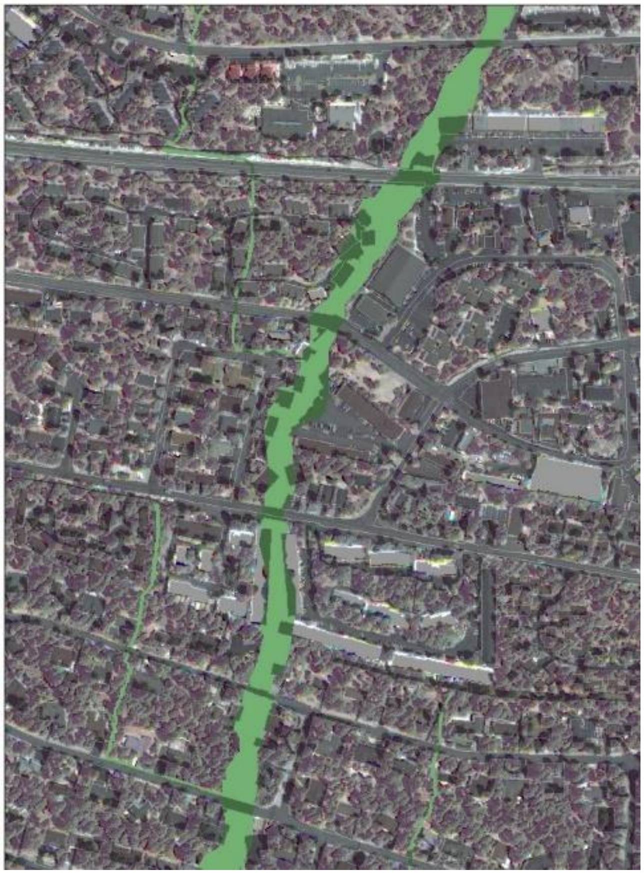

Figure 56: mapped riparian corridor (light green) in Incline Village overlaid with impervious cover (dark green) shows development within the sensitive riparian corridor.

Methods: Habitat fragmentation in riverine and forested systems will be measured through the amount of development in riparian corridors. Riparian corridors were mapped in 2015 by Spatial Informatics Group (Roby, et al., 2015). Stream channels were derived from LIDAR-based bare-earth data and the riparian zone was developed along this LIDAR-derived stream using a variety of factors. Habitat fragmentation within these systems will be assessed based on the amount of development (hard impervious cover, golf courses, etc.) within the riparian zone using aerial satellite imagery and LIDAR-derived impervious cover. Streams that have been moved underground will also be counted as development within the riparian corridor because the entire riparian corridor has been lost. In order to only assess the riparian corridors of selected riverine units, riparian corridors were clipped to only include the riparian area around assessed streams. Additionally, some riparian areas were not mapped as part of the SIG SEZ map if they were completed developed. In these situations, the average width of the riparian area immediately upstream and downstream of the segment were used to calculate an average riparian width. This width was then applied to the unmapped riparian area. Unlike meadows, riparian areas were not delineated using field methods. Therefore, the degree of accuracy of the location of historic and current riparian areas is less than for meadows. Consequently, there is lower confidence in the amount of development in historic riparian areas. Decisions on removing development from these areas based on this analysis should be field verified. However, the general amount of development in historic riparian areas is mostly accurate.

Figure 57: Development within the riparian corridor corresponding to the Incline Village location mapped above.

RATING	ALTERNATIVE STATES
A	<1% of riparian corridor has been developed
B	>1% and <10% of riparian corridor has been developed
C	>10% and <20% of riparian corridor has been developed
D	>20% of riparian corridor has been developed

Table 16: Habitat Fragmentation Rating (riverine)

Indicator 7: Conifer Encroachment (channeled meadows; non-channeled meadows)

Relation to existing monitoring programs: The general idea and indicator ratings for this indicator were derived from the American Rivers Meadows Scorecard. The remote-sensing approach to collection of data from this indicator is novel.

Methods: To determine the extent of conifer encroachment into meadows, two steps were taken. First, likely historic meadow extent was determined. Second, the current extent of conifer encroachment into historic meadows was determined. These two steps will be discussed in general terms here, with much more detail provided in Appendix 5. Historic meadow extent was determined using a variety of field and remotely sensed indicators such as soil, vegetation, slope, and historic aerial imagery. In many cases, historic meadow extent is obvious based on these factors and a detailed field delineation was not required. In other cases, remote delineation was not possible, and a field visit was required. Following the 2019 field season, historic meadow extent for all meadows in the Tahoe Basin had been delineated using remote sensing or field verification. Once historic meadow extent was determined, the second step was determining how much historic meadow has been lost to current conifer encroachment. This second step was accomplished using a remote sensing method known as Light Detection and Ranging (LIDAR). LIDAR for the entire Tahoe Basin was taken from an aircraft in summer 2009. This LIDAR was processed to identify each tree in the Basin along with its height and other characteristics (Kelly, 2013). Any tree that is within the historic meadow extent is counted as a conifer within the historic meadow. Next, 300 square meter hexagons were overlaid on the historic meadow. Any hexagon that has at least 1 conifer within it is counted as "encroached". The overall percent of "encroached" hexagons within the historic meadow is used to determine the degree of overall conifer encroachment within each meadow. Aspen stands (regardless of height) and any trees under 6 meters were excluded from the analysis to ensure that only conifers were counted instead of common meadow riparian shrubs such as willow and alder. While this height cut-off also excludes young conifers, it is necessary to avoid counting desirable species as conifers and focuses on conifers that are becoming well-established in meadows. Organizations looking to identify areas of young conifer growth will be able to access the data without the height cut-off on a site-by-site basis if needed. More detailed methods can be found in Appendix 5.

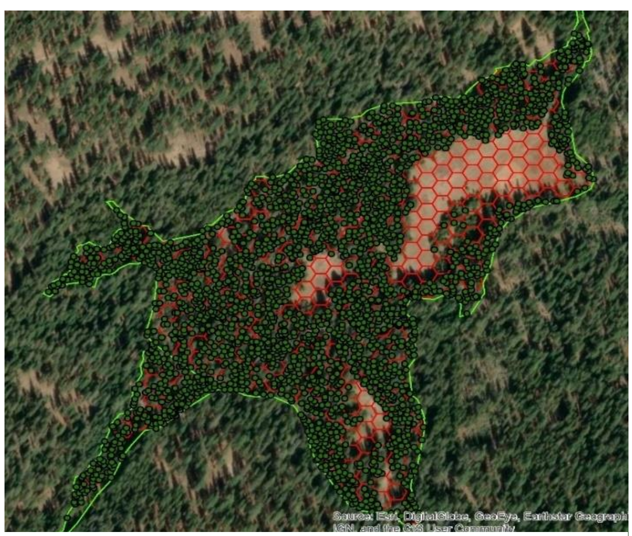

Figure 58: A meadow heavily encroached by conifers. LIDAR derived tree data allows for highly accurate analysis of conifer encroachment. Green dots are LIDAR-derived conifers and red polygons are the hexagons within the meadow analyzed.

RATING	ALTERNATIVE STATES
A	0-20 % of hexagons with conifer encroachment
B	21 – 40% of hexagons with conifer encroachment
C	41 – 70% of hexagons with conifer encroachment
D	71-100% of hexagons with conifer encroachment

Table 17: Conifer Encroachment Ratings

Indicator 8: Biotic Integrity (channeled meadows; perennial riverine)

Relation to existing monitoring programs: The methods and ratings for this indicator were derived from the California Surface Water Ambient Monitoring Program (SWAMP).

Methods: Methods are derived from the California Surface Water Ambient Monitoring Program (SWAMP) and detailed methods can be found here.

While the collection and processing of macroinvertebrates is somewhat labor intensive, TRPA has an existing, well-established bioassessment program that will continue. Therefore, data collected from this program can inform the health of riverine and channeled meadow SEZ. Benthic macroinvertebrates will be collected according to the State of California's Surface Water Ambient Monitoring Program (SWAMP). Samples will then be processed and given a "score" based on the California Stream Condition Index (CSCI), which rates a streams overall macroinvertebrate composition based on how closely it resembles what would be expected to be found in a pristine stream in a similar geographic / climatic setting.

*Biotic integrity will not be assessed in stream or channeled meadows that are very low gradient (less than 0.5% slope). These types of channels in the Tahoe Basin are naturally dominated by sandy or silty substrate and therefore will not support healthy BMI populations even if the system is healthy. Biotic integrity will also not be assessed in non-perennial streams. Some streams (even larger ones that appear to be perennial) run dry in portions or for their entire length during late summer or early fall. These streams will have low biotic integrity compared to perennial streams and therefore are not directly comparable. Finally, some perennial streams (especially in high alpine meadows) are simply too small to sample and will not be assessed for biotic integrity.

RATING	ALTERNATIVE STATES
A	>0.92 CSCI score
B	0.79 – 0.92 CSCI score
C	0.62 – 0.79 CSCI score
D	<0.62 CSCI score

Table 18: Biotic Condition Rating

Indicator 9: Terrestrial Invasive Plant Species (channeled meadows; non-channeled meadows)

Relation to existing monitoring programs: The methods and ratings for this indicator were derived from recommendations from a representative of the Lake Tahoe Weed Management Coordination Group.

Methods: Terrestrial invasive plants of concern are derived from the list of high priority species listed by the Lake Tahoe Weed Management Coordination Group, Level 1 and 2 priority species. This list can be found here (Lake Tahoe Basin Weeds Coordinating Group, 2011). Simply walk around the entire meadow and look for invasive species of interest. Note the total number of different species found. Large amounts of existing data on invasive species in meadows are present from USFS and CA State Parks.

RATING	ALTERNATIVE STATES
A	0 invasive plant species present
B	1 Level 2 invasive plant species present
C	2 Level 2 invasive plant species present OR 1 Level 1 invasive plant species present
D	3+ Level 2 invasive plant species present OR 2+ Level 1 plants species present

Table 19: Invasive Plant Species Rating

Indicator 10: Aquatic Organism Passage (channeled meadows; perennial riverine)

Relation to existing monitoring programs: The vast majority of data comes from a 2 year project by the USFS Lake Tahoe Basin Management Unit (Vacirca, 2010).

Methods: The methods for this indicator are derived from the US Forest Service San Dimas protocol (Clarkin, et al., 2005).

Stream crossings by roads can pose serious threats to fishery ecosystems. The cumulative effect of culverts, fords, and other structures throughout a stream channel can significantly change the stream geomorphology and impair fish passage by blocking valuable spawning and rearing habitat.
The three main attributes
assesssed for fish passage were outlet drop, culvert slope, and culvert width to bankfull ratio. Stream crossings that were rated in the “impassable” category for adult salmonids were counted as fish passage barriers. The number of barriers per stream mile is used to score this indicator. Detailed descriptions of the protocol can be found at https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5275315.pdf.

RATING	ALTERNATIVE STATES
A	0 barriers per mile
B	>0 – 1 barriers per mile
C	>1 – 3 barriers per mile
D	>3 barriers per mile

Table 20: Aquatic Organism Passage ratings

APPENDIX 2: Revision Log

Comments from SEZ Technical Advisory Committee: This document was reviewed by members of the SEZ Technical Advisory Committee. Representatives of the following organizations provided comments thus far:

- United States Forest Service
- California Tahoe Conservancy
- League to Save Lake Tahoe
- California State Parks
- Lake Tahoe Basin Weed Coordinating Group
- City of South Lake Tahoe
- United States Environmental Protection Agency
- Nevada Department of Environmental Protection
- Desert Research Institute

Summary of document changes: Below is a summary of changes made to this document based on recommendations of the SEZ Technical Advisory Committee.

- The invasive plant scoring system was changed to account for the difference between Level 1 and Level 2 priority invasive weeds. Level 1 weeds are of higher importance and are a larger ecological risk. Therefore, Level 1 weeds gave the indicator a lower score than Level 2 weeds.
- Photos of each "assessment unit" were added to the mapping part of this exercise. Documenting current conditions and changing conditions over time using photos was recommended by members of the TAC.
- Added invasive species as an indicator of meadow health. It was recommended that invasive species be used as an indicator of meadow health because of their role in a meadow's overall ecology. It was recommended to use simply the number of invasive species present because it is a rapid approach rather than attempting to estimate total invasive species cover.
- Headcuts added as an indicator of meadow health. Field practitioners in the Tahoe Basin have noted headcuts in almost all degraded meadow systems.
- Leverage remotely-sensed digital elevation models to help assess channel incision. Concern was expressed by TAC members about the comparability of channel bankfull measurements made by different field crews. Accurately measuring bankfull width and depth (a necessary measure to establish channel incision ratios) is widely known as difficult and can vary among different field crews.
- Assessment units to include historic meadows, Areas that have historically been meadows by were converted by development were added as "assessment units" at the request of the TAC. These former meadows will be scored a "D" since they have lost all function. These were added because it is important for agencies and the public to understand where meadows have been lost, and because some lost meadows may be restored in the future and their restoration will need to be tracked.

- Some former SEZ in the urbanized portion of the south shore have been constructed as stormwater conveyance systems or restored as constructed stormwater treatment systems and turned into registered stormwater BMP's. At the recommendation of a TAC member, these areas will be specially noted as constructed BMP's because they are required to be managed different than other natural SEZ (periodic vegetation management, etc.).
- Stream habitat complexity (large woody debris, riffle / pool habitat, etc.) was removed as an indicator. Although closely related to desired SEZ conditions and important SEZ functions, and the subject of restoration resources, it was removed for multiple reasons. First, there is a large amount of natural variability in stream habitat complexity in the Tahoe Basin. Some streams are naturally very complex while others (especially meadow systems) are naturally simple. Therefore, it is difficult to assign a "rating" to stream habitat complexity. Second, assessment of habitat complexity is a very time-intensive field process and requires expertise in the resource area. There are not enough resources to perform these surveys on a basin-wide scale.
- Biotic integrity (macroinvertebrate composition) will not be assessed in some very low gradient (less than 0.5% slope) stream or channeled meadows. These systems are often stagnant and impossible to get a good BMI sample from, and therefore will not be sampled and assessed.
- Added heacuts and channel incision to all stream and channeled meadow system. It was decided that these indicators are important for all system not just meadow systems.
- Added aquatic organism passage as an indicator at request of several TAC members.
- Changed the scoring system for the headcut indicator to be based more on the size of headcuts as opposed to simply the number of headcuts.
- For channeled meadows, the channel has been scored separately so that the channel score can be viewed separately from the meadow and can be compared to non-meadow channels throughout the basin. Channeled meadows will also be scored as a combination of the channel and meadow score, so that the meadow score can be viewed as a whole as well.

APPENDIX 3: Summary of current and potential data sources for the assessment

Indicator	Integrated data	Potential data sources
Headcuts	TRPA CRAM meadow data; UC Davis Meadow Scorecard data	USFS Fire adapted ecosystem monitoring, Project level data
Vegetation vigor	DRI NDVI statistics	
Channel incision	TRPA CRAM meadow data; UC Davis Meadow Scorecard data; USFS project data; project level data	USFS stream condition inventory data, project level data
Invasive plant species	TRPA / CTC CRAM meadow data; CalFlora invasive mapping, USFS Invasive plant monitoring; Cal Parks invasive plant monitoring	USFS Region 5 meadow monitoring plots, project level data
Presence of ditches / gullies / berms	TRPA / CTC CRAM meadow data; remotely sensed bare-earth LIDAR data	
Conifer encroachment	Tree Approximate Object (TAO) LIDAR data	Remotely sensed data from UNR, project level data
Channel stability	TRPA / CTC bioassessment data; Trout unlimited UTR study; Simon sedimentation study	USFS stream condition inventory data, project level data
Biotic Integrity (Benthic macroinvertebrates)	TRPA / CTC / NDEP bioassessment data	
Habitat fragmentation	TRPA impervious cover lidar data	
Aquatic Organism Passage	USFS Aquatic Organism Passage	

Table 21: Current and potential data sources for the assessment

APPENDIX 4: Bridge between conditions indicators and draft Stream and Meadow desired conditions derived from Lake Tahoe West Partnership

SEZ Desired Conditions *(from Lake Tahoe West Landscape Restoration Strategy)*	**SEZ Condition Indicator** *(TRPA-suggested measurable indicator related to desired conditions)*
MEADOWS - Meadow and riparian areas exhibit a high degree of hydrologic connectivity horizontally upstream and downstream, both laterally across the floodplain and vertically between surface and subsurface flows.	• Channel incision • Presence of ditches • Presence of head cuts • Vegetation vigor • Floodplain Inundation Frequency and Duration • Aquatic Organism Passage
MEADOWS - Meadows and riparian areas include a mosaic of habitats and successional plant communities that support native plant and animal populations, including aquatic species dependent upon cool and high-quality water flows in downstream reaches	• Benthic macroinvertebrate composition (BMI) • Invasive plant species • Stream Temperature • Species of Concern (plants and wildlife) • Edge Species (wildlife)
MEADOWS - Natural processes are sufficient to maintain desired vegetation structure, species diversity, and nutrient cycling	• Vegetation vigor • Conifer encroachment
STREAMS - Stream processes associated with the geologic setting, valley type, geomorphology, and sediment transport influence erosion and deposition such that streams are in dynamic equilibrium.	• Channel stability • Channel Sinuosity • Aquatic Organism Passage
STREAMS - Streams do not exhibit signs of chronic sediment overloading (aggradation) or accelerated (human-caused) bank and bed erosion (incision and gully formation).	• Channel stability • Channel incision
STREAMS - Coarse woody debris forms and maintains pool and cover habitats	• Physical stream habitat • Canopy cover • Diversity of flow habitats
STREAMS - The physical structure and vegetative condition of streambanks minimizes erosion and sustains desired habitat diversity.	• Channel stability • Physical stream habitat
STREAMS - In-stream flows and floodplain inundation frequencies sustain healthy aquatic habitat conditions, and naturally reproducing populations of native plant and animal species.	• Channel incision • Vegetation vigor • Benthic macroinvertebrate composition (BMI) • Floodplain Inundation Frequency and Duration

	• Species of Concern (plants and wildlife)

Table 22: Bridge between conditions indicators and draft Stream and Meadow desired conditions derived from Lake Tahoe West Partnership

APPENDIX 5: Methods for determining conifer encroachment into meadows in the Lake Tahoe Basin.

Background: One of ten indicators selected for assessing meadow health is conifer encroachment. Since meadows are more diverse than adjacent forests, replacement of meadow vegetation by conifer forest reduces local and landscape biodiversity. Conifer encroachment into mountain meadows has been attributed to several (non-exclusive) causes including climate effects, cessation of grazing, reduced groundwater levels, and fire suppression. While meadows, by nature, are somewhat temporary and transitory in the landscape, the loss of meadows due to conifer encroachment has generally been seen by land managers as negative and many resources have been allocated to manage conifer encroachment into meadows in the Tahoe Basin. Therefore, the extent conifer encroachment has reduced meadow size is of interest for establishing overall meadow condition.

General Methods: To determine the extent of conifer encroachment into meadows, two steps were taken. First, likely historic meadow extent was determined. Second, the current extent of conifer encroachment into historic meadows was determined. Historic meadow extent was determined using a variety of field and remotely sensed indicators such as soil, vegetation, slope, and historic aerial imagery. In many cases, historic meadow extent is obvious based on these factors and a detailed field delineation was not required. In other cases, remote delineation was not possible, and a field visit was required. Following the 2019 field season, historic meadow extent for all meadows in the Tahoe Basin had been delineated using remote sensing or field verification. Once historic meadow extent *was* determined, the second step *was* determining how much historic meadow has been lost to current conifer encroachment. This second step was accomplished using a remote sensing method known as Light Detection and Ranging (LIDAR). LIDAR for the entire Tahoe Basin was taken from an aircraft in summer 2009. This LIDAR was processed to identify each tree in the Basin along with its height and other characteristics. Any tree that falls within the historic meadow extent is counted as a conifer within the historic meadow. Next, 300 square meter hexagons were overlaid on the historic meadow. Any hexagon that has at least 1 conifer within it is counted as “encroached”. The overall percent of “encroached” hexagons within the historic meadow is used to determine the degree of overall conifer encroachment within each meadow. Aspen stands (regardless of height) and *any* trees under 6 meters were excluded from the analysis to ensure that only conifers were counted instead of common meadow riparian shrubs such as willow and alder. While this height cut-off also excludes young conifers, it is necessary to avoid counting desirable species as conifers and focuses on conifers that are becoming well-established in meadows. Organizations looking to identify areas of young conifer growth will be able to access the data without the height cut-off on a site-by-site basis if needed. Much more detailed descriptions of the methods for 1) determining historic meadow extent and 2) current conifer encroachment are described below.

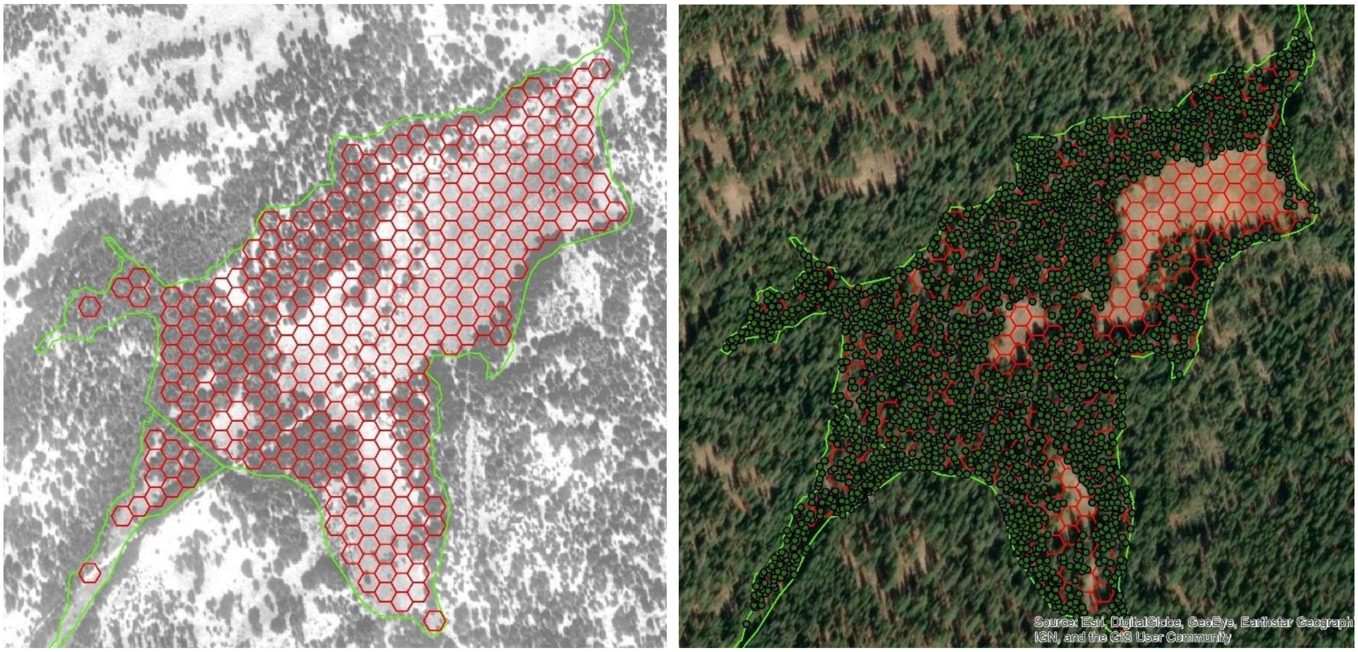

Figure 59: (Left) 1940 aerial imagery of Saxon Creek meadows. By 1940, it appears some conifer encroachment into the meadow was already taking place, while large areas were still open meadow. (Right) By 2009, LIDAR data shows a large number of trees within the historic meadow. This meadow was determined to have lost 84% of its historic meadow extent to conifer encroachment. Green dots are LIDAR-derived Tree Approximate Objects (TAO) and red hexagons are analyzed for presence / absence of TAO's.

Detailed Methods, Step 1: Establishing historic extent of meadows in the Tahoe Basin:

Margin of error: It is important to understand the level of error that is expected and accepted with this analysis. Because we are looking at the entire Tahoe Basin and are looking at historic meadow extent, some error is acceptable. Establishing *exact* boundaries of historic meadow extent is not possible with given resources. Generally, mapping of historic meadows edges that is within 5 meters of its correct location is acceptable. It is unlikely that small errors in defining the edge of historic meadows will greatly impact the overall level of conifer encroachment detected and will not impact the detection of change in conifer encroachment over time.

To delineate historic meadows, the following data was utilized: existing meadow mapping, historic imagery, soil maps, LIDAR-based elevation data, and field verification when necessary. First, meadows were defined. For this exercise, the meadow definition used by the U.S. Forest Service was used (Weixelman, et al., 2011). This definition includes the following:

- A meadow is an ecosystem type composed of one or more plant communities dominated by herbaceous species
- Meadows support plants that use surface water and/or shallow groundwater (generally at depths less than 1m)
- Hydrologic sources include snowmelt, surface water from streams, and/or groundwater discharge near the land surface (generally at depths of less than one meter)
- Woody vegetation, like trees or shrubs, may occur and be dense but are not dominant
- Soils range from mineral soils to highly organic soils (peats).

Because we are interested in identifying historic meadow habitat, the vegetation definitions of meadows are somewhat problematic. First, grazing in meadows was very common throughout meadows in the Tahoe Basin in the 19th and early 20th centuries. Therefore, woody vegetation structure may have been drastically influenced by heavy grazing. Areas that are currently dominated by woody species such as willows may not be covered by willows in historic aerial imagery because of grazing. Likewise, areas that are now covered in woody vegetation may have been free of woody vegetation because of fires, different hydrologic regimes, etc. in the past. Second, conifer encroachment may turn historic meadow habitat into areas that don't meet the definition for meadows because conifers now are dominant. Because of these reasons, a few caveats were added to the U.S. Forest Service definition of meadows for the purposes of detecting conifer encroachment into historic meadows.

- Many areas were delineated as meadows in the UC Davis Sierra Nevada meadows layer that are in fact dominated by willows or other riparian woody species. Areas that have more than 75% riparian woody cover in historic *and* current aerial imagery were eliminated from the meadows map.

Figure 60: Willow-dominated area: Aerial imagery shows an area that was delineated as meadow in the UC Davis Sierra Nevada meadows map. This area is obviously dominated by woody riparian plants (more than 75%) and was therefore eliminated from the meadows map.

- Areas were considered historic meadow habitat if they either had less than 75% woody vegetation in either historic aerial imagery *or* current aerial imagery.

Figure 61: Trout Creek meadows - (Left) imagery from 1940 shows meadows with little to no woody vegetation. (Right) The same meadow in 2018 shows large amounts of woody vegetation (willows and conifers). Because of these changes in woody vegetation, an area will be considered historic meadow if, at any time, it contained less than 75% woody vegetation.

- Conifer presence in potential meadow habitat was not considered part of woody vegetation cover because we are attempting to quantify the amount of conifer encroachment into meadows. If the understory beneath conifers is dominated by herbaceous hydric vegetation that is the same or very similar to the vegetation found in the adjacent meadow (no matter how much conifer cover there is), this area was considered part of potential historic meadow habitat.

Figure 62: Conifers in meadows: This area, despite being dominated by greater than 30% conifer cover, is adjacent to existing meadow and the understory is comprised of hydric meadow vegetation. Therefore, it was considered part of the historic meadow.

With these definitions in mind, likely historic meadows were mapped within the Tahoe Basin. To accomplish this, remotely sensed data as well as some field verification were utilized. Many meadows have enough existing data and imagery to determine its status as historic meadow without field verification, while other meadows have conflicting, or unclear data associated with them and required field verification.

Historic meadows that DID NOT require field verification:

- Begin with the USFS-created Sierra Nevada meadows layer. While not perfect, this is the best layer to begin identifying potential historic meadows.
- Next, the 2007 NRCS soil map (Loftis, 2007) was used to help further identify historic meadow habitat. Areas that have been mapped in the below NRCS soil categories were searched for, which are soil types generally associated with meadows, and are adjacent to existing mapped meadows.
    a. NRCS Soil Type 7021 - Typical vegetation: Sphagnum bogs dominated by a mat of floating Sphagnum moss and mountain blueberry, bog laurel, sedges, and a variety of alpine forbs growing on mat
    b. NRCS Soil Type 7041 - Typical vegetation: Moist meadows dominated by sedges, rushes, and grasses with a variety of forbs
    c. NRCS Soil Type 7043 - Typical vegetation: Moist meadows dominated by sedges, rushes, and grasses with a variety of forbs
    d. NRCS Soil Type 7071 - Typical vegetation: Seasonally flooded basins dominated by sedges (Carex utriculata and/or Carex vesicaria); also, other grasses, rushes, and forbs with small patches of willow
    e. NRCS Soil Type 9001 - Typical vegetation: Upper elevation meadows dominated by graminoid species, primarily Nebraska sedge and tufted hairgrass, with a diversity of forbs.
- Next, we looked at aerial imagery from 1940. We searched for areas that appear to meet the definition for meadows in terms of vegetation type (less than 75% riparian woody species) and are adjacent to, or within, existing mapped meadows.
- Areas that fit the above definitions, and where there is obvious stratification from meadow to upland is visible in satellite imagery, did not require field delineation. On initial analysis, it appears that this covered over 50% of meadows.


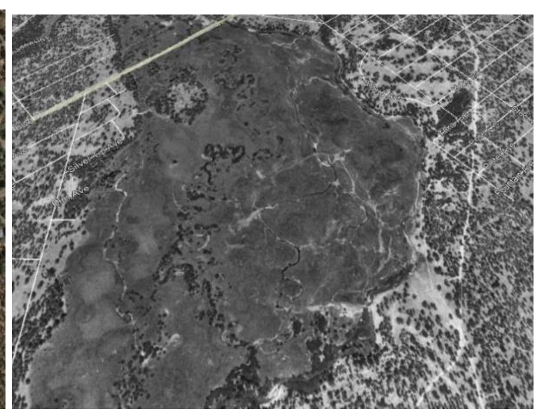

Figure 63: Johnson meadow: Johnson meadow is mapped the same in NRCS soil mapping, 1940 vs. 2018 aerial imagery, and stratification is obvious between meadow and upland habitats. Therefore, meadows like this will not require field delineation.

Historic meadows that DID require field verification:

- If an area was **not** identified as a historic meadow in all three of the above categories, field verification was required.
- To identify areas that require field verification, several steps were required:
    a. Identify areas mapped as meadows in the USFS-created meadow map layer
    b. Identify areas adjacent to these mapped meadows that fall in the below NRCS soil categories. These soil categories can support meadow vegetation, but also can support non-meadow vegetation.
        i. 7042 - Typical vegetation: Patches of Lemmon's willow intermixed with scattered forbs and Grasses
        ii. 7431 - Typical vegetation: Patches of Lemmon's willow intermixed with scattered forbs and Grasses
        iii. 7471 - Typical vegetation: Lodgepole pine forest with a few white fir and Jeffrey pine trees in moist areas surrounding meadows; willows, grasses, and forbs included in the understory
        iv. 7491 - Typical vegetation: Lodgepole pine forest with grasses in the understory (Figure 5)

Figure 4: Meadow in Washoe Meadows State Park: Despite being mapped in NRCS Soil unit 7431 which is listed as being dominated by lodgepole pine, this area is clearly a meadow and will require field verification to determine historic extent of the meadow.

    c. Identify areas using aerial imagery (historic and current) that appear to be meadow but where there are questions based on presence of woody vegetation.
    d. Using LIDAR bare-earth imagery, identify areas that are adjacent to known meadows and at the same relative elevation of the known meadow surface.

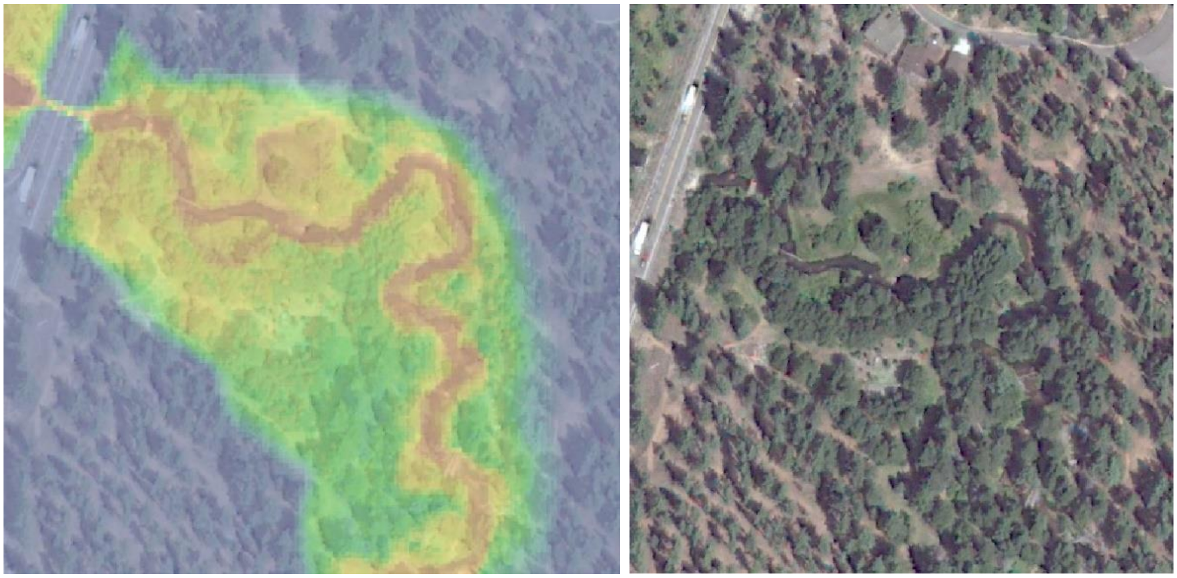

Figure 64: Trout Creek above Pioneer Trail - LIDAR bare-earth elevation data (left) overlaid on aerial imagery reveals likely historic meadow borders based on changes in elevation. Aerial imagery (right) shows many conifers in likely historic meadow habitat. LIDAR data will be coupled with field verification to determine the extent of historic meadows in these cases.

Field verification of potential historic meadow extent: Once these areas in question were identified, field verification occurred. Rules for field verification were developed in the field with the U.S. Forest Service and California Tahoe Conservancy. Field verification relies mostly on the following:

- Presence / absence of meadow vegetation such as herbaceous plants, wetland grasses, sedges, and rushes
- Changes / breaks in slope
- 1940 aerial imagery

Because there are many different types of meadows in the Tahoe Basin (as identified in the USFS Hydro-geomorphic Types document), each meadow will have its own indicators of historic meadow extent. Unfortunately, this means there are not steadfast rules that can be used across all meadow types. Instead, depending on the meadow type and whether disturbance has occurred at the site, field indicators of historic meadow extent varied. It is important to note that in some areas where the hydrology of the meadow has been drastically impacted (i.e. fill, channel incision, etc.), field indicators of historic meadow extent may be completely lost and a "best guess" was needed based off historic aerial imagery. Below, field indicators for identifying historic meadow boundaries are listed depending on the meadow characteristics. Accompanying photos based off field testing of protocols are included.

1) In meadow types where frequent flooding and deposition has resulted in a flat depositional surface immediately adjacent to sloped uplands, elevation changes from flat to sloping along with changes from meadow vegetation to upland vegetation mark the edge of the meadow. These areas are simple to delineate in the field. As is the case with all meadow types, 1940 aerial imagery was used whenever possible to verify field indicators of historic meadow extent.

Figure 65: Riparian low gradient meadows with a flat depositional surface immediately adjacent to sloping upland. Red line marks edge of historic meadow. (Left) Trout Creek above Pioneer Trail, Lake Tahoe Basin. (Right) Spooner meadows, Lake Tahoe Basin.

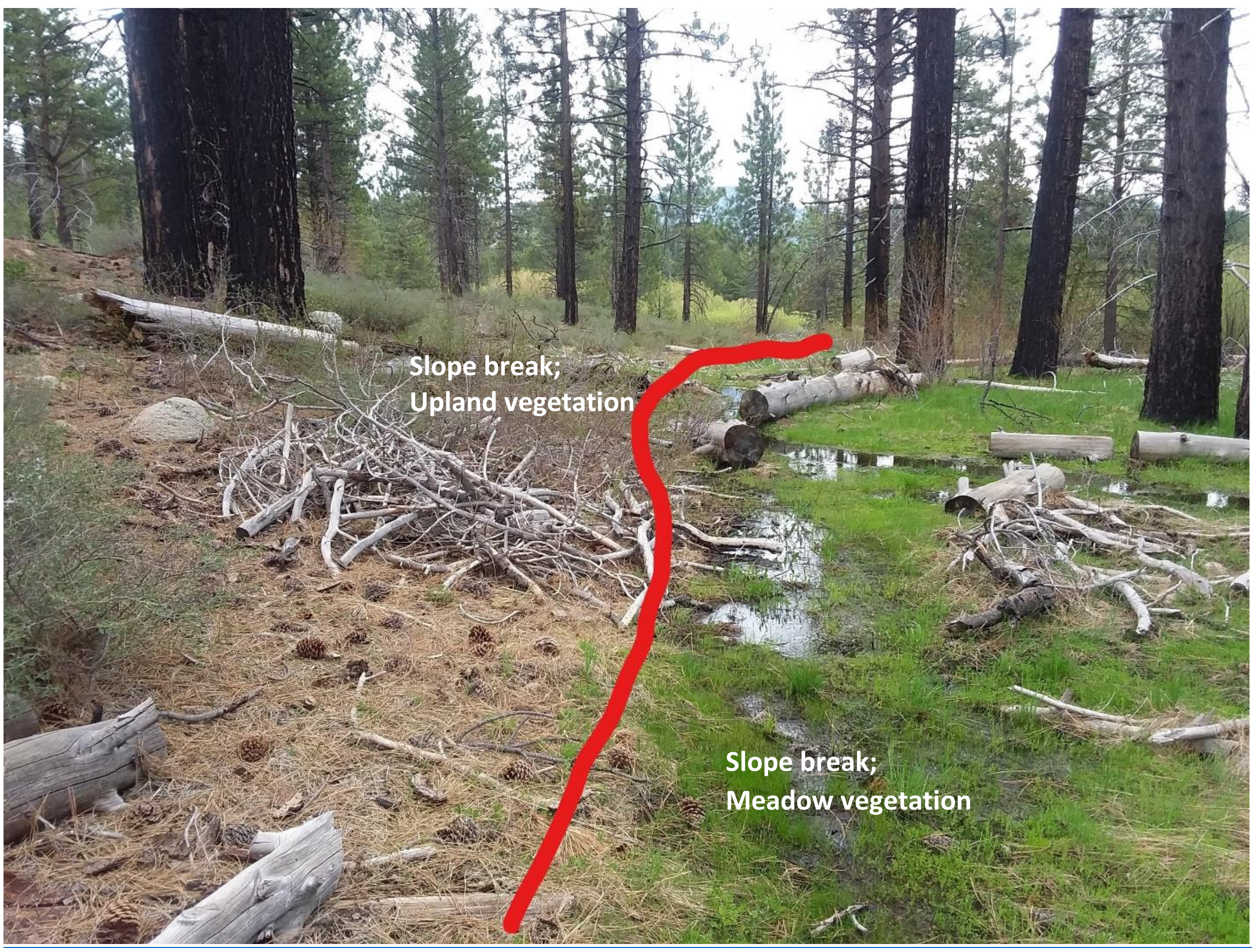

Figure 66: Flat depositional meadow area adjacent to sloped upland. Change in slope and transition from herbaceous meadow vegetation to upland plants signify the edge of the historic meadow. Angora area meadows, Lake Tahoe Basin.

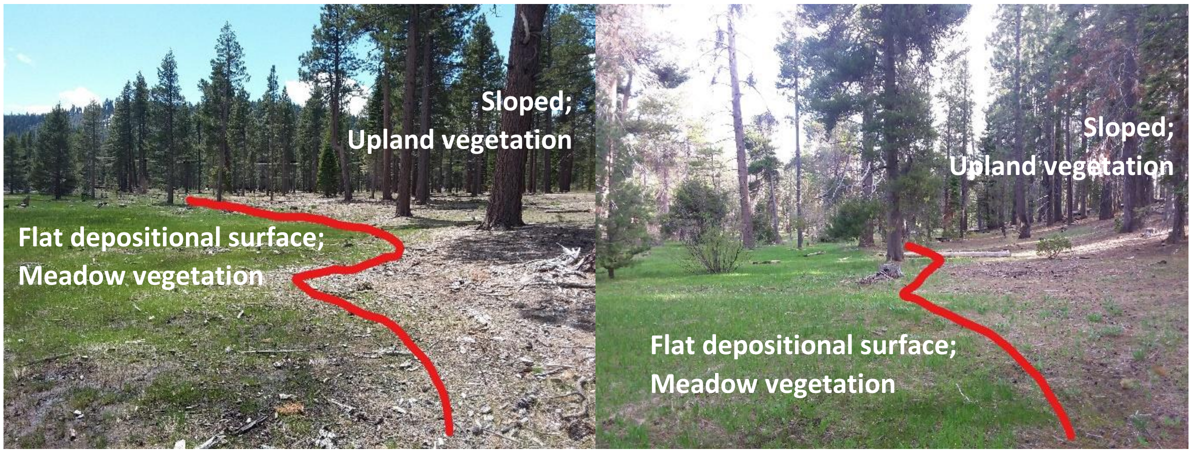

Figure 67: Subsurface low gradient meadows with flat depositional surfaces. In these meadows, the flat depositional surface with meadow understory is easy to distinguish between the sloped upland area.

2) In slope discharge meadows where a flat dispositional surface is not present, changes in slope are not as obvious and not as useful for delineating potential historic meadow extent. Many times, there will not be an obvious change in slope from the upland area to the meadow area. Therefore, vegetation changes are the primary method for determining the edge of the historic meadow. The area where there is a break from primarily understory meadow vegetation (herbaceous meadow vegetation; wetland grass, sedges, rushes) to primarily upland understory (bare dirt, duff, whitethorn, etc.) were used to mark the boundary of the historic meadow. The presence of conifers was not used to delineate the historic meadow boundary as conifers can often live in wet meadow habitats. In some cases, conifer encroachment may be so intense that the understory meadow vegetation has been eliminated. In these cases, it is necessary to look at the larger meadow area to determine if the area surrounding the area with conifers and lack of meadow understory is truly upland or not. The age of conifers was also used to help delineate the historic meadow extent. In many cases, younger conifers will have a meadow understory while old, mature conifers will have upland understory. The age of the trees can therefore help to show the edge of the historic meadow. 1940 aerial imagery was used to verify what was observed in the field.

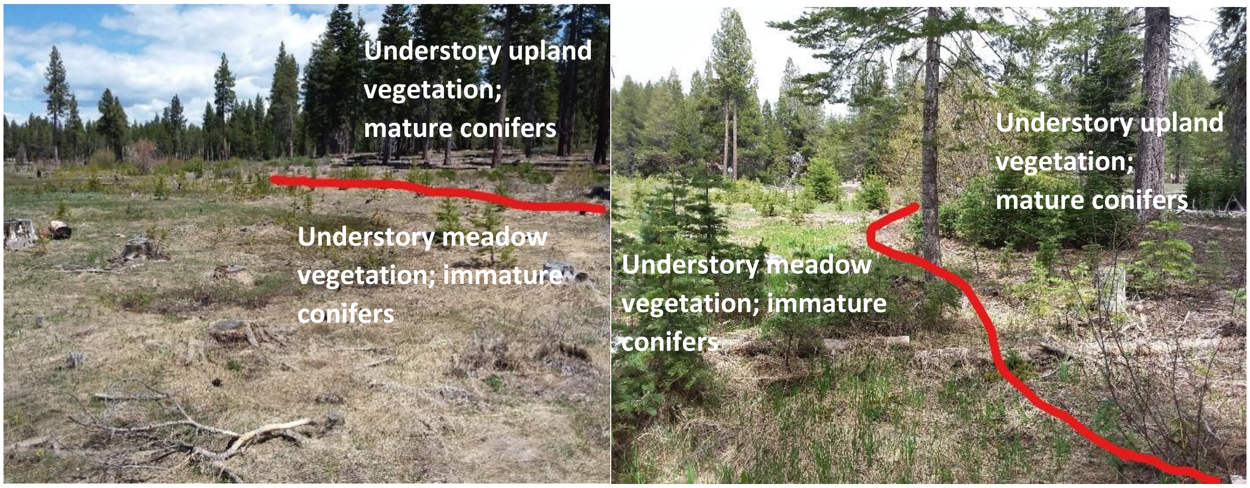

Figure 68: Discharge slope meadows. For sloping meadows, changes in slope are not as obvious and do not necessarily represent transition from meadow to upland. In these meadows, vegetation is the primary indicator of transition from meadow to upland. (Left) Gardner meadow, Lake Tahoe Basin. (Right) Spooner meadow, Lake Tahoe basin.

3) Discharge slope meadows with sagebrush encroachment offer an additional challenge for delineation. Sage brush often grows on the margins of drier meadows, especially on the east side of Lake Tahoe. These sagebrush areas often appear to be part of upland at first glance, but upon further investigation, they are often within the historic meadow extent. Because sagebrush often encroaches into drier slope discharge meadows, they often occur on the slopes on the outer edge of a meadow. In some cases, the sagebrush does in fact signify the outside edge of the historic meadow. In other cases, sagebrush is encroaching into the historic meadow and is within the historic meadow extent. To determine the difference between these two cases, we used understory vegetation and breaks in slope. In areas where the sagebrush is outside the historic meadow, there will not be understory meadow vegetation beneath the sagebrush, there will often be a break in slope, and the sagebrush may be surrounded by mature conifers. In areas where sagebrush has encroached into the historic meadow, there will be meadow understory vegetation underneath the sagebrush, there will often not be a break in slope, and the sagebrush area may be surrounded by young, immature conifers or no conifers. 1940 aerial imagery was used to verify what was observed in the field.

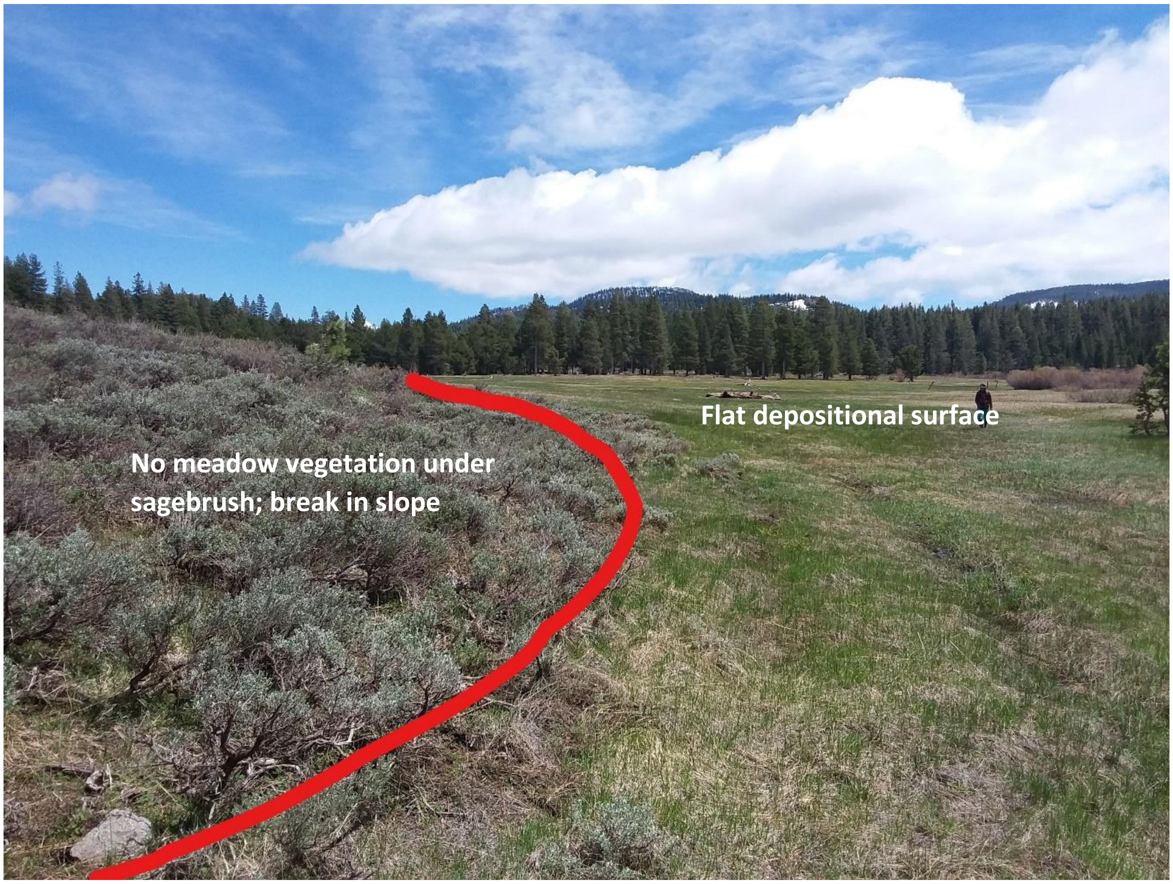

Figure 69: Where a flat depositional meadow surface is adjacent to a sloping area with sagebrush, the type of vegetation underneath the sagebrush will indicate the edge of the historic meadow. In this example, there is not meadow vegetation underneath the sloping sagebrush area, there is a major break in slope, and the field indicators are backed up by historic aerial imagery and therefore will not be considered historic meadow. Kahle meadows, Lake Tahoe Basin.

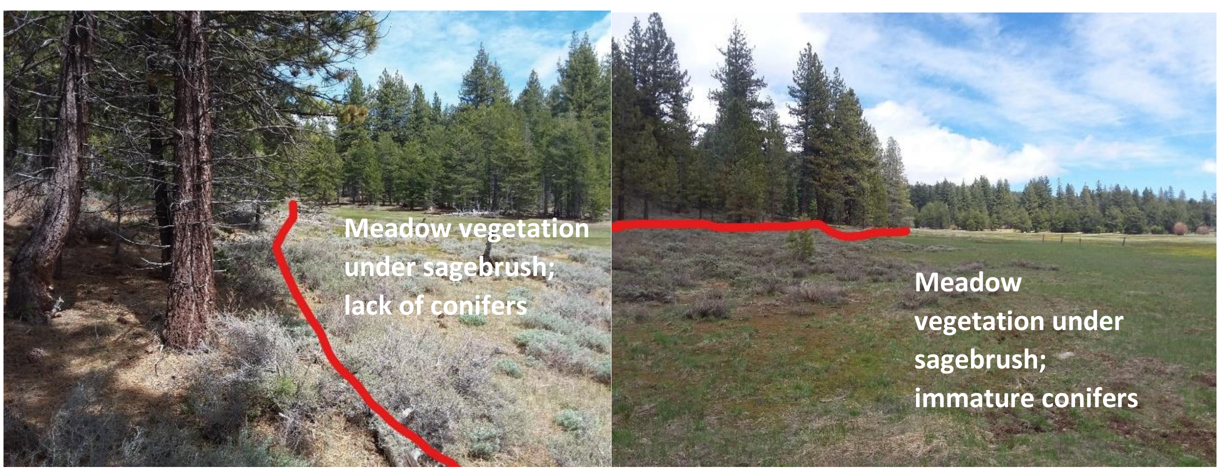

Figure 70: Where there is no flat depositional surface and the meadow is sloping the same as the upland area, vegetation will be used as the primary key to delineate historic meadow extent. Spooner meadows, Lake Tahoe Basin.

4) **Aspen and willow stands adjacent to meadows; where is the edge of the meadow?** A common attribute of meadows are adjacent stands of riparian woody vegetation like aspen and willow stands

adjacent or within a meadow. This makes meadow delineation difficult in these situations, so some rules were needed.

A) Riparian woody vegetation stands that are surrounded by meadow and have meadow understory beneath the woody vegetation were considered part of the larger meadow complex.

Figure 71: Despite thick patches of woody vegetation, this entire area will be considered meadow because the patches are surrounded by meadow and there is meadow vegetation in the understory.

B) Riparian woody vegetation stands on the outsides of meadows that have meadow understory were considered part of the larger meadow complex. Conversely, woody vegetation stands on the sides of meadows that transition to non-meadow understory were not considered part of the meadow complex.

Figure 72: (Left) Fallen Leaf meadow. This meadow is surrounded by aspen stands with hydric meadow vegetation in the understory. Therefore, these aspen stands will be considered part of the larger meadow complex. (Right). Cookhouse meadow. This meadow is surrounded by aspen stands as well. However, these aspen stands are in a different soil type as the meadow. They are on a steep rocky slope with no understory meadow vegetation. Therefore, they will not be considered part of the meadow complex.

Removing development from historic meadows: Once historic meadow extent has been established, we then removed all existing development (including golf courses) or historic meadows that have been converted to non-meadow types. This allowed direct comparison over time based solely on conifer encroachment and not loss of meadow habitat due to development.

Detailed Methods, Step 2: Determining conifer encroachment into meadows

Once historic meadow boundaries were mapped, the amount of conifer encroachment into these meadows was calculated. The following steps were taken to analyze conifer encroachment.

- *Map each tree within meadows in the Tahoe Basin.* LIDAR data creates a GIS point for every tree in the Tahoe Basin called Tree Approximate Objects (TAO). The TAO's were clipped to only include TAO's that were within the historic meadow polygons.
- *Eliminate non-conifer trees such as willow and aspen.* LIDAR does not distinguish between types of trees. However, we are only interested in conifer encroachment and not willow / aspen encroachment. To eliminate willow and other riparian trees from the analysis, multiple steps were taken. First, all mapped Aspen stands (mapped by Tom Dilts at University of Nevada – Reno) were removed from analysis. Next, a height cut-off of 6 meters was applied. Any tree under 6 meters was removed from the analysis to eliminate most willow and other riparian shrubs from the analysis. 6 meters was determined to be the best height cut-off using "natural breaks" in the statistics and applying them to willow-dominated areas. While this step will also results in young conifers under 6 meters being excluded from the analysis, it allows the analysis to focus only on conifers that are becoming established and removes desirable vegetation such as willows from the analysis.
- *Overlay 300 square meter hexagons on top of historic meadow polygons.* 300 square meter polygons were overlaid on top of historic meadow polygons to help determine conifer density and distribution within the meadow. Only hexagons that fall completely within the meadow polygon are used. This is to ensure that density calculations are all the same using a full hexagon size. This results in some small edge areas of the meadow not being included in the analysis.
- *Calculate conifer density within hexagons.* An analysis was run to determine the number of conifers within each hexagon. The conifer density per hexagon will be used to assess changes over time once LIDAR data for subsequent years is available. To determine the current status of conifer encroachment, any hexagon with at least one conifer in it is determined to be "encroached".
- *Calculate the percent of hexagons with the historic meadow extent that are "encroached".* The percent of hexagons within a historic meadow that are encroached will determine the overall amount of encroachment in the meadow. For example, if 74% of hexagons have at least one conifer in them, the meadow will be considered 74% encroached.
- *Establish a rating system based on the percent of hexagons encroached.* Each meadow will be "rated" and given a score based on the percent of hexagons within the historic meadow that are encroached. The rating system is below:

Percent of hexagons encroached	Rating	Score

0-20%	A	12
21-40%	B	9
41-70%	C	6
71-100%	D	3

Table 23: Conifer Encroachment Ratings

- *Data limitation and caveats.* It is recognized that conifer encroachment analysis using these methods are imperfect. However, these methods use the best available data and science and are applicable on a basin-wide scale. Therefore, they offer the best available analysis for conifer encroachment into meadows for the Lake Tahoe Basin on a basin-wide scale. Detailed field-based analysis for individual meadows may supplement this analysis where available. A description of known limitations and caveats for this analysis is below, and each of these caveats is discussed for each meadow in the "conifer encroachment comments" column of the analysis:
    - *Young conifers below 6 meters are missed*. While this in unfortunate, excluding trees under 6 meters is the only way to ensure desirable species such as willows are not counted in the conifer encroachment analysis. If young conifers are managed prior to becoming established (and growing over 6 meters), a meadow will continue to receive a high score in this category.
    - *Some aspen stands continue to be included in the analysis*. The current aspen map completed by UNR in 2020 represents the best available aspen map and is highly accurate. However, it still misses some small aspen stands in meadows that will be counted as conifers if they are over 6 meters.
    - *Some tall willows continue to be included in the analysis.* While the vast majority of willows in the Tahoe Basin are under 6 meters and are excluded from the analysis, some tall willows are still included if they are over 6 meters. Shining Willow (Salix lasiandra) is one of the few willow species in the Tahoe Basin that commonly grows over 6 meters and are therefore counted sometimes.
    - *Some small meadows can have an inflated amount of encroachment because of the small number of hexagons analyzed.* Some very small meadows have less than 10 hexagons in them. In these cases, even a small number of hexagons with conifers in them can result in a low score for conifer encroachment.
    - *True historic meadow extent can never be truly known.* While all efforts were made to determine the most accurate possible historic meadow extent, meadows by nature are transitional in the landscape and the true historic extent is impossible to know for sure. The earliest aerial imagery for the Tahoe Basin is 1940, centuries after the Comstock era had dramatic impacts on the watersheds and forests of the Lake Tahoe Basin. Therefore, it is possible that the amount of current conifer presence in meadows is greater than or less than true historic conifer extent. This is a question that goes beyond this analysis. Instead, best available science and data were used while knowing that this larger question cannot currently be answered.

Figure 73: Step 1 - Begin with delineated historic meadow.

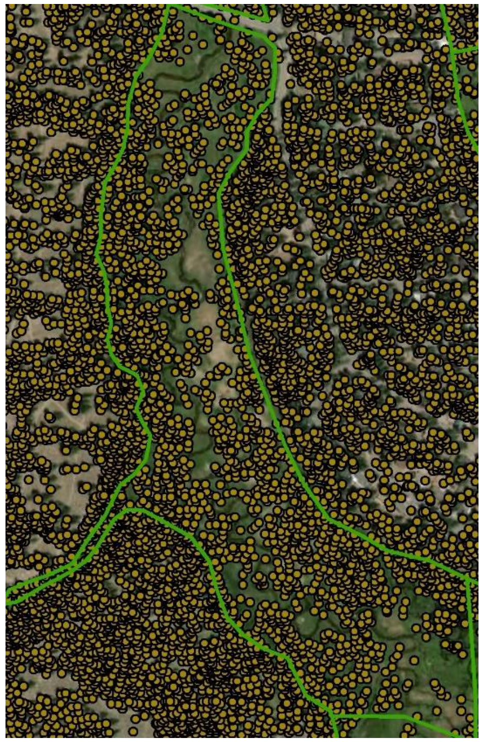

Figure 74: Step 2 - Add in all Tree Approximate Objects (TAO)

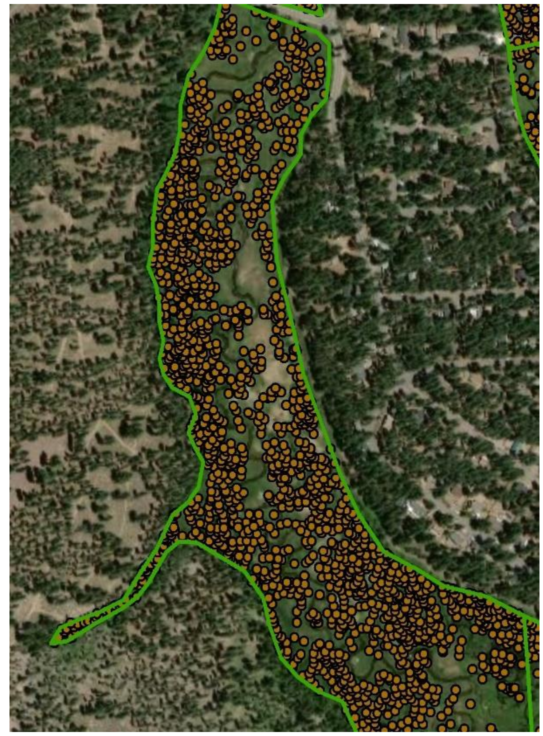

Figure 75: Step 3 - Clip TAO's to only TAO's within historic meadow polygon.

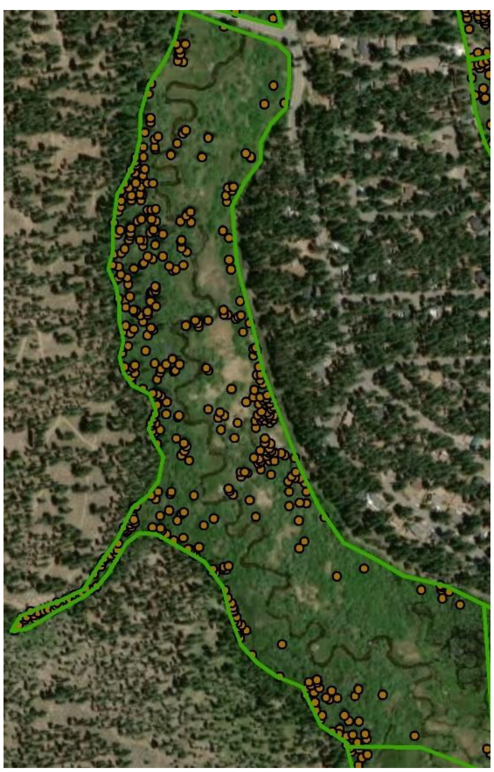

Figure 76: Step 4 - Remove all aspen stands and any TAO's under 6 meters. Remaining TAO's will be considered conifers for analysis.

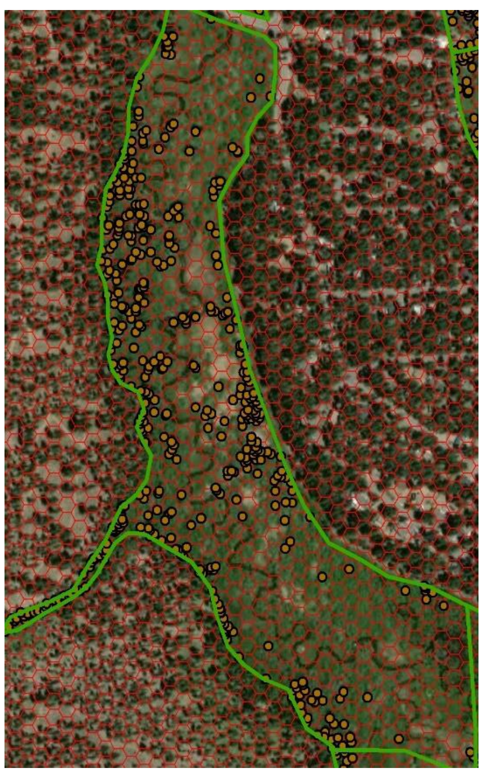

Figure 77: Step 5 - Overlay 300 square meter hexagons.

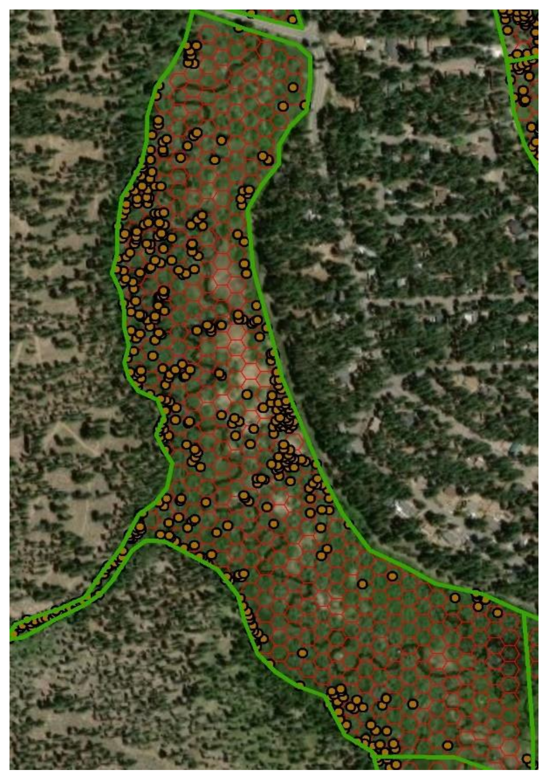

Figure 78: Step 6 - Remove all hexagons that do not fall completely within historic meadow polygon. Remaining hexagons will be analyzed for conifer encroachment.

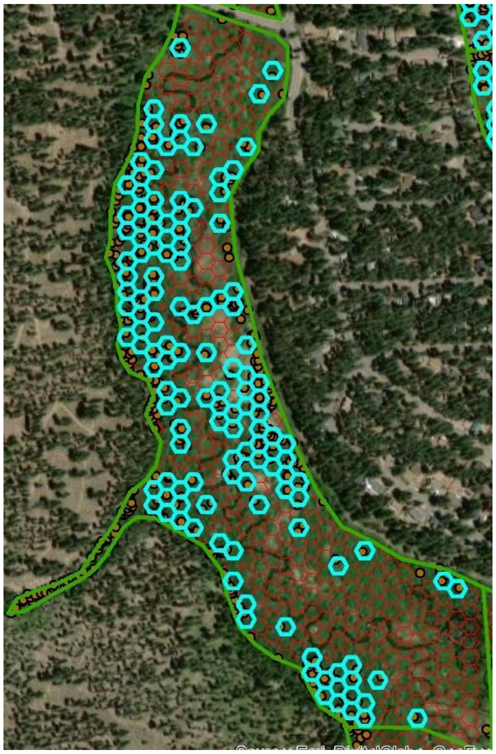

Figure 79: Step 7 - Determine the percent of hexagons that have 1 or more TAO's in them. This percent will be used to determine the rating for the conifer encroachment indicator. This meadow has 29% of hexagons encroached and therefore received a "B" rating.

APPENDIX 6: Development of Remote Sensing Analyses to Support Management of Mountain Meadows in the Lake Tahoe Basin by Desert Research Institute

DRI
Desert Research Institute

Development of Remote Sensing Analyses to Support Management of Mountain Meadows in the Lake Tahoe Basin

Christopher Pearson[1]
Mark B. Hausner[1]
Charles Morton[1,2]
Justin L. Huntington[1,3]

June 2020

Publication No. 41XXX

Prepared by

1. Division of Hydrologic Sciences
2. Division of Earth and Ecosystem Science
3. Western Regional Climate Center

Desert Research Institute

Prepared for

Nevada Division of State Lands
Lake Tahoe License Plate Program

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EXECUTIVE SUMMARY

Mountain meadows provide a variety of ecosystem services, including water supply, wildlife habitat, biogeochemical cycling, and carbon sequestration. The impacts of these ecosystem services propagate well beyond the boundaries of the meadows themselves. In recognition of this fact, resource managers within the Lake Tahoe Basin have made meadows and the ecosystems occurring them focal points of conservation efforts. To support the Tahoe Regional Planning Agency (TRPA) and other land managers in the basin, the Desert Research Institute (DRI) performed an exploratory analysis of satellite and gridded climate data relevant to these ecosystems and their ecological functions.

DRI analyzed 315 meadows delineated as individual management units by TRPA. The analysis focused on the normalized difference vegetation index (NDVI), a measure of vegetation greenness and vigor. Spatially and temporally integrated values of late summer NDVI were obtained for each meadow for each year of the Landsat record (1984-2019) and were examined using multiple statistical approaches. Statistical analyses followed non-parametric methods that can be confidently applied to data from a wide variety of distributions. Different analyses considered:

- basin-wide trends in NDVI,
- trends and temporal variability of individual meadow NDVI,
- meadow NDVI in relation to other meadows in the basin,
- the effect of climate drivers, and
- spatial distribution of NDVI within the meadows.

NDVI integrates a wide range of phenomena (climate and land use change, geomorphological processes, fire and other disturbances, vegetative succession, etc.) into a single metric. For this reason, these data must be carefully examined and interpreted in the context of other available information. In depth discussion is provided for a number of examples, demonstrating the utility and limitations of these analyses and the need for additional context. The full data set accompanying this report includes quantitative data on these analyses over three different timescales (1984-2019, 2000-2019, and 2010-2019,).

One of the primary advantages of remotely sensed data is its ability to trace and quantify changes over long periods of time. These data can be used to fill gaps between site visits and to place on-site observations into a larger context, but are not a complete substitute for field visits. For meadows in particular, field assessments can take into account numerous factors that will not show up in NDVI observations. However, remotely sensed data can be very effective in identifying long-term trends that may not be apparent in field surveys and in quantitatively evaluating hypotheses formulated based on site visits.

Recommendations are provided on future work needed to effectively integrate remotely sensed data into management planning and actions. Remotely sensed data used during this study are freely available and continually collected, and the analyses presented here can be updated annually. In summer 2019, TRPA completed an extensive field survey of meadows within the basin and reconciling those survey results with remote sensing analyses would provide significant context to both the satellite and the field data. Finally, the expansion and development of new tools may increase the utility of these methods for understanding disturbance and recovery in meadow ecosystems.

CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

API	application programming interface
CDF	cumulative distribution function
DRI	Desert Research Institute
EPA	Environmental Protection Agency
GEE	Google Earth Engine
NDVI	normalized difference vegetation index
PDF	probability distribution function
PET	potential evapotranspiration
PPT	precipitation
RMSE	root mean square error
SR	surface reflectance
StdDev	standard deviation
TOA	top of atmosphere
TRPA	Tahoe Regional Planning Agency
USGS	United States Geological Survey

INTRODUCTION

Meadows represent a critical zone of biodiversity and ecosystem services in mountainous regions such as the Sierra Nevada. Naturally functioning meadows provide water late into the growing season, facilitate biogeochemical cycling and nutrient removal, and sequester carbon in organic-rich soils. When this function is altered by historical management practices such as grazing or channelization, the reduced function leads to increased erosion and nutrient export which in turn impairs downstream water quality and clarity. Lake Tahoe and its surrounding mountains are a renowned tourist destination, and environmental sustainability and protection are primary objectives of multiple stakeholders and management agencies in the basin. The Lake Tahoe Restoration Act identified restoration of stream environment zones, such as mountain meadows, as a key improvement initiative and detailed the need for clear accountability and oversight of ongoing restoration efforts. Effective management of these resources, including the planning, implementation, and assessment of restoration work, requires both the knowledge of current status of the meadows and an understanding of the historical context and changes in those meadows. Stakeholders and managing agencies agree on the need for a sustainable and consistent assessment framework to guide management strategies moving forward.

On-the-ground field assessments of the hundreds of meadows throughout the Tahoe Basin are invaluable for benchmarking vegetation diversity and meadow hydrology; however, continuous annual and sub-annual updates and evaluations are unrealistic. Remote sensing based on freely available datasets, such as Landsat, can complement in-situ evaluations and add additional temporal and spatial information to difficult to access areas with limited or no historical monitoring. Recent advances in cloud-based data access and distributed computing have combined to allow sophisticated analyses of long-term remotely sensed data sets. The Landsat archive combines a long-term, continuous record (dating back to 1984) with high frequency (overpasses every 8-16 days) data collected at high spatial resolution (30 m pixels). We applied this capability to an analysis of mountain meadows in the Lake Tahoe Basin.

Ecological applications of Landsat data have increased since the Landsat archive was made freely available in 2008. Previous studies have demonstrated the ability of remote sensing to capture both degradation and recovery of vegetation within stream dependent ecosystems (Albano et al. 2020; Hausner et al. 2018). Importantly, remote sensing products such as Landsat provide both current and historical data and can be used to capture trends and provide additional context to current conditions. Beyond structural and management driven degradation, meadow vegetation is also sensitive to transient disturbances such as fire or drought and to long-term changes in climate such as increasing temperature and precipitation shifts from snow to rain. Remotely sensed data are thus often combined with gridded climate data to understand how climate variability affects vegetation.

In this study, we used the Landsat archive and other climate and topographic data to examine more than 300 different mountain meadows in the Lake Tahoe Basin. We used statistical analyses to focus our work on three different aspects of Tahoe Basin meadows:

1. Basin-wide trends in meadow vegetation,
2. Inter-annual variability and long-term trends within single meadows, and

3. Comparing trends and variability in numerous meadows across the entire basin.

This work demonstrates both the utility and the challenges of using remotely sensed data to inform resource management decisions.

METHODS

Study Location

Lake Tahoe and its surrounding watershed are located near the crest Sierra Nevada mountain range intersecting the border of Nevada and California. The lake lies at approximately 1897 m above sea level and surrounding the lake on all sides are mountains up to elevations of 3068 m. The lake surface (495 km^2) accounts for approximately one-third of the total watershed surface area (1310 km^2). At the lake's surface, summer temperatures reach on average 27 ˚C and wintertime lows reach −9 ˚C. Precipitation patterns in the watershed are strongly affected by elevation with an average annual precipitation of 0.76 m at lake level and an average of 2.03 m falling at higher elevations in the surrounding mountains (Fram and Belitz, 2011). Rain shadow effects typically lead to decreased precipitation and snow loading on the downwind, eastern side of the basin. Approximately two-thirds of Lake Tahoe Basin parent material is granitic and one-third is volcanic (LTTMDL, 2008). Vegetation, consisting of mixed coniferous forest and montane-subalpine species, cover approximately 80 % of the basin (LTTMDL, 2010). Furthermore, over 400 individual meadows have been identified by management agencies. Meadows are spatially scattered throughout the basin existing at both high and low elevations. Snowmelt based runoff and recharge serves as the primary source of water for vegetation throughout the summer and fall. Areas of dense urban development occur along the shoreline at South Lake Tahoe, Tahoe City, and Incline Village. Large portions of the northern and western shores are occupied by seasonal cabins, while much of the eastern shore is undeveloped.

Data

The Tahoe Basin mountain meadow polygon dataset was provided to the Desert Research Institute (DRI) by the Tahoe Regional Planning Agency (TRPA; Figure 1). The meadow dataset was preprocessed by TRPA to remove areas of water ponding and known conifer growth. Prior to satellite data extraction, a negative 15m buffer was applied to each polygon to avoid edge overlap issues related to the 30m satellite image pixel resolution. The polygon dataset was then rasterized and snapped to the Landsat grid in order to best capture Landsat image pixels that fall completely within each meadow extent (Figure 2).

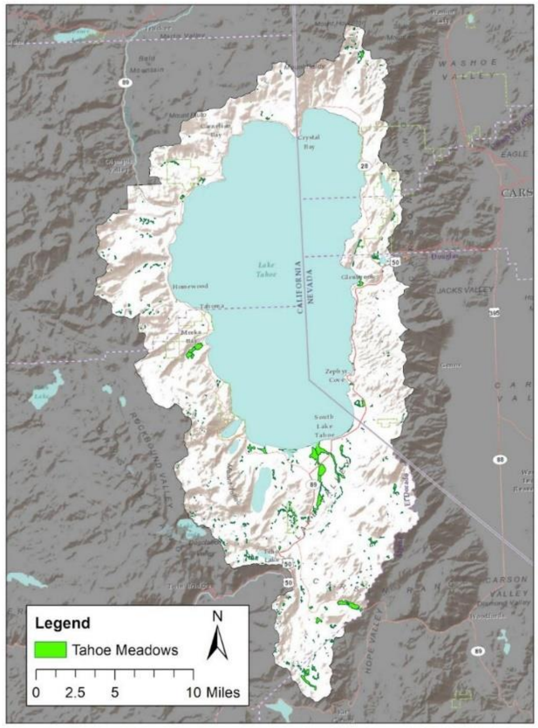


Figure 1: Map showing mountain meadow extents throughout the Lake Tahoe Basin. Polygon outlines have been exaggerated for display purposes.

Historical Landsat surface reflectance images from 1984 to present were acquired and processed using the Google Earth Engine and custom Python software. Landsat at-surface (SR) data was extracted from the USGS Tier 1 collections via the Google Earth Engine Python Application Programming Interface (API) (Gorelick et al., 2017). The Google Earth Engine cloud computing platform provides collections of historic satellite imagery and other geospatial datasets for near real-time access and on-the-fly processing. The USGS converts Landsat TM (Landsat 5), ETM+ (Landsat 7), and OLI (Landsat 8) top-of-atmosphere (TOA) reflectance to at-surface reflectance (SR) using the Landsat ecosystem disturbance adaptive processing system (LEDAPS) (for TM and ETM+) and Landsat Surface Reflectance Code (LaSRC) (for OLI) atmospheric correction algorithms (Schmidt et al., 2013; USGSb, 2018). OLI/Landsat 8 Red and NIR bands were adjusted for spectral bandwidth differences from ETM+/Landsat 7 according to methods presented by Huntington (2016). Cloud masks were also applied during data processing using F-Mask (Zhu and Woodcock, 2012) to further ensure image quality.

A proprietary DRI coding package ('ee_tools/summary_tools') was utilized along with custom scripts to download and process zonal statistics (i.e. area weighted averages) for each meadow polygon for all images in the Landsat record (1985-2019). ee_tools is a python-based analysis package that utilizes Google's Earth Engine processing platform to parallelize data analysis of satellite and climate datasets within a cloud-based environment. End of summer (August-September), median values for each year were calculated to assess state and trends in meadow greenness on an annual basis. End of summer meadow imagery captures key interannual vegetation variability related to water supply and growth dynamics and has been used to track vegetation health in groundwater dependent ecosystems (Huntington, 2016) and vegetation change in response to restoration work (Hausner et al. 2018). In addition to satellite imagery, meteorological data including water year precipitation, potential evapotranspiration, and temperature (minimum, maximum, and mean) were acquired from the gridMET gridded climate dataset (Abotzoglou, 2013). gridMET provides estimates of historic daily weather parameters at 4km resolution based on downscaling of the regional NLDAS-2 reanalysis products. Finally, topographic data, including slope, aspect, and elevation, were provided for each meadow by TRPA.

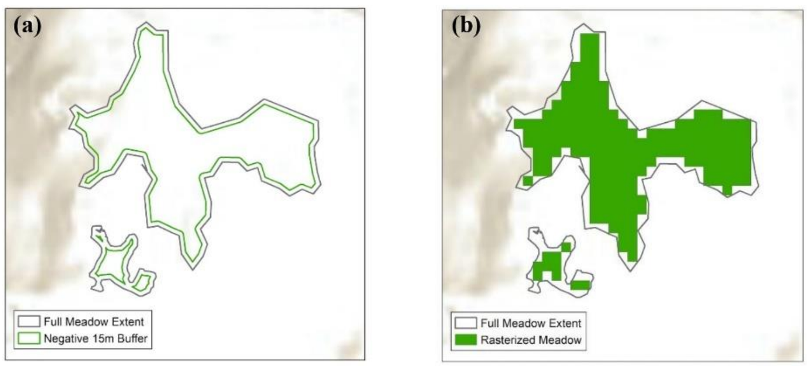


Figure 2: Example meadow polygon delineation. a) Full meadow extent (black) and extent after applying a negative 15m buffer (green). b) Final rasterized meadow extent used to pull only pixels within the meadow area.

After buffering and image extraction, 315 meadows were viable for Landsat based remote sensing analysis (i.e. contained at least 1 Landsat pixel). Small and narrow meadows with limited 30-m pixel overlap should be analyzed with caution. Mean NDVI statistics were provided for relative change monitoring.

Data Processing

Normalized Difference Vegetation Index (NDVI) was used as the proxy for meadow vegetation state. NDVI is representative of vegetation greenness or vigor and is based on the visible-red and near-infrared spectral bands (eq. 1). NDVI ranges from -1 to +1, with higher values indicating healthier vegetation.

$$NDVI = (NIR - Red) / (NIR + Red) \qquad \text{eq. 1}$$

NDVI was calculated for all pixels in each Landsat image. Composite end-of-season reflectance images were calculated by taking the median August-September pixel value for each year from 1984-2019. Summary zonal statistics for each meadow were calculated on the yearly median composite images. It is important to note that satellite based NDVI represents all surfaces within the image pixel and differs from NDVI measured at the plant leaf/tissue level. Mean NDVI of all pixels within the meadow represents bulk vegetation vigor and greenness of the system. In general, meadows with higher mean NDVI are greener and contain more plant biomass than meadows with lower NDVI values; however, natural spectral differences related to vegetation diversity, areas of un-masked open water (e.g. streams, ponds) or bare ground, soil types, and hydrology make direct comparisons or threshold style scoring potentially misleading.

In order to overcome bias due natural spectral differences, temporal trend and temporal variability statistics were utilized to assess all meadows throughout the basin. Temporal trend represents the overall activity and direction of meadow vegetation greenness in time (i.e. stable, increasing, or decreasing). Temporal variability (i.e. volatility) represents the range of values in time and is related to the meadow's sensitivity to interannual climate variability. Analyzing trends and anomalies gives temporal context to current conditions and provides a relative measure of state. In addition to greenness, the standard deviation of NDVI pixels throughout each meadow was calculated to characterize spatial homogeneity. Spatial homogeneity or uniformity can be considered a metric of hydrologic connectivity between the vegetation and the shallow groundwater.

Statistical Testing

Trends were assessed using the Mann Kendall non-parametric trend test to determine significantly increasing, decreasing, and stable systems. When applied to temporal datasets, the Mann Kendall trend test measures monotonically increasing and decreasing patterns with no assumption about the underlying distribution (Mann, 1945). Mann Kendall significance levels were adjusted for temporal autocorrelation using techniques proposed by Hamed and Rao (1998). All autocorrelation adjustments were implemented at the 95% confidence threshold. The non-parametric Theil-Sen slope estimator was utilized to determine the rate of change for each significant trend. Analyzing trends and anomalies gives temporal context to current conditions and provides a relative measure of state and variability (Theil, 1950; Sen, 1968).

Meadow Analyses

Meadow vegetation responds to both regional drivers (e.g. precipitation, temperature) and local drivers (e.g. fire, grazing, restoration). Identifying anomalous vegetation response or sensitivity outside of longer synoptic climate signals is important for management and monitoring of meadow state. The first set of analyses focused on basin-wide changes in vegetation vigor over the Landsat period of record (1984-2019). The basin wide mean NDVI was determined for each year as the mean NDVI of the 315 individual meadows for that year. All meadows were weighted equally, regardless of area or pixel count. Average basin-wide standard deviation was calculated for each year as the mean of the 315 individual meadows NDVI standard deviation for that year.

Individual meadows were examined using the annual observed values of NDVI. The temporal variability of the meadow was assessed using the root mean square error (RMSE), which is equivalent to the standard deviation of the observations around the trend line. To avoid potential bias and influence of outliers, the trend line was defined by the Theil-Sen slope (*m*) with the intercept (*b*) defined as the median value of ($y_i - mx_i$) for each pair of points (x_i, y_i) in the time series. In addition to the observed values, we adjusted observed NDVI to account for interannual climate variability following the method presented by Albano et al., (2020), which correlates NDVI in riparian areas throughout Nevada to the standardized precipitation evaporation index (SPEI; Vicente-Serrano et al. 2010). SPEI is a drought index that considers the difference between precipitation (PPT) and potential evapotranspiration (PET) at different timescales. Albano et al. (2020) determined timescales on the basis of EPA level IV ecoregion (US EPA 2019); the Tahoe basin falls into ecoregion 5c (Northern Sierra upper montane forests) and the SPEI timescale with the greatest correlation to late summer NDVI is November-May (Albano et al. 2020). SPEI is determined by summing the cumulative difference between PPT and PET over that time period for each water year and applying a non-parametric standardization (Farahmand and AghaKouchak 2015) to the time series. The SPEI time series was calculated individually for each meadow and regressed against the NDVI percent difference from mean (Eq. 2), where *NDVI* is the observed annual value in a meadow and $\overline{NDVI}$ is the mean of the annual NDVI values for that meadow over the period of record. When NDVI and SPEI were correlated (α=0.05), a meadow-specific multiplier *m* was determined using simple linear regression, and the annual values of NDVI were adjusted by $m(SPEI)(\overline{NDVI})$. Time series of adjusted NDVI values were examined similarly to the raw time series.

$$\text{Percent difference from mean} = \frac{NDVI - \overline{NDVI}}{NDVI} \qquad \text{eq. 2}$$

Meadows were compared to one another using basin-wide percentile rankings. The ranking was applied to yearly end of season mean NDVI to consider long-term trends in meadow vegetation relative to other meadows and to remove longer-term synoptic climate signals common to the entire basin (i.e. declimatize). Percentile ranking effectively normalizes the dataset allowing for identification of anomalous patterns relative to the average basin benchmark signal. Percentile rankings were also analyzed at a range of timescales.

Trends in each meadow were assessed at multiple timescales (last 10 years; 20 years; and the full period of record) using the Mann-Kendall tests described above. While data for all three timescales are provided in the accompanying data package, the examples discussed in this report focus primarily on the full period of record. Shorter time period analyses should be assessed in terms of the longer record and utilized only when distinct breakpoints (e.g. fire event) or temporal patterns (e.g. increase/decrease) result in biased and skewed results.

RESULTS AND DISCUSSION

Basin-wide Increases: Global Greening and Synoptic Climate Signals

Throughout the Tahoe Basin, the mean end of season meadow NDVI exhibits an increasing trend from 1984 to 2019 with an NDVI increase rate of 0.0025 per year (Figure 3).

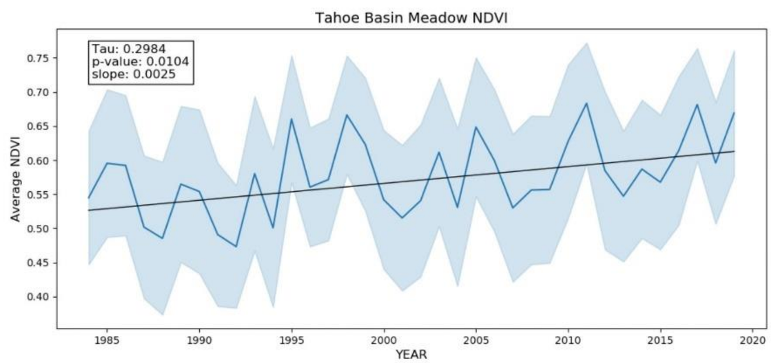
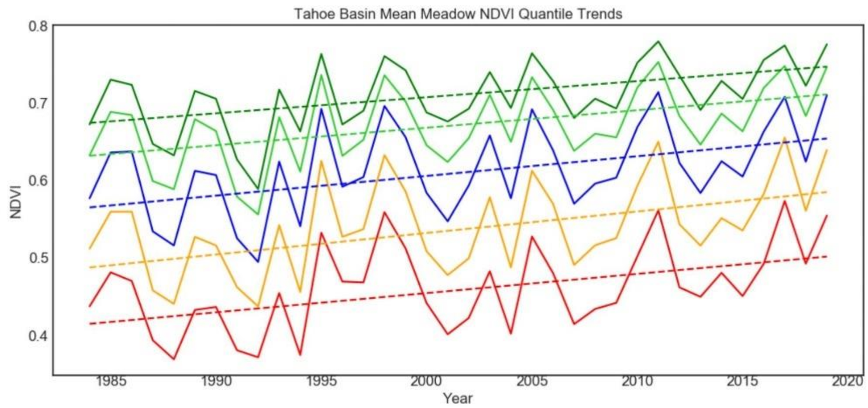


Figure 3: 1984-2019 average Tahoe Basin meadow NDVI time series. The blue line shows mean meadow NDVI, light blue shading represents +/- 1 standard deviation, and the black line is the Theil-Sen trend line.

Furthermore, an analysis of trends at multiple NDVI quantiles shows that meadows with relatively high and low mean NDVI are increasing at similar rates (Figure 4). Similar patterns throughout the entire range of NDVI indicates that observed NDVI increases are independent of vegetation vigor and that both wet and dry meadows are potentially responding to the same regional drivers.

The increasing trend holds even after adjusting NDVI values for interannual climate variability (Figure 5). Interannual variability in NDVI is driven in part by differences in annual precipitation (i.e. snowpack) and summertime temperatures (Albano, 2019). In the Tahoe Basin, the majority of water year precipitation falls during the winter and spring as snowfall, with late spring and summertime melt serving as the main water supply mechanism for meadow vegetation. The climate adjustment based on November-May SPEI is designed to account for this year-to-year variability (Albano et al. 2020). During years with below average precipitation, meadows with shallow groundwater access are less susceptible to drought induced vegetation stress and exhibit less variable NDVI from year to year. Meadows without shallow groundwater access are more likely to become stressed during dry years and exhibit more variable NDVI.



	TAU	SEN SLOPE	P-VALUE
Q10	0.32381	0.00249	0.00546
Q25	0.30794	0.00278	0.00823
[illegible]	0.29524	0.00254	0.01129
Q75	0.31429	0.00227	0.007
Q90	0.33968	0.00208	0.00356

Figure 4: 1984-2019 Tahoe Basin meadow NDVI time series for the 10th, 25th, 50th, 75th and 90th quantiles. Dashed lines show significant Theil-Sen trends based on the Kendall Tau trend test.

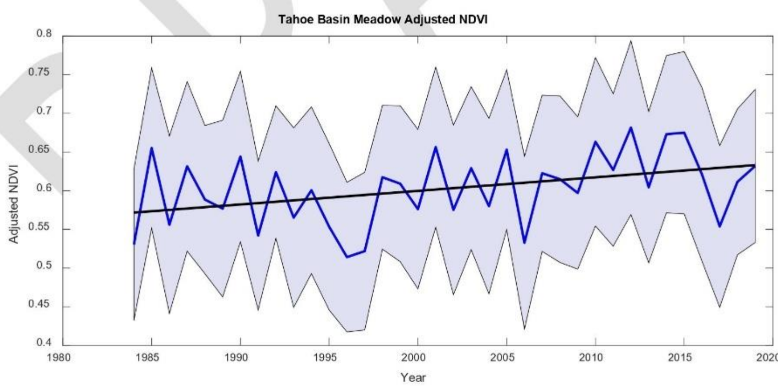


Figure 5: 1984-2019 average Tahoe Basin meadow adjusted NDVI time series. The blue line shows mean meadow NDVI, light blue shading represents +/- 1 standard deviation, and the black line is the Theil-Sen trend line.

The basin wide adjusted NDVI, however, increases more slowly than does the raw NDVI (0.0018 /year as opposed to 0.0025 /year), and correlation between the adjusted NDVI values and time is slightly weaker (tau=0.24; p=0.039) than for the raw values. The increasing trends in both raw and adjusted NDVI and the rate of increase in the raw NDVI signal are consistent with the 'Global Greening' phenomenon. Whereas the climate adjustment takes into account the availability of water and a changing growing season, it neglects other potential drivers of greening. Increased atmospheric CO2 levels and temperature caused by global climate change lead to increased plant photosynthesis and conversion of CO_2 to organic matter (Campbell, 2017; Emmett, 2019). Additional photosynthesis and CO_2 uptake increase vegetation structure and in turn NDVI and greenness throughout the meadow. A robust meadow assessment must take into account synoptic climate patterns and change to properly inform management and restoration planning.

Unlike mean NDVI, meadow NDVI variability (i.e. standard deviation of NDVI pixels throughout each meadow) shows no significant trend from 1984 to 2019 (Figure 5). The standard deviation (StdDev) of NDVI throughout each meadow is a measure of the spatial homogeneity of vegetation and can serve as a proxy for hydrologic connectivity. Meadows with high spatial dispersion contain pixels with both high and low NDVI values showing a combination of stressed and non-stressed vegetation. On the other hand, meadows with low spatial dispersion exhibit high connectivity with the majority of vegetation throughout the meadow experiencing similar stress/growth levels. It is important to note that low spatial dispersion can occur throughout the entire NDVI spectrum and is not necessarily indicative of healthy vegetation (e.g. all green pixels versus all brown pixels.). The lack of trend in spatial dispersion indicates that NDVI homogeneity is not sensitive to the same synoptic climate patterns as mean NDVI.

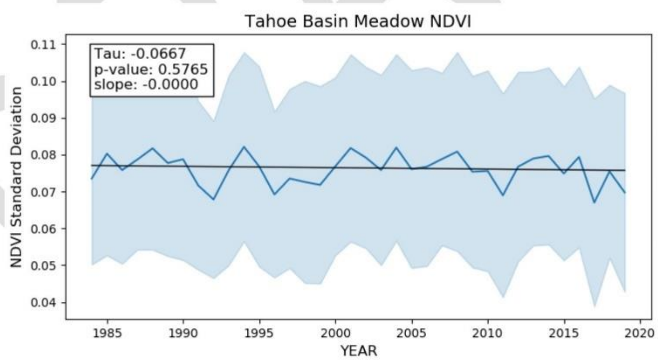


Figure 6: 1984-2019 average Tahoe Basin intra-meadow NDVI standard deviation time series. The blue line shows mean meadow NDVI standard deviation, light blue shading represents +/- 1 standard deviation, and the black line is the Theil-Sen trend line. Intra-meadow NDVI homogeneity shows no significant trend from 1984-2019.

The constant basin-wide spatial dispersion indicates that hydrologic connectivity in meadow systems does not appear to be changing significantly over time. Hydrologic connectivity refers to the access that vegetation has to shallow groundwater. Although it is difficult to quantify, hydrologic connectivity is a characteristic of healthy meadow ecosystems, and improved connectivity is frequently a goal for restoration work.

Individual meadows may change in ways that are inconsistent with the basin-wide trend. Figure 7 shows three meadows that deviate from that basin wide trend: one declining (Osgood Swamp); one stable (Paige Meadow); and one improving faster than the basin average (Cookhouse Meadow).

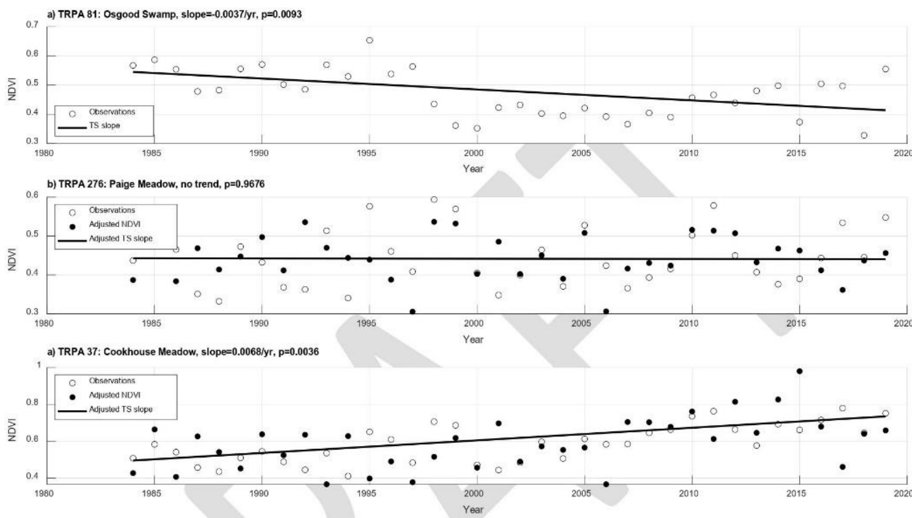


Figure 7: 1984-2018 observed and adjusted NDVI at three different meadows. In each plot, the open circles represent the observed NDVI. In (b) and (c), the filled circles represent adjusted NDVI values (Osgood swamp did not show a significant relationship between NDVI and SPEI, and thus was not adjusted). The heavy black line indicates the Theil-Sen slope in adjusted NDVI over the period of record.

It is critical to put analyses of individual meadows into an overall context. Trends that are seen in these individual analyses reflect the overall condition of the meadow, but do not differentiate between chronic (e.g. long-term climate change) and transient (e.g. fire or drought) drivers of change; nor do they differentiate between management-drive changes (e.g. restoration work, urban runoff effects) and changes that may be out of the control of resource managers.

Temporal Trends: Improvement, Decline, Stable

Because of the basin-wide trend in NDVI and the difficulty in isolating management-driven changes in NDVI, characterizing meadow NDVI as "improving, stable, or declining" is best accomplished through comparison with the basin-wide baseline. Trend in each meadow's mean NDVI percentile rank tracks change in relative greenness over time, while trends in NDVI StdDev track spatial homogeneity over time. Meadows with significant increases in NDVI rank are outperforming the basin average, while meadows with significant decreases in NDVI rank are under performing the basin average. Meadows without significant trends in NDVI rank are performing in-line with the basin average. NDVI StdDev trends are meadow specific and monitor the homogeneity of pixels throughout each system. Meadows with significant decreases in NDVI StdDev exhibit increased uniformity, while meadows with significantly increased NDVI StdDev exhibit decreased uniformity. Trends were assessed at 10-yr, 20-yr, and 35-yr (entire Landsat record) timescales using the non-parametric Mann-Kendall trend test. Multiple analysis intervals allow for evaluation of near-term, intermediate, and long-term patterns. Meadows are dynamic systems that experience fluctuations caused by both step changes and longer-term drifts and trends. Binning into three analysis windows allows for general basin-wide assessment. Meadows exhibiting anomalous characteristics due to changes not well captured by these windows should be analyzed at refined timescales using on-the-ground knowledge (e.g. restoration dates) and more detailed examination of time series datasets. The following section highlights examples of improving, degrading, and stable systems.

Improvement: Cookhouse Meadow

Cookhouse Meadow was recently restored, with construction spread in summer 2005 and summer 2006. The project included 2,400 feet of new stream channel designed to reconnect the stream with the adjacent floodplain (Oehrli et al. 2013). This project was designed to encourage periodic inundation of the floodplain, allowing it to play a more natural role in slowing flood flows and filtering sediments. Post-restoration assessments of the project have been generally positive (Norman and Immeker 2009; Oehrli et al. 2013), and the NDVI analysis shown below is consistent with those assessments.

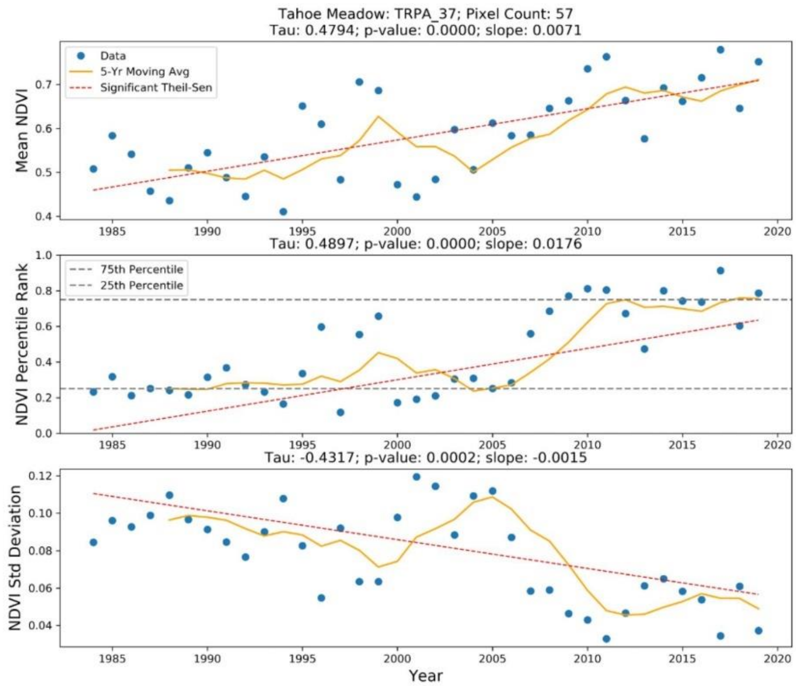


Figure 8: Cookhouse Meadow, restored 2005. Summary time series of mean NDVI, NDVI rank, and NDVI StdDev. Kendall Tau statistics are included for each subplot. Theil-Sen trend lines are shown in red for trends significant at the 95% confidence level.

Prior to restoration, the mean NDVI of Cookhouse Meadow consistently ranked in the lowest quartile of all meadows (Figure 7). After restoration, meadow NDVI ranks in the highest quartile. Furthermore, NDVI StdDev significantly decreased over this same time period. Post-restoration assessments documented both periodic overbank flows (increasing available water for meadow vegetation) and an increase in plant species indicative of a wet meadow condition (Oehrli et al. 2013) - both of these phenomena would contribute to the increased spatial homogeneity of meadow vegetation that is indicated by the decrease in NDVI StdDev.

Improvement at Cookhouse Meadow is even more apparent with the adjusted NDVI values (Figure 8). Pre-restoration (1984-2004), the NDVI is relatively consistent, with a Theil-Sen slope less than 0.001/year. After restoration began in 2005, however, that slope drastically changed, rising to a Theil-Sen slope of 0.006/year (more than twice the basin-wide average). A two-sided t-test shows that the pre- and post-restoration data shown in Figure 9 are significantly different from one another (p=0.0012). These changes are apparent in the adjusted NDVI data, but do not show up as well in the raw data shown in the top panel of Figure 8.

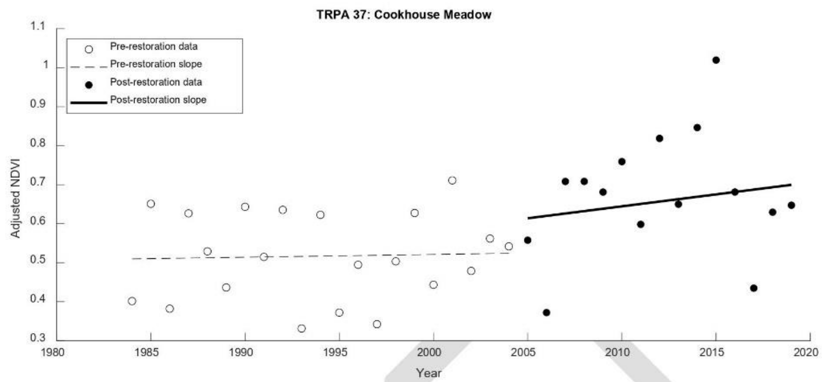


Figure 9: Adjusted NDVI over time at Cookhouse Meadow. Restoration began in 2005. Note the adjusted NDVI value greater than 1 in 2015 – this indicates that the meadow is much greener than expected based on the climate and historical mean NDVI.

<u>Degradation:</u>

Meadow TRPA 401 (no common name noted) appears to be stable based solely on the annual NDVI data (Figure 10 top; no significant trend). However, a comparison between that meadow and basin-wide trends indicate that it is not keeping pace with the regional trends (Figure 10 middle; significant decreasing trend). The simultaneous changes in both NDVI ranking and NDVI StdDev indicates a change in this meadow that is not being experienced by other meadows in the basin. The increased NDVI StdDev over time indicates an increasing spatial variability in greenness. This could be caused by a transient disconnection from the meadow's water source. A decreased connection to shallow groundwater is consistent with the increasing variability of the annual NDVI values over time, where the most extreme NDVI values - both positive and negative - occur in the last 15 years. The declining status of this meadow would not be apparent from a simple analysis of NDVI but is seen by these methods.

This is supported by an examination of the adjusted NDVI values (Figure 11). The adjusted NDVI values are widely scattered (the standard deviation of adjusted NDVI over time is in the 90th percentile of all meadows). The Theil-Sen slope shows a decline in adjusted NDVI over time, although the trend does not rise to statistical significance.

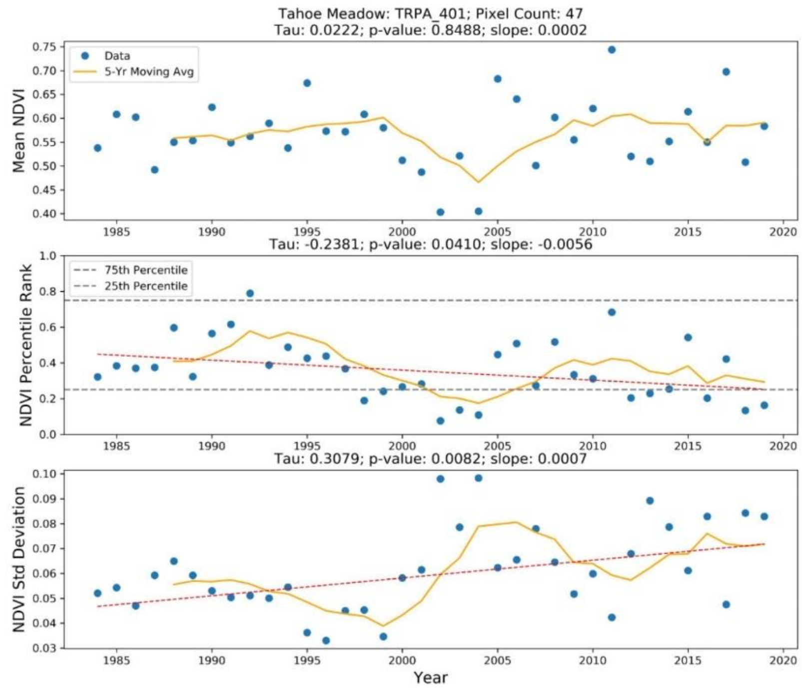


Figure 10: TRPA_401, an example of a declining meadow. Summary time series of mean NDVI, NDVI rank, and NDVI StdDev. Kendall Tau statistics are included for each subplot. Theil-Sen trend lines are shown in red for trends significant at the 95% confidence level.

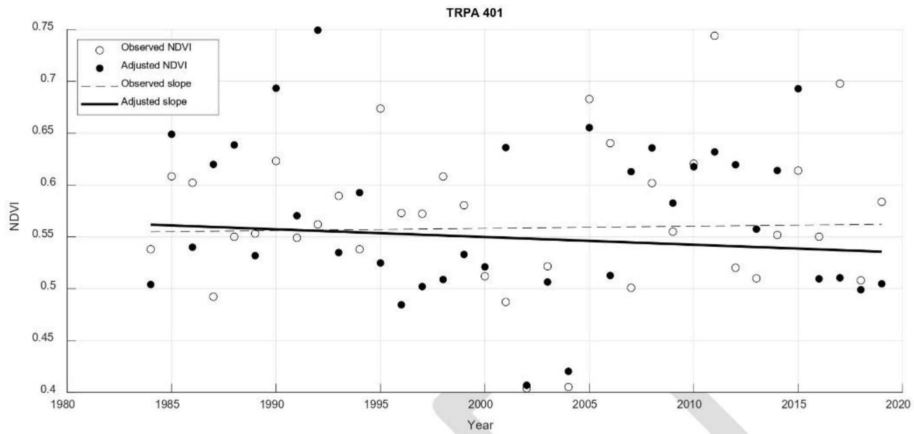


Figure 11: Observed and adjusted NDVI at TRPA 401. The dashed and heavy black lines represent the Theil-Sen slopes of the observed and adjusted NDVI values, respectively.

Stable Healthy: Antone Meadows 294

Like TRPA_401 above, Antone Meadow (Figure 12) appears to be stable from the annual NDVI data. Unlike TRPA_401, the relative ranking of NDVI and the NDVI StdDev are not changing significantly over time. This is consistent with reports from on the ground surveys, which indicate that Antone Meadow is both very wet and very healthy (S. Tevlin, Tahoe Regional Planning Agency, personal communication). Analysis of the adjusted NDVI values for Antone revealed similar results, showing no significant trend.

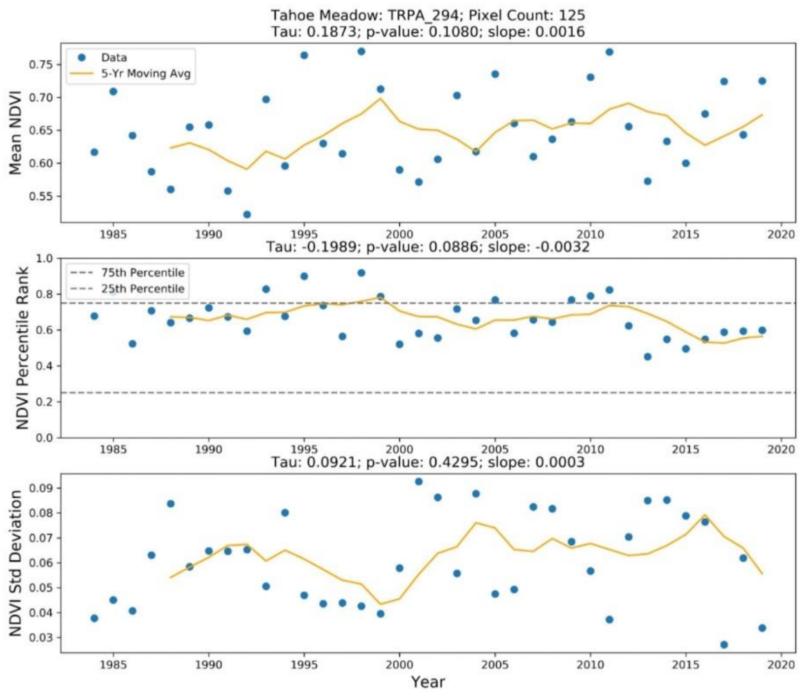


Figure 12: Antone Meadow (TRPA 294), an example of a stable healthy meadow. Summary time series of mean NDVI, NDVI rank, and NDVI StdDev. Kendall Tau statistics are included for each subplot. Theil-Sen trend lines are shown in red for trends significant at the 95% confidence interval.

Stable Healthy: Incline Lake Meadows 2 (TRPA_311)

Incline Lake Meadows 2 (Figure 13) appears from the NDVI data to be greening. However, an examination of the data in context indicates that its rate of NDVI increase is similar, but slightly below the rate of the basin as a whole. This is reflected in the percentile rank analysis, which shows that its rank is not changing significantly over the period of record. This is reflected in both the raw (Theil Sen slope in the meadow is 0.0019/yr vs. 0.0025 /yr for the entire basin) and adjusted NDVI data (meadow slope of 0.0016 /yr vs. 0.0018 for the entire basin). In addition to the fact that the meadow is greening at approximately the same rate as the basin, its standard deviation over time is showing a significant decline, indicating an increasingly uniform meadow. The combination of a slight positive trend in NDVI and adjusted NDVI, a stable percentile ranking, and a negative trend in NDVI standard deviation points toward a stable and healthy meadow ecosystem.

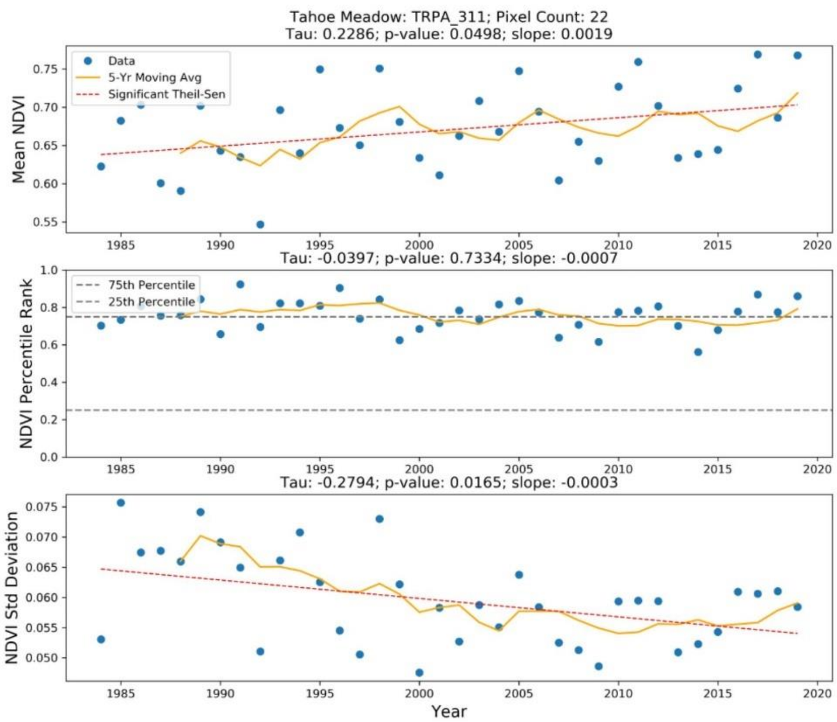


Figure 13: Incline Lake Meadows 2 (TRPA 311), an example of a stable healthy meadow. Summary time series of mean NDVI, NDVI rank, and NDVI StdDev for Incline Lake Meadows. Kendall Tau statistics are included for each subplot. Theil-Sen trend lines are shown in red for trends significant at the 95% confidence level.

Stable Healthy: Paige Meadows (TRPA 276)

Paige Meadow (Figure 14) has a mean NDVI of approximately 0.47 compared to the basin-wide meadow mean NDVI of 0.64 and a relatively low percentile ranking. However, Paige Meadow is classified as a dry meadow (S. Gross, US Forest Service, personal communication), and these lower values are expected. Whereas Paige Meadow exhibits more variability than do most meadows in the basin, with an RMSE of 0.099 compared to a basin-wide mean of 0.066, this discrepancy is consistent with Paige Meadow being a dry meadow rather than a meadow with perennial access to shallow groundwater. Due to this lack of access to perennial water supply, Paige Meadow is more sensitive to interannual variability in climate drivers. Despite the high interannual variability, the central tendency of the NDVI of Paige Meadow is stable over the period of record.

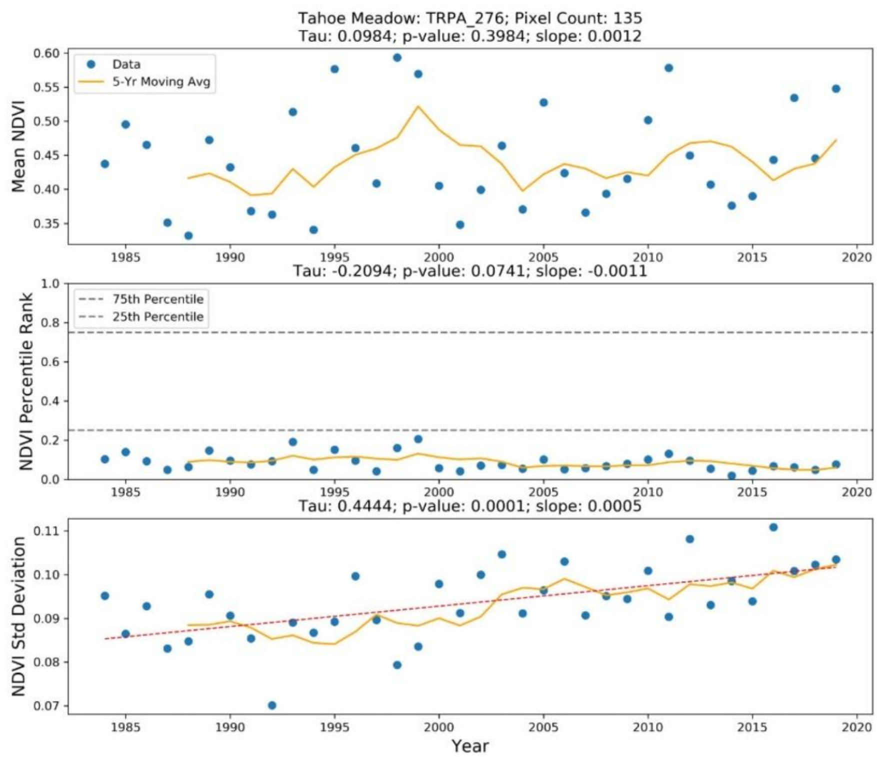


Figure 14: Paige Meadows (TRPA 276), an example of a stable dry meadow. Summary time series of mean NDVI, NDVI rank, and NDVI StdDev. Kendall Tau statistics are included for each subplot. Theil-Sen trend lines are shown in red for trends significant at the 95% confidence level.

Stable Healthy: TRPA_269

This unnamed meadow (Figure 15) has a consistently high late-season NDVI, with a ranking that remains in the upper quintile of the period of record. The adjusted NDVI is similarly relatively high and stable, but the slope is reduced by an order of magnitude and the p-value increased from 0.06 to 0.49, indicating that the meadow is stable after accounting for interannual climate variability. The NDVI StdDev is lower than the basin-wide mean standard deviation and is consistent over time, indicating persistent access to a source of water. This meadow appears from these metrics to be as stable and healthy as any in the basin.

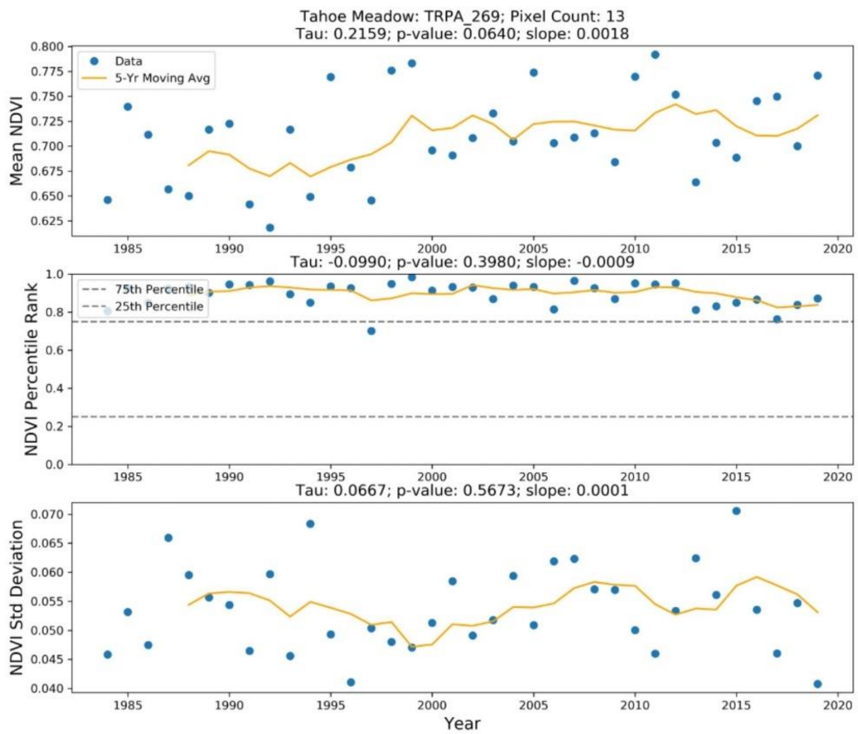


Figure 15: Unnamed Meadow TRPA 269, an example of a stable healthy meadow. Summary time series of mean NDVI, NDVI rank, and NDVI StdDev. Kendall Tau statistics are included for each subplot. Theil-Sen trend lines are shown in red for trends significant at the 95% confidence level.

Stable Degraded: Johnson Meadow

Johnson Meadows (Figure 16), which abuts Lake Tahoe Blvd. in South Lake Tahoe, is an example of a stable, but degraded meadow. Like Paige Meadow, it has a low mean NDVI and is highly variable, responding to variations in precipitation. However, Johnson Meadow has a channel running through it and is expected to function as a wet meadow rather than as a dry meadow. While it is temporally stable (the NDVI ranking and NDVI StdDev are both constant over time), the relatively low NDVI and higher-than-average standard deviation both indicate that it is significantly degraded from its ideal condition.

Figure 16: Johnson Meadows (TRPA 323), an example of a stable, degraded meadow. Summary time series of mean NDVI, NDVI rank, and NDVI StdDev. Kendall Tau statistics are included for each subplot. Theil-Sen trend lines are shown in red for trends significant at the 95% confidence level.

Temporal Variability: Climate Sensitivity

Temporal variability was assessed using a Theil-Sen based root mean square error (RMSE) of each meadow's late-summer NDVI time series. Meadows that exhibit higher spread in NDVI residuals show larger response to interannual climate differences. Monitoring residuals about the Theil-Sen trend line accounts for significant linear trends within the analysis window. Similar to spatial variability, temporal variability statistics can exhibit similar signals for naturally brown and green systems and should be considered in the context of other metrics including overall greenness (i.e. mean NDVI) and field assessments. For example, a drier system with relatively brown vegetation during both wet and dry years will show similar variability to a consistently green system.

Temporal variability is presented for all meadows over the period of record. Assessing temporal variability relative to the basin-wide distribution provides context to RMSE results (Figure 17). The 1984-2019 25th percentile, median, and 75th percentile RMSE values for all 315 meadows in the Tahoe Basin are 0.0431, 0.0530, and 0.0645, respectively. Meadows that fall in the highest quartile show greater interannual sensitivity than over 75 percent of meadows in the basin.

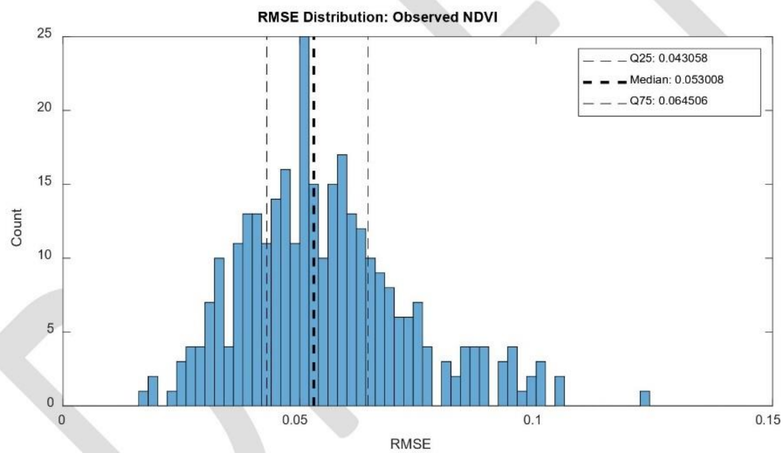


Figure 17: Histogram of Tahoe meadows NDVI Theil-Sen RMSE for the period of 1984-2019. Meadows with RMSE values below 0.0431 rank the lowest 25 percent NDVI temporal variability, while meadows with RMSE values above 0.0645 rank in the highest 25 percent.

This analysis is repeated for the adjusted NDVI values (Figure 18), with the values of the 25th, 50th, and 75th percentiles falling slightly differently due to the adjustment for interannual climate variability. The overall parameters of the distribution remain similar

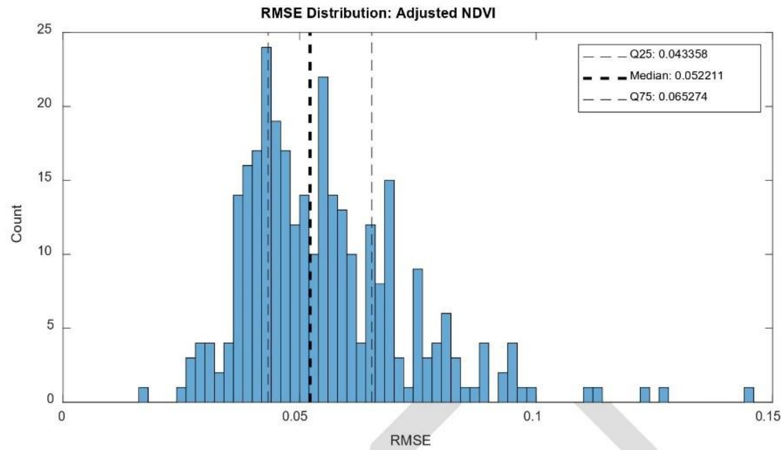


Figure 18: Histogram of Tahoe meadows Adjusted NDVI Theil-Sen RMSE for the period of 1984-2019.

Figure 19 shows Thiel-Sen residual time series for TRPA 323 (Johnson Meadow, described earlier as stable and unhealthy) and TRPA 66 (unnamed), which is adjacent to Echo Lake. The RMSE of Johnson Meadow (0.0803) is more than twice that of the unnamed meadow (0.0295), indicating much greater temporal variability. Whereas the vegetation in TRPA 66 is likely stabilized by the availability of water from the lake, the vegetation in Johnson Meadow is much more dependent on precipitation.

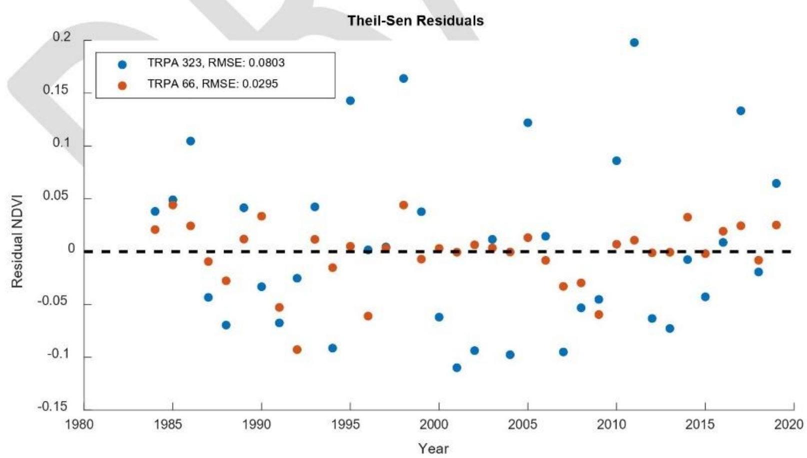


Figure 19: NDVI Theil-Sen residual time series plot. Meadows with higher RMSE values exhibit more year to year variability possibly caused by degradation and increased climate sensitivity.

The restoration of Big Meadow Creek in Cookhouse Meadow illustrates one potential application of this metric. Prior to restoration, the creek channel was severely incised, with vertical walls more than two meters high. Performed in 2005-2006, the restoration replaced 1,400 feet of existing channel with 2,400 feet of newly constructed channel, raising the stream elevation by 6-10 feet and reducing the elevation difference between riffles and top-of-bank (Norman and Immeker 2009). This work was designed to allow more frequent inundation of the floodplain and to enhance shallow groundwater storage in the meadow adjacent to the stream. The project was assessed two years (Norman and Immeker 2009) and five years (Oehrli et al. 2013) after completion, and both of those assessments judged that the project goals had been largely achieved. This judgment is supported by an analysis of the temporal variability of NDVI in Cookhouse Meadow.

Based on NDVI observations and trends in the NDVI ranking, Cookhouse Meadow was noted earlier as an improving meadow (Figure 8). Here, we break the time series of NDVI observations into pre-restoration (1984-2004) and post-restoration (2007-2019) subsets; 2005-2006 were excluded from this analysis, as the restoration work was performed during those years. A non-parametric Theil-Sen linear regression was determined for each subset of the data and the RMSE of each regression calculated (Figure 20). The pre-restoration RMSE 0.0829 was more than 50% greater than the basin-wide median RMSE of 0.0554; the post-restoration RMSE of 0.0545 was slightly below the basin-wide median. The changing RMSE indicates that the post-restoration Cookhouse Meadow is more consistent and less sensitive to the interannual variability of climate drivers. This is consistent with the on-site post-restoration monitoring, which noted increases in the elevation of shallow groundwater and an increase in vegetation associated with wet meadows (Oehrli et al. 2013).

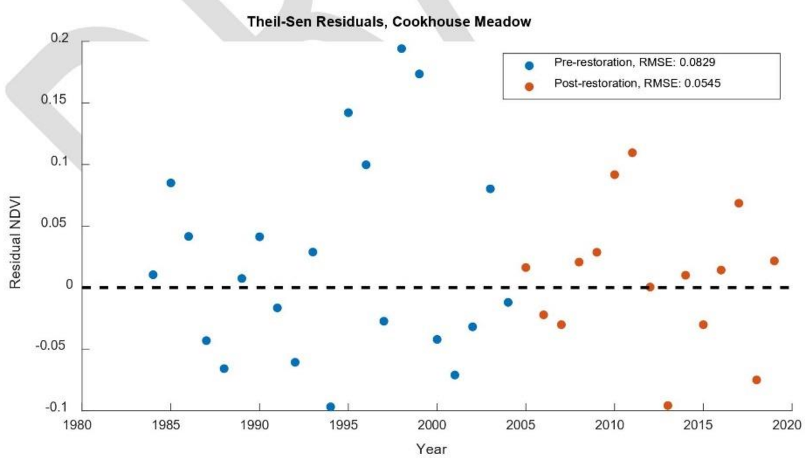


Figure 20: Cookhouse Meadow Thiel-Sen residuals for Pre-Restoration (1984-2004) and Post-Restoration (2007-2019) time periods.

Analysis of the Theil-Sen residuals can also be used to consider the influence of interannual climate variability on a meadow's vegetation. Two examples of this are shown in Figure 21. Fallen Leaf Meadows 3 (TRPA 141; Figure 21a) is located approximately 400 meters southeast of Fallen Leaf Lake, in a relatively undeveloped setting. The RMSE of the NDVI observations at TRPA 141 is 0.0645, approximately 20% higher than the basin-wide median. After adjusting for interannual climate variability, however, the RMSE of the adjusted NDVI time series is 0.0381, more than 20% lower than the basin-wide median. Interannual climate variability plays a greater role in controlling the NDVI of this meadow than it does in most of the basin.

This contrasts to TRPA 197, an unnamed meadow near Zephyr Cove. This meadow is in a natural drainage and extends to just 60 meters from the shore of Lake Tahoe, but it is also bisected by a 4-lane highway (US 50) and includes a boardwalk that allows pedestrian access to the meadow area. The observed RMSE is 0.040, less than the basin-wide median, but the climate-adjusted RMSE jumps to 0.085, 60% more than the climate-adjusted median RMSE. In this case, year-to-year changes in the meadow NDVI appear to be driven largely by changes other than climate. Urban runoff and relatively intensive land use may be affecting this meadow.

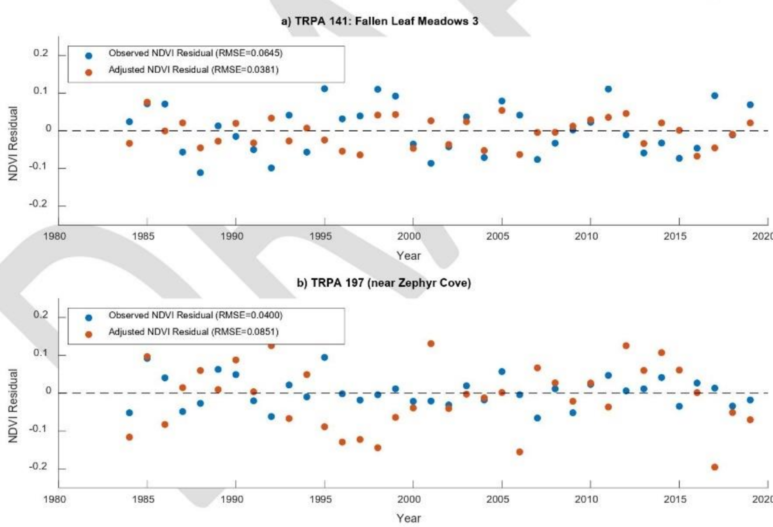


Figure 21: Theil-Sen residuals for (a) TRPA 141, Fallen Leaf Meadows 3 and (b) TRPA 197, an unnamed meadow near Zephyr Cove.

Cumulative Distribution Visualization and Skew

In addition to trend and variability analyses, methods were developed to visualize each meadow's underlying pixel distribution throughout time. Cumulative Distribution

Function (CDF) plots (Figure 22) allow for visualization of both the magnitude and distribution of end-of-summer NDVI. The bounded nature of NDVI (-1 to +1) leads to non-symmetrical distributions (i.e. non-normal) as the system trends towards minimum and maximum greenness levels. The skewness statistic measures the symmetry of a dataset and describes the direction of the dataset's tail (i.e. right vs. left; positive vs. negative). In general, meadows with negatively skewed NDVI distributions (Figure 22c) exhibited more uniform greenness at the higher end of the distribution, while meadows with positively skewed distributions (Figure 22a) exhibited less uniform greenness at the low end. A uniform greenness at the upper range of the distribution (negative skewness) indicates a meadow where most of the vegetation has access to a similar amount of water, and the outliers are the more water stressed plants. In contrast, a positively skewed meadow has mostly water-stressed plants, and the outliers are those greener plants that have greater access to water.

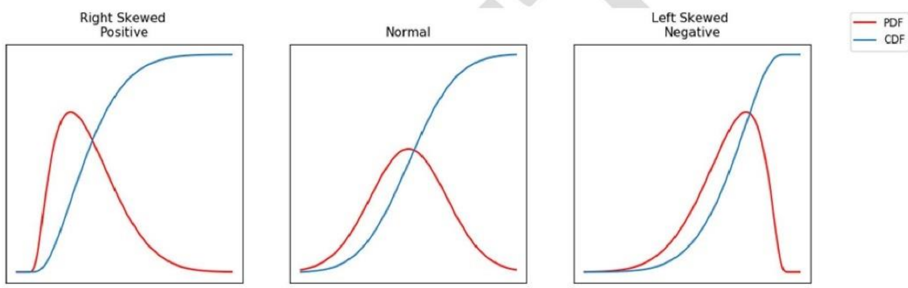


Figure 22: Example figure demonstrating positive, normal, and negative skew CDF and PDF plots:

NDVI CDF plots reveal additional detail about the vegetation coverage and signals captured within each meadow polygon. Tracking the distribution over time can help identify intra-meadow patterns related to climate sensitivity and vegetation change that may not be observed with bulk-averaging statistics (e.g. mean, median, StdDev) across an entire meadow. Figure 22 demonstrates right, normal, and left skewed curve shapes for both probability distribution (red) and CDF (blue) plots.

Positive-skewed Distribution (right)

- Mean > Median
- Outliers tend to be on the high-end
- Most pixels fall on the lower end of NDVI values within the meadow

Normal Distribution (center)

- Mean = Median
- Outliers may fall on either end
- Most pixels fall near the mean NDVI value of the meadow

Negative-skewed Distribution (left)

- Mean < Median
- Outliers tend to be on the low-end
- Most pixels fall on the higher end of NDVI values within the meadow

Figure 23 shows the average distribution of NDVI throughout Cookhouse Meadow before and after restoration. Prior to restoration Cookhouse exhibited consistent positive to neutral skew values with approximately 80 percent of its pixels having values below 0.58 NDVI. After restoration, Cookhouse Meadow shifted to a more left skewed distribution with over 80 percent of its pixel having NDVI values near and above 0.7. Monitoring distribution changes reveals significant shifts in NDVI magnitude throughout the majority meadow. Averaging statistics are susceptible to influence from outliers and may not identify impacts or changes that affect a smaller portion of the system.

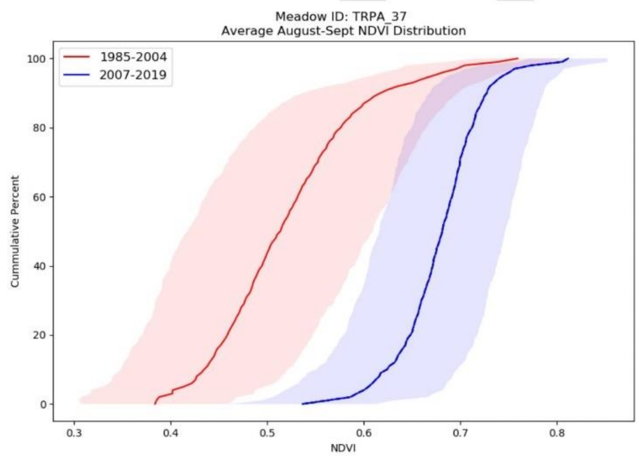


Figure 23: Average CDF plot of Cookhouse Meadow NDVI before (1985-2004) and after restoration (2007-2019). Shading represents ± 1 standard deviation. The pre-restoration NDVI distribution was consistently right and neutral skewed, while post-restoration NDVI values increased and exhibit more left skewed distributions.

In addition to before and after visualization, CDF plots can be utilized to monitor interannual fluctuations in magnitude and distribution. The top panel of Figure 24 shows the end of season NDVI distribution for Trout Creek (TRPA 148) from 1985-2019. Similar to Cookhouse Meadow, Trout Creek underwent restoration from 1999-2001. NDVI distribution within Trout Creek Meadow shows a clear pattern of change from right skew (positive) to left skew (negative) during this time frame. The accompanying time series of NDVI and Skew in the lower panel of Figure 24, confirms significant changes (positive trend in NDVI; negative trend in Skew) in the magnitude and distribution of vegetation vigor at Trout Creek.

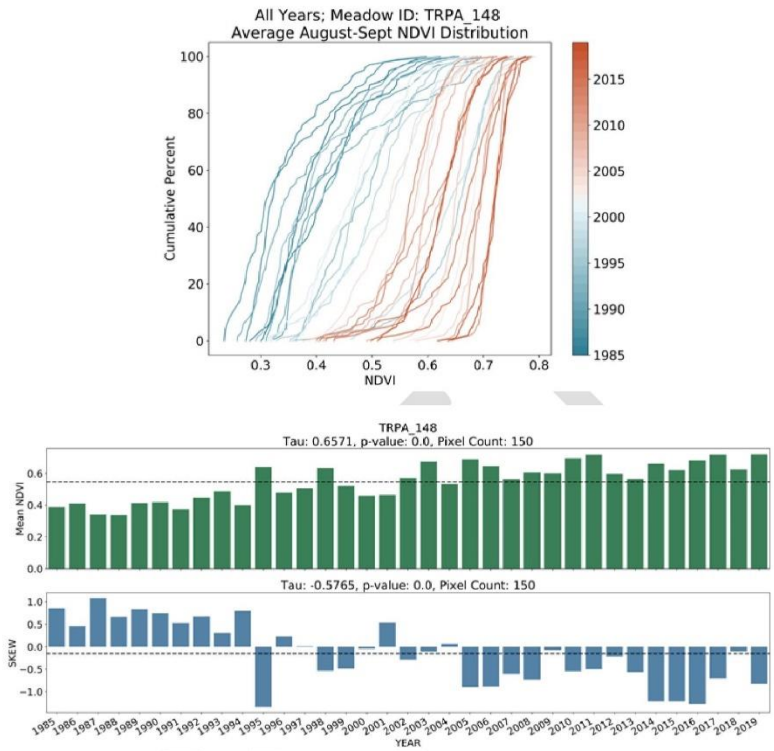


Figure 24: Top) Trout Creek (TRPA 148) CDF time series showing a consistent shift from right to left skew from 1985-2019. Bottom) Time series of NDVI and Skew showing the significant increase in NDVI and decrease in Skew from 1985-2019. CDF plotting allows for visualization of both the positive shift in NDVI as well as the underlying distribution change (i.e. right to left skew).

CDF plots can also give insight into the year to year temporal stability of meadows. Figure 25, demonstrates a a) stable left-skewed system, b) a stable right-skewed system, and c) a temporally variable system.

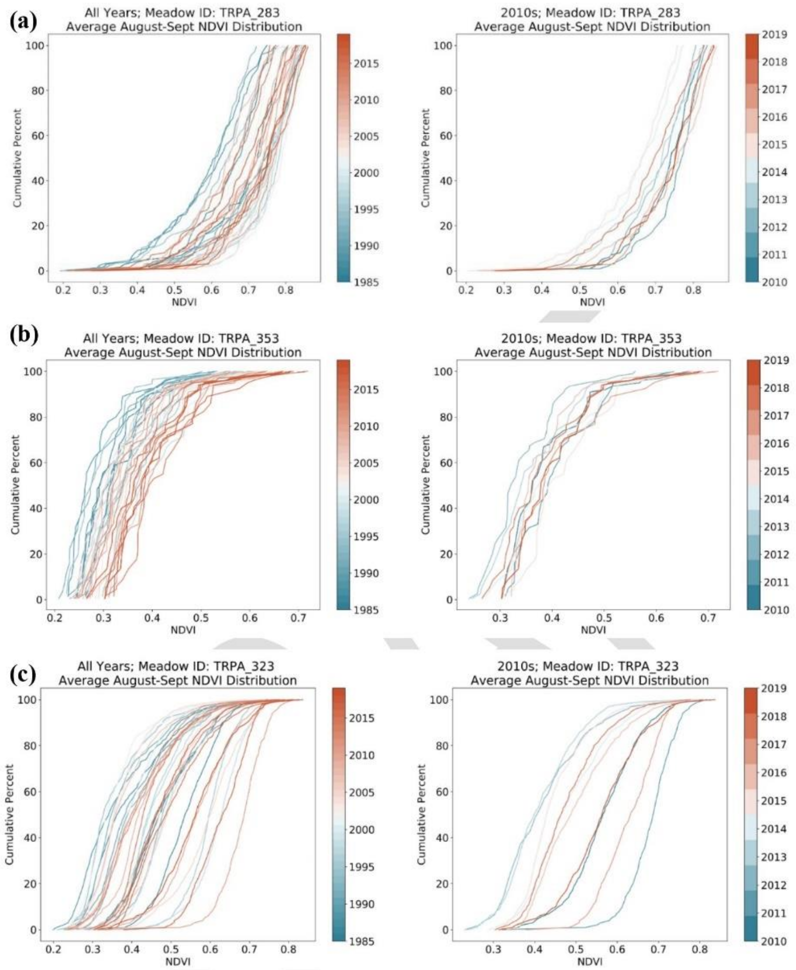


Figure 25: a) Example CDF plots of late season meadow NDVI for a) consistently left skewed NDVI distribution, b) example meadow with consistent right skewed, c) example meadow with highly variable NDVI distribution exhibiting both right and left skew throughout time. Plots in the left column cover annual statistics from 1984-2019. Plots in the right column cover annual statistics from 2010-2019.

CDF plotting supports visualization and analysis of multiple meadow properties including NDVI magnitude and distribution as well as temporal fluctuations. Analysts should use caution when interpreting distribution statistics for meadows with limited pixel counts (i.e. small sample size). Limited sample size reduces statistical power and can distort results. In cases with limited pixel count, users should rely on averaging statistics and trends for monitoring.

SUMMARY

This analysis provided a thorough exploration of the utility for satellite-based remote sensing to support mountain meadow management planning and decision making. Temporal and spatial statistics were applied to assess meadow vegetation state and trends within the Tahoe Basin. Results include basin-wide trends in meadow NDVI over time, as well as meadow-specific NDVI trends presented in terms of individual meadows and in comparison, to the rest of the basin.

One of the primary values of this methodology is the ability to visualize and quantify trends over time. These trends still need to be interpreted in the context of the meadow's history and the physical processes causing the changes, and a remote sensing analysis is not a substitute for on the ground site visits. These methods, however, can add valuable quantitative data to the information collected through on-site surveys. Remote sensing analyses can be particularly effective in (a) quantitatively evaluating a hypothesis formulated based on site visits, or (b) identifying trends or changes that are not yet apparent in surveys.

Finally, the inter-meadow rankings represent a potentially important management tool to help prioritize limited resources to achieve intended management goals. Understanding how meadows are behaving relative to one another will allow managers to make better informed decisions on these questions and to allocate resources in a way that most effectively reflects desired outcomes.

NEXT STEPS AND RECOMMENDATIONS

The above analysis identified remote sensing workflows capable of supporting mountain meadow restoration and monitoring efforts within the Tahoe Basin. We recommend continued data exploration and collaboration with agencies and stakeholders to combine and fuse on-the-ground field and remote sensing-based datasets. Areas for improved application and analysis could include:

- Automated processing and annual updates
    - Current analysis workflows require manual updates of satellite datasets and rerunning of trend analysis and summary statistics workflows. Automation and database storage of results would provide users with consistent and timely access to updated datasets and statistics
- Refine results based on 2019 field assessments
    - TRPA completed an extensive field survey of the majority of Tahoe Basin meadows during Summer of 2019. Combining field knowledge with historical spatial and trend information will give insight into monitoring capacity and limitations.
- Complementary analyses with higher resolution platforms should be performed, however, limited temporal coverage may limit regression and trend-based analyses.
    - Landsat: 1984-present, 30m, 8-16 overpass frequency
    - Sentinel-2: 2015-present, 10, 3-5 overpass frequency

- Change Detection and Temporal Segmentation
    - GEE has recently released an automated application of LandTrendr change detection algorithm (Kennedy et. al, 2018). Combining temporal segmentation approaches with trend analysis can give further insight into disturbance breakpoints and help refine analysis windows.

ACKNOWLEDGEMENTS

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Before DRI was able to process NDVI data for all Tahoe meadows, meadow polygons had to be cleaned up. This process undertaken by TRPA is described below.

Data clean-up for calculating NDVI: There are a few important parts of the methodology to determine NDVI. First, conifers in meadows give off a different signal than herbaceous meadow vegetation. This can create unwanted noise in the signal NDVI gives off for a meadow. To eliminate unwanted noise, large areas of conifers were removed from the meadow area for NDVI calculation, and all meadows were buffered in 10 meters to eliminate conifers on the edge of the meadow. An analysis was conducted to determine the impact of small areas of conifers on meadow NDVI scores. The analysis found that in general small areas of conifers do not significantly impact the overall LANDSAT based meadow NDVI scores if the conifers are dispersed and encroaching on a relatively small portion of the meadow.

Figure 80: (Left) The polygon delineated to calculate NDVI excluding conifers encroaching into the meadow. (Right) The polygon delineated to calculate conifers including conifers encroaching into the meadow.

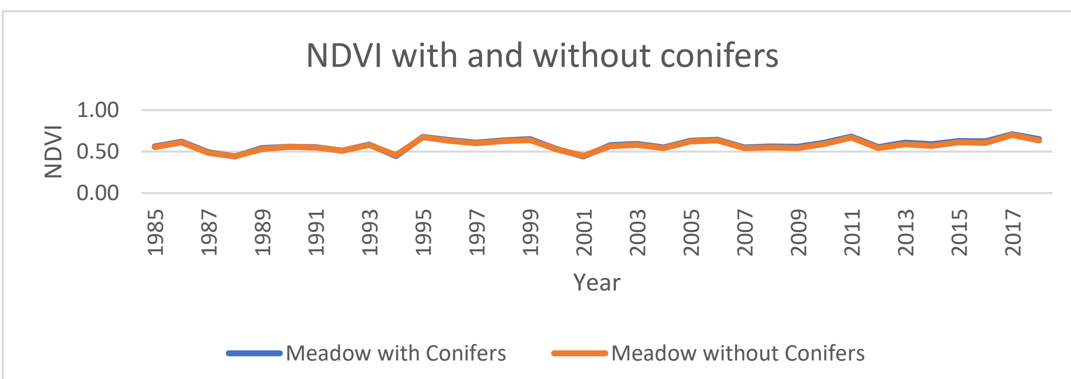

Figure 81: Data shows that there is little to no difference in calculated NDVI when conifer encroachment is sparse.

Similar to conifers, standing water gives off a skewed NDVI value and therefore can greatly change total NDVI values. Several areas at Lake Tahoe contain standing water all summer when Lake Tahoe is high and are very dry when Lake Tahoe is low. Areas like this include Baldwin Marsh, Taylor Creek marsh, and sections of the Upper Truckee Marsh among other places. These areas show substantial differences in NDVI values based on the level of Lake Tahoe. Therefore, NDVI values can be highly correlated to naturally fluctuating lake levels and flooded marshes can give off negative NDVI values. Where standing water is regularly present, NDVI based measures of condition need to account for the presence of water. Consequently, areas of standing water were eliminated from NDVI analysis.

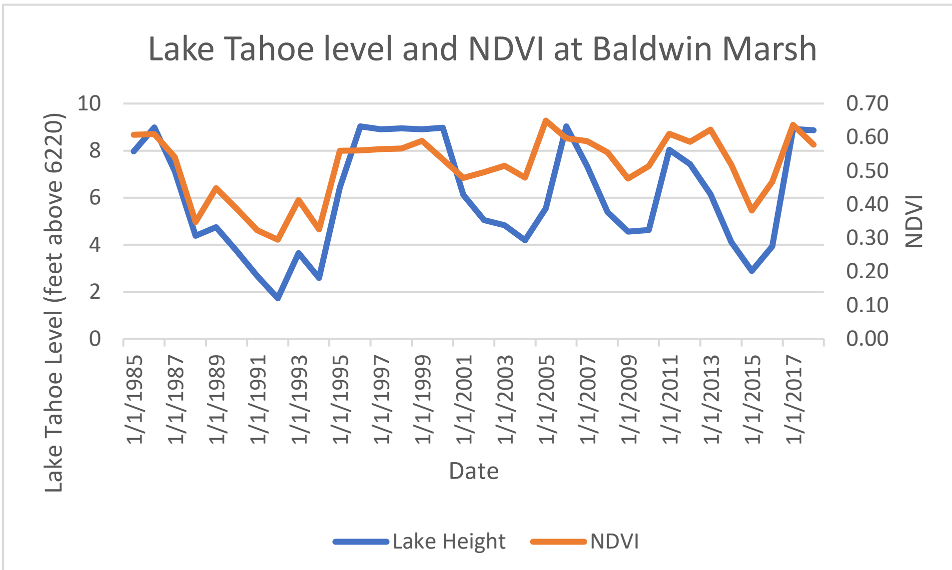

Figure 82: Data shows strong correlation between lake level and NDVI at Baldwin Marsh. Because Baldwin Marsh floods at high lake levels and is dry at low lake levels, NDVI based indicators need to account for the presence of standing water.

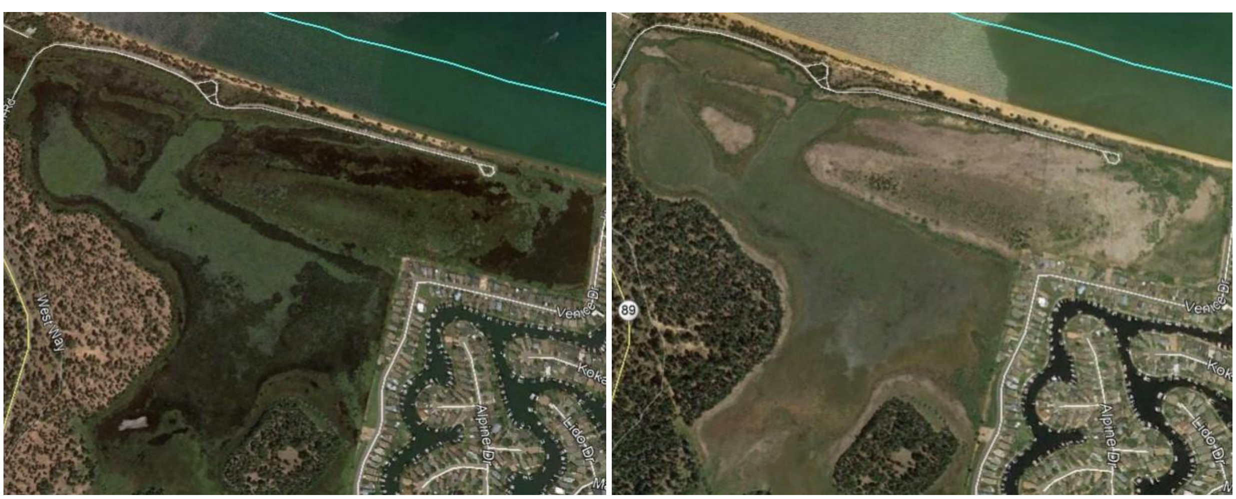

Figure 83: (Left) Baldwin Marsh flooded at high lake levels. (Right) Baldwin Marsh dry at low lake levels.

APPENDIX 7: Identifying riverine systems formed in alluvial soils

BALANCE HYDROLOGICS, Inc.

MEMO

To: Sean Tevlin (Tahoe Regional Planning Agency)

From: Jack Jacquet, Zan Rubin, and Dave Shaw, P.G.

Date: June 11, 2017

Subject: SEZ Alluvial Reaches Desktop Identification

Balance Hydrologics was tasked by the TRPA to help identify alluvial channel reaches that may be susceptible to incision and could potentially be included in the Stream Environment Zone (SEZ) Monitoring Program currently under development by TRPA. The program is designed to asses the status and trends of streams and riparian corridors over time. The work described in this memo consisted of a desktop exercise using publicly-available spatial data, and it is understood that TRPA and/or others will perform field verification. The following sources of data were used to perform this analysis:

- 2015 Stream Environment Zones (SEZs) (Spatial Informatics Group)
- 2010 Tahoe LiDAR (Tahoe Regional Planning Agency and U.S. Geological Survey)
- 2007 Tahoe Soil Survey (USDA Natural Resource Conservation Service)
- 2005 Geologic Map of the Lake Tahoe Basin (California Geological Survey) (Due to inconsistent projection of the map units, the geologic map was only used for visual verification.)

Characteristics of Alluvial Soils

Geologic composition of the channel bed, channel banks, and floodplain is one of the most important characteristics to consider when developing a monitoring program. Reaches prone to incision are composed of material capable of being transported by the stream, such as alluvium. Alluvium is characterized by unconsolidated material composed of moderately to poorly sorted sand, silt, gravel, and/or cobbles that were deposited in relatively recent geologic time by a stream. In contrast, a bedrock-controlled channel will not have the same susceptibility to erosion or incision. In general, bedrock in the Tahoe Basin is comprised of erosion-resistant rocks such as granitic rocks on the southwest, south and east side of the Basin and extrusive volcanic rocks such as andesite or basalt typically located on the west and north sides of the Basin.

Procedure to Identify Alluvial Channel Reaches

For this study, a digital elevation model developed from the 2010 Tahoe LiDAR was used to create a slope map of the Tahoe Basin at 3-meter resolution. Since alluvial channels typically exist in low-gradient depositional zones, cells in the raster with slopes less than 5-percent were identified, extracted, and then converted to polygons. Previously mapped SEZs (by SIG (2015) plus a 100-foot buffer were removed from the polygons with less than 5-percent slopes. This prevented us from duplicating the mapping results of SIG (e.g. we did not want to select meadow-fringe areas). A similar approach was taken with the NRCS alluvial soil areas. Existing mapped SEZs by SIG plus a 100-foot buffer were removed from the areas of mapped alluvial soils. The riverine (confined channel) SEZ were then intersected with the less than 5-percent slope and alluvial soils polygons to identify alluvial channel reaches that may be incised or suspectable to incision. Extremely small areas (<1000-square-feet) were removed from the shapefile.

Finally, the identified alluvial channel reaches were visually inspected against aerial imagery, hillshades, and geologic maps. Those reaches that were found to be reasonable given the setting and locations have been retained and are now being transmitted to TRPA for review and eventual field verification.

Results

We identified 89 riverine SEZs within potential and previously unmapped alluvial zones, totaling approximately 100 acres within the Tahoe Basin. This area sites represents low-gradient alluvial zones crossed by mapped riverine SEZ reaches as described above. Sites are grouped based on sub-watersheds, similar to the approach that SIG used for its riverine SEZ layer.

If you have any questions or would like to discuss these results further, please don't hesitate to call or email us.

Enclosures: Shapefiles: Potentially_impacted_alluvial_channel_reaches
5_percent_slope_areas_SEZ_removed
NRCS_Alluvial_Soils_SEZ_removed

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