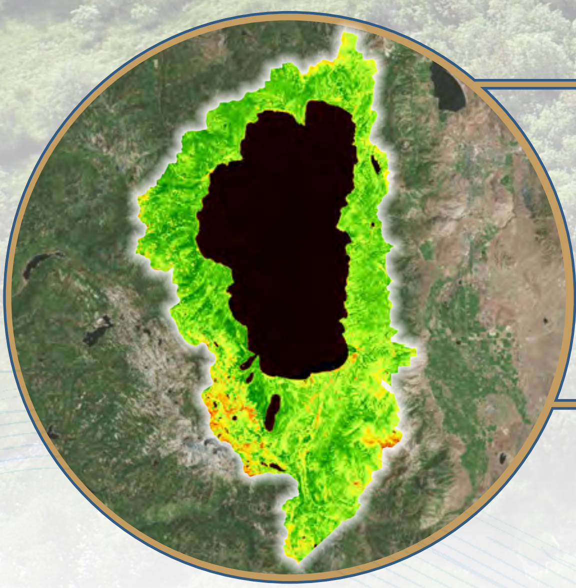

Preliminary Application of Using Landsat to Prioritize & Assess the Effectiveness of Meadow Restoration

March 2016

2NDNATURE
ecosystem science + design

This work was performed by 2NDNATURE, LLC with funding from the US Army Corps of Engineers, Sacramento District, and assistance from the California Tahoe Conservancy.

For more information please contact:

2NDNATURE, LLC
500 Seabright Ave., Suite 205
Santa Cruz, CA 95062
(831) 426-9119
info@2ndnaturellc.com

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1 EXECUTIVE SUMMARY

Land mangers continue to struggle with finding technically defensible and feasible means to prioritize where investments will provide the greatest environmental return, and how to quantify and report the effectiveness of investments once actions are implemented. There is a collective desire to measure the ecosystem changes that are attributable to management actions, and this desire is a common requirement of funders, managers, and stakeholders to justify investments. The quest to monitor and track the environmental benefits specific to riparian and meadow restorations are no different.

This report describes a pilot study conducted by 2NDNATURE, LLC, with funding from the Army Corps of Engineers, Sacramento District and support from resource managers in the Lake Tahoe Basin, to use the rich catalog of Landsat imagery to assess the effectiveness of alpine and wet meadow restoration projects. To do this we used a remote sensing derived index called the Normalized Difference Vegetation Index (NDVI). NDVI is a well-known index that quantitatively indicates the relative differences in "greenness" across a landscape. Higher greenness values, particularly when assessed during the late growing season when water availability is limited, are hypothesized to indicate a more functional wet meadow hydrology which in turn supports desired ecosystem services. We calculated the NDVI for riparian areas where restoration projects have been implemented to evaluate if distinct changes in meadow greenness can be detected and used as measure of restoration effectiveness.

Late summer mean site NDVI values from 1984 to 2015 were collected for nine current and past meadow SEZ (Stream Environment Zone) restoration projects in the south Tahoe Basin. For each project, precipitation-adjusted values sampled from years before the restoration were compared to precipitation-adjusted values sampled from years following the restoration. A number of clear shifts in NDVI values were documented. A simple linear regression method based on pre-restoration NDVI value and water year precipitation totals was used to extrapolate what site NDVI values might have been for years post project had the restoration actually not occurred. These predicted NDVI values were compared to the measured NDVI values, and following effective restoration actions, the measured NDVI values for a site diverge upward from the predicted values, clearly indicating the influence of management actions.

All nine of the completed restoration sites analyzed illustrate a precipitation-adjusted shift in NDVI values following restoration. Furthermore, the data show that prior 10-month cumulative precipitation can be a strong predictor for NDVI. This analysis demonstrates that mean site NDVI values sampled during the late growing season can be a useful comparative metric for assessing the relative effectiveness of restoration actions in montane wet meadows. Annual or biennial re-assessments of these and other sites will continue to inform the performance of this metric as a means of quantifying the benefits of management actions.

A preliminary effort to spatially compare NDVI values from recent wet years and dry years to identify other potential high priority areas for meadow restoration in the Upper Truckee River and Trout Creek watersheds was conducted. While some results are presented, additional

resources are necessary to better develop and apply NDVI techniques to restoration prioritization approaches.

This pilot use of NDVI as a restoration effectiveness metric shows substantial promise; however, further investigation of a number of outstanding research questions along with field data verification would allow for substantial improvements and refinement of the methodology and analyses. Recommended next steps include: (a) testing and validating the radiometric precision of the data sources both spatially and across time; (b) pursuing a means to account and adjust for the presence of standing water in meadow image pixels; and (c) field verification of NDVI values with site specific measurements including the hydrological, geomorphic, vegetative and other biological conditions of existing sites. Additional funding would allow protocol refinement, validation of results and a more robust methodology to apply this invaluable dataset to prioritizing and tracking riparian restoration effectiveness.

2 INTRODUCTION

2NDNATURE continues to strive to identify technically defensible and cost effective approaches to measure and quantify the environmental benefits of land management improvements. This technical report summarizes the overwhelming promise of using remote imagery data (i.e., Landsat) as a cost effective and defensible data source to objectively assess the effectiveness of fluvial and meadow restoration efforts. While more work is needed, we believe a similar promise also exists to use this same data source to help prioritize where meadow restoration actions may have the greatest environmental return on investment. The availability, consistency and ease of processing and reporting the data to assess the integrated functional conditions of any meadow system makes this approach very compelling. This document shares initial results from a preliminary effort to meet a number of monitoring challenges associated with comparing, assessing and tracking meadow restoration conditions before and after restoration actions have been implemented.

This effort has been completed with limited resources provided by the Army Corps of Engineers, Sacramento District for application of these concepts to completed fluvial and associated meadow restoration projects within the drainage area of the Upper Truckee River Marsh in South Lake Tahoe, CA. The primary objective of this initial investigation was to evaluate the promise of using Landsat imagery and associated Normalized Difference Vegetation Index (NDVI) values as a reliable and cost effective performance measure to quantify and track fluvial and meadow restoration benefits and identify next steps to test and verify the approach.

2.1 Statement of Need

Land mangers continue to struggle with finding technically defensible and feasible means to prioritize where investments will provide the greatest environmental return, and how to quantify and report the effectiveness of investments once actions are implemented. There is a collective desire to measure the ecosystem changes that are attributable to management actions, and this desire is a common requirement of funders, managers, and stakeholders to justify investments. When land management changes, BMPs are implemented, or restoration actions are constructed with the intent of providing a myriad of environmental benefits, designing and implementing a proper monitoring scheme to isolate, with confidence, the change in the site conditions as result of the management actions is extremely challenging to do properly. These challenges are mostly attributed to: (1) a lack of focus on maximizing sampling precision to a level that minimizes sampling uncertainty in the results obtained pre- and post-implementation, (2) a fundamental deficiency in experimental design specifically oriented towards detecting changes over time, and (3) adequately controlling or accounting for seasonal or annual variability in the datasets obtained over the duration monitored. Numeric landscape modeling allows us to estimate system condition in places/times that are difficult or impossible to measure – e.g., in the future or at very large spatial scales. But such modeling is constrained by finite system understanding, predictive uncertainty, and high cost of operation. Analysis of satellite time-series is comparatively less limited by these factors.

The quest to monitor and track the environmental benefits of riparian and meadow restorations are no different. Riparian and meadow restoration actions are implemented to restore fluvial and ecosystem function and successful projects are intended to have a wide-reaching impact on physical, chemical and biological processes that support the resident ecosystem (Chambers et al. 2004). Fluvial restoration efforts typically involve some combination of geomorphic or hydrologic modifications in an effort to restore physical functions and processes. If successful, the benefits are expected to iterate through to restore surface and groundwater interactions, hydroperiods, floodplain interactions, sediment balance, and other elements. While each restoration effort will vary in specifics, a fluvial system with functional physical processes will lead to improved chemical processes and water quality improvements (2NDNATURE 2014), riparian and meadow vegetation transitions to more desired communities, and other habitat improvements that support the desired aquatic, terrestrial and other biotic communities (2NDNATURE et al. 2010). Recent research also suggests significant carbon sequestration benefits can be achieved by restoring degraded meadows into functional systems (Norton et al. 2011).

The challenges in measuring and quantifying the changes due to fluvial restoration actions include those mentioned above regarding designing and implementing experimental designs that can properly sample and compare pre- and post-restoration site conditions in a manner that minimizes the sampling error and constrains the inherent natural variability across seasons and water years. In addition, a fluvial modification may include significant site modifications during construction that prohibit re-occupation of the same pre-restoration monitoring locations in the post-restoration landscape. In all instances an extended delay is expected from restoration completion to the time at which the site geomorphology, vegetation and biological communities have reached their new equilibrium.

3 REMOTE SENSING DATA AND LINK TO MEADOW FUNCTION

3.1 Landsat and NDVI

The Landsat Earth-observation program was started in 1966 and is currently operated by the USGS and NASA. Over the past 40+ years it has launched 8 satellites, each with instruments on board to acquire multispectral imagery of the earth's surface. Original generations of Landsat satellites—Landsat 1, 2 and 3—collected images with a spatial resolution of 60 meter pixels. More recent generations—Landsat 4, 5, 7 and 8—collect images with a spatial resolution of 30 meters. While Landsat satellites have been orbiting and collecting images since the 1970s, the extent of their spatial coverage and the availability of historical imagery from the 1970s, '80s and '90s, varies by region and by satellite. Imagery from the 2000s through the present covers most places on earth. Most importantly, as of 2008, the entire Landsat data archive—images from the 1960s to the present—is available to the public free of charge (Woodcock et al. 2008).

In the Tahoe Basin, the Landsat 5 (1984-2013), LS7 (1999-present), and LS8 (2013-present) satellites provide continuous bi-weekly imagery from 1984 to the present. Each of the satellites collects data at the same spatial resolution (30m), and similar radiometric resolutions for the blue, green, red, and near-infrared spectral bands (B: 0.45-0.52μm, G: 0.52-0.60μm, R: 0.63-0.69μm, NIR: 0.76-90μm) making their data directly comparable and yielding a continuous 30+ year dataset (Loveland and Dwyer 2012).

Remote images of the Earth's surface are an incredible tool when it comes to tracking and viewing landscape changes over time, but an additional value in multispectral remote imagery lies in the fact that the spectral bands can be viewed and combined in ways that allow us to see landscape elements as we never could in simple red/green/blue fashion. One tried and tested product of spectral band combinations is the Normalized Difference Vegetation Index (NDVI) (Pettorelli et al. 2005). NDVI is a remote sensing-derived index that quantitatively indicates the relative differences in "greenness" across a landscape. NDVI is a defined ratio of the near-infrared and visible spectral bands from remote sensing imagery, such as that from the Landsat missions (or any imagery that collects images in unique blue, green, red and near-infrared bands). NDVI is calculated as: *NDVI = (NIR-RED)/(NIR+RED)*. Index values range from -1 to +1 where open water is the most negative, concrete, rock and bare ground are close to 0, and a lush, dense forest is close to +1 (FIGURE 1).

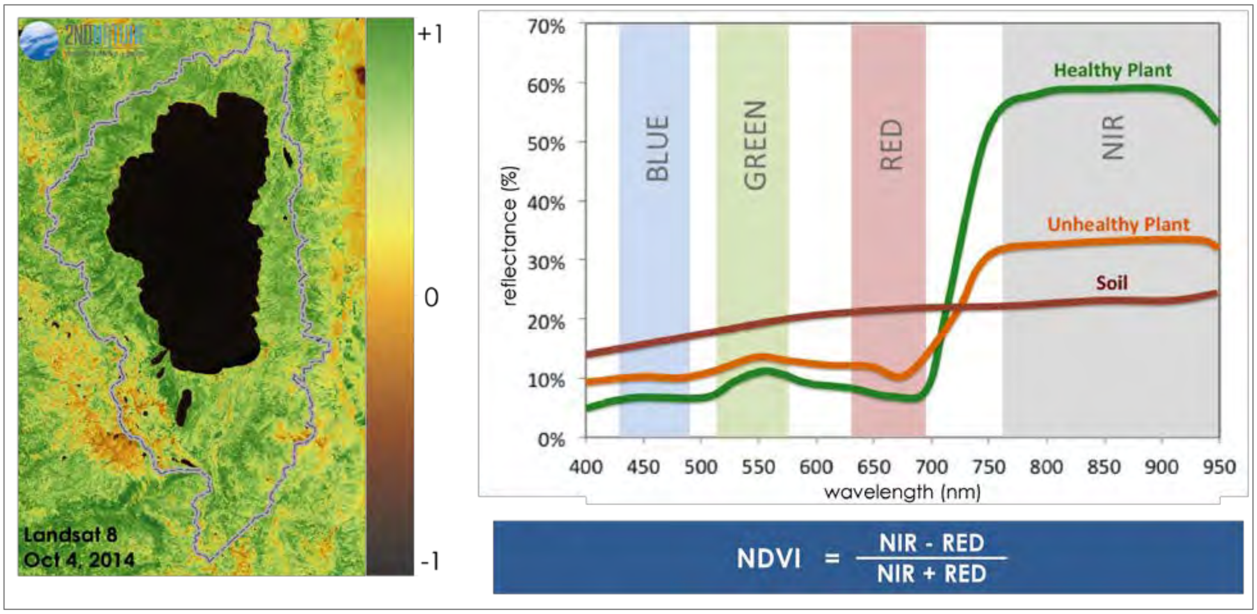
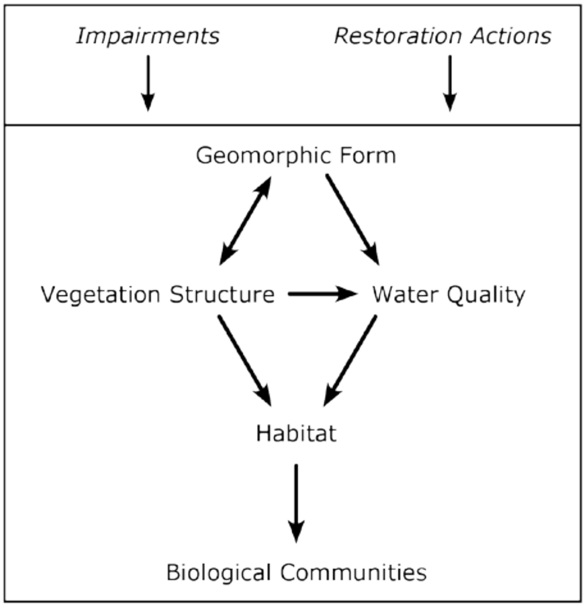


Figure 1 - (Left) *Example of mapped October NDVI values of the Lake Tahoe region. Dark greens depict high NDVI values and healthy, dense vegetation, while yellows and browns depict drier areas with sparser vegetation and areas of bare rock.* (Right) *Chart showing the spectral reflectance curves of healthy vegetation, unhealthy vegetation, and bare soil, alongside the blue, green, red, and near-infrared data collection bands of Landsat. The equation to calculate NDVI is shown at the bottom.*

NDVI can be derived from any imagery with a red and a near-infrared spectral band, but due to the spatial and temporal resolution and the history and availability of its data, Landsat imagery is an exceptional data source for monitoring long-term and ongoing landscape trends at a fairly high spatial resolution and for little to zero cost (Wulder et al. 2012). There are many online sources for viewing and downloading Landsat data. USGS's Earth Explorer website (earthexplorer.usgs.gov) is one tool that allows the user to search for imagery based on date(s), location and satellite/sensor (e.g., LS5 vs. LS7). Additionally, there are ways to filter results based on % cloud cover and other qualities of the image, making this a useful tool for browsing and downloading data. There are also third-party tools such as Google Earth Engine (explorer.earthengine.google.com) that allow the user to query data and specifically request pre-processed imagery outputs such as Landsat-derived NDVI. However, downloading pre-processed imagery from Google Earth Engine may require permissions. If pre-processed NDVI data is not accessible, NDVI can be easily calculated from orthorectified Landsat images using GIS or image processing software – see equation in FIGURE 1.

3.2 Measuring Meadow Restoration and Function

FIGURE 2 below shows a conceptual illustration of the ecosystem attribute linkages in a meadow system. Meadow complexes are essentially extensions of groundwater features (Chambers and Miller 2011) meaning that the vegetation condition and structure, and in addition the habitat and biological communities, of the meadow are directly linked to the underlying hydro-geomorphology. Numerous collaborative efforts have been undertaken to better understand the interplay of these meadow ecosystem attributes in order to guide the planning, monitoring, evaluation and adaptive management of meadow restoration projects in the Tahoe Basin (2NDNATURE et al. 2010). By understanding these linkages and being able to anticipate how a channel realignment or bank-lowering meadow restoration project, for example, will change the gaining vs. losing nature of a stream and how the vegetation might respond to the resulting alteration in groundwater dynamics, managers can better complete post project appraisals and follow through with adaptive management strategies.



Ecosystem Attributes:

- geomorphic form
  (reslilient channel morphology)
- hydrologic function
  (floodplain inundation frequency & duration; shallow groundwater levels)
- water quality benefits
  (downstream fine sediment particle load reductions)
- vegetative condition
  (vegetation community composition, structure & vigor)
- carbon burial rates
  (sequestration per unit area per year)
- habitat quality
  (habitat elements necessary to support desired indicator species)
- bilogical communities
  (utilization by desired species)

Figure 2 - (Left) *Ecosystem attribute linkage diagram showing a conceptual model of the cause and effect connections among ecosystem categories of riparian and alpine meadow systems. (Adapted from the "Riparian Ecosystem Restoration Effectiveness Framework", 2010).* (Right) *The physical, chemical and biological functional ecosystem attributes (multi-benefits) of the riparian/meadow areas.*

Resource managers face a persistent difficulty when it comes to collecting quantitative data for project effectiveness appraisals that is consistent across both pre- and post-restoration conditions. Remote sensing data, particularly the Landsat data catalog and NDVI, show huge promise as a means of sourcing a continuous and consistent dataset that can be used to evaluate meadow system condition. Specifically, NDVI can be used as a way to quantify the vigor, coverage and condition of meadow vegetation and identify any changes in vegetation over time as a result of management actions (Bartlett et al. 1989, Duncan et al. 1993, Hope et al. 1993, Everitt et al. 1996, Jorgensen and Nohr 1996, Lloyd 1990, Reed et al. 1994, Lancaster et al. 1996, Peters et al. 1997). As such, NDVI can also serve as a proxy for the condition and functional state of the underlying geomorphology and groundwater table, and of the meadow system's habitat. Landsat data presents an advantage in that the imagery is repeated for the same georeferenced grid cells over time, and these grid cells are easily locatable on the ground allowing for field verification of remotely sensed data if needed.

This report investigates if, using NDVI, there is a quantifiable difference in NDVI across meadows of varying conditions, and if it can be used to directly compare pre- and post-restoration conditions at the same site. Depending on these observable differences, it may also be possible to use NDVI to inform the prioritization of projects based on existing pre-project conditions and the geographic location in a watershed.

Using remotely sensed data, or long term datasets in general, to analyze a landscape attribute such as vegetation condition and compare it over time can be challenging due to the large degree of seasonal and annual variability included in the measurements. Annual variability in precipitation and water availability needs to be constrained in order to reliably assess changes due to management actions. Considerations need to be made for how to sample NDVI seasonally to account for the wetness conditions so that the NDVI is more representative of other elements of meadow functioning (e.g., physical and hydrological improvements). The ability to correlate remotely-sensed NDVI values to visible measures on the ground and long-term field datasets (describing vegetation, geomorphology, biological attributes, etc.) has potential. A huge opportunity exists to use NDVI to observe meadow ecosystems and to isolate the signal of management actions both cost-effectively and repeatedly.

4 CORRECTING FOR TEMPORAL VARIABILITY

In order to defensibly assess the effectiveness of restoration projects, we must be able to isolate the remote sensing signal due to management actions (the restoration) from variations due to sampling error and other variables such as climatic changes over time. Specific site locations are carefully defined within each project area where the management actions should have influence, and NDVI is calculated from imagery collected at a time when the differences between sites in good condition and poor condition are the most apparent. The data is then corrected for variations in precipitation or other climatic variables in order to quantify any changes due exclusively to management actions.

4.1 Constraining Seasonal Variability

NDVI is a way to quantify how "green" each cell on the landscape is and it thus provides insight into the relative health and condition of the vegetation. Over the course of the growing season the NDVI value of any one cell will vary as the phenology of its composite vegetation changes from early spring "green-up", to peak summer growth, to autumn "brown-out". (FIGURE 3). Additionally, the shape of this phenology greenness curve will vary depending on the type and condition of the vegetation in each cell. The working assumption of this research is that an effective restoration action will improve the condition of the vegetation and thus increase its NDVI values.

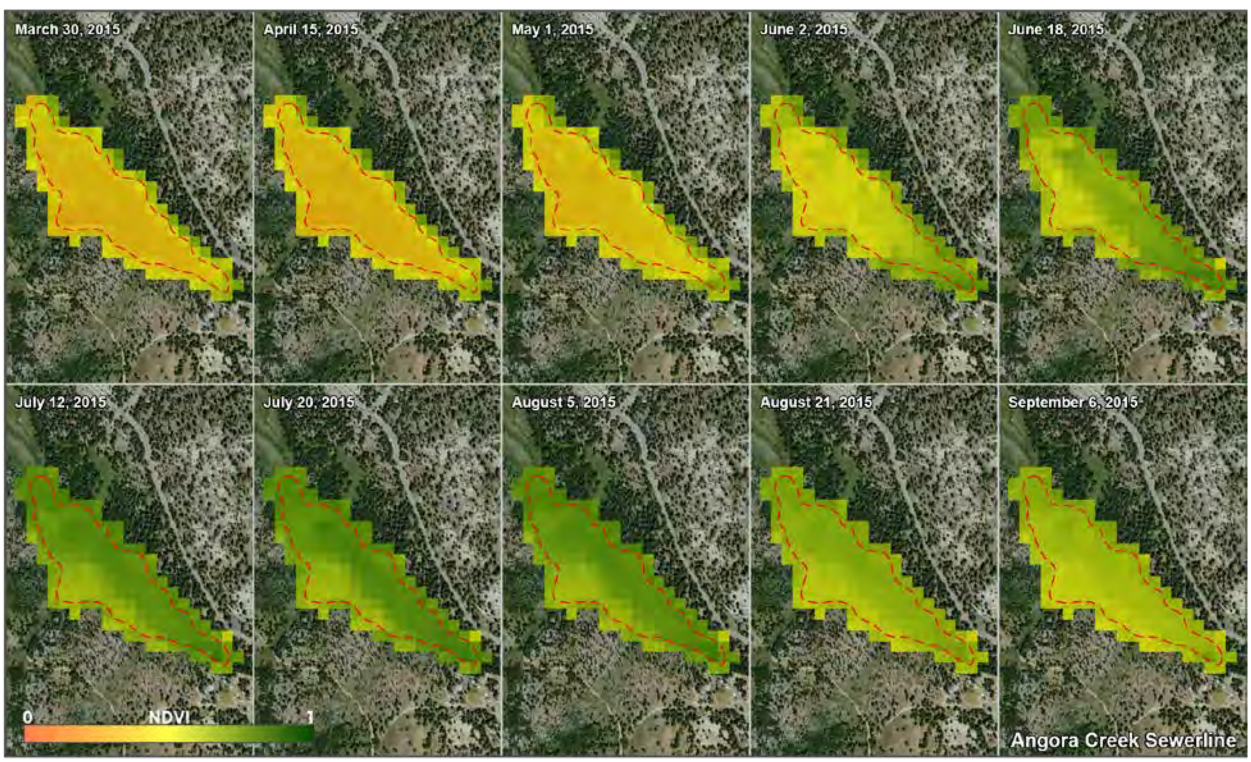


Figure 3 - Seasonal variability of NDVI, showing spring "green-up" through autumn "brown-out", at an example meadow site.

In order to isolate the effects of a restoration action, we want to calculate NDVI at a time during the growing season where NDVI differences across sites in varying levels of function are easiest to detect. We can then compare those values over time (pre- and post-restoration) in order to determine if the restoration indeed was effective. Our hypothesis is that effective restoration actions at a site will increase the hydrologic connectivity of the channel to the floodplain and improve shallow groundwater vegetative access and retention. Therefore, the late growing season, when water from spring snowmelt and summer rains has been diminished, is hypothesized as an indicative time to sample NDVI values. The theory is that restored/functioning sites will still have access to shallow groundwater and thus have higher NDVI values, while unrestored/non-functioning sites will dry out by late summer and thus have lower NDVI values (FIGURE 4).

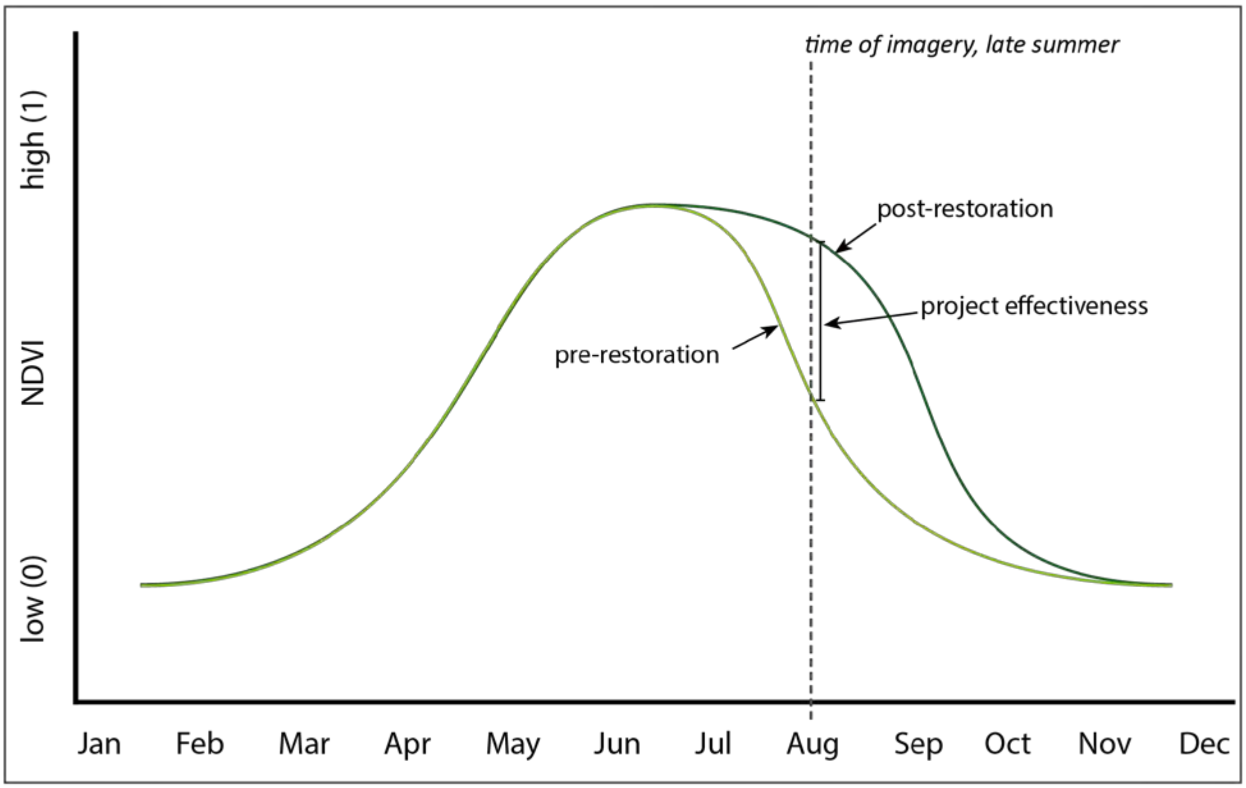
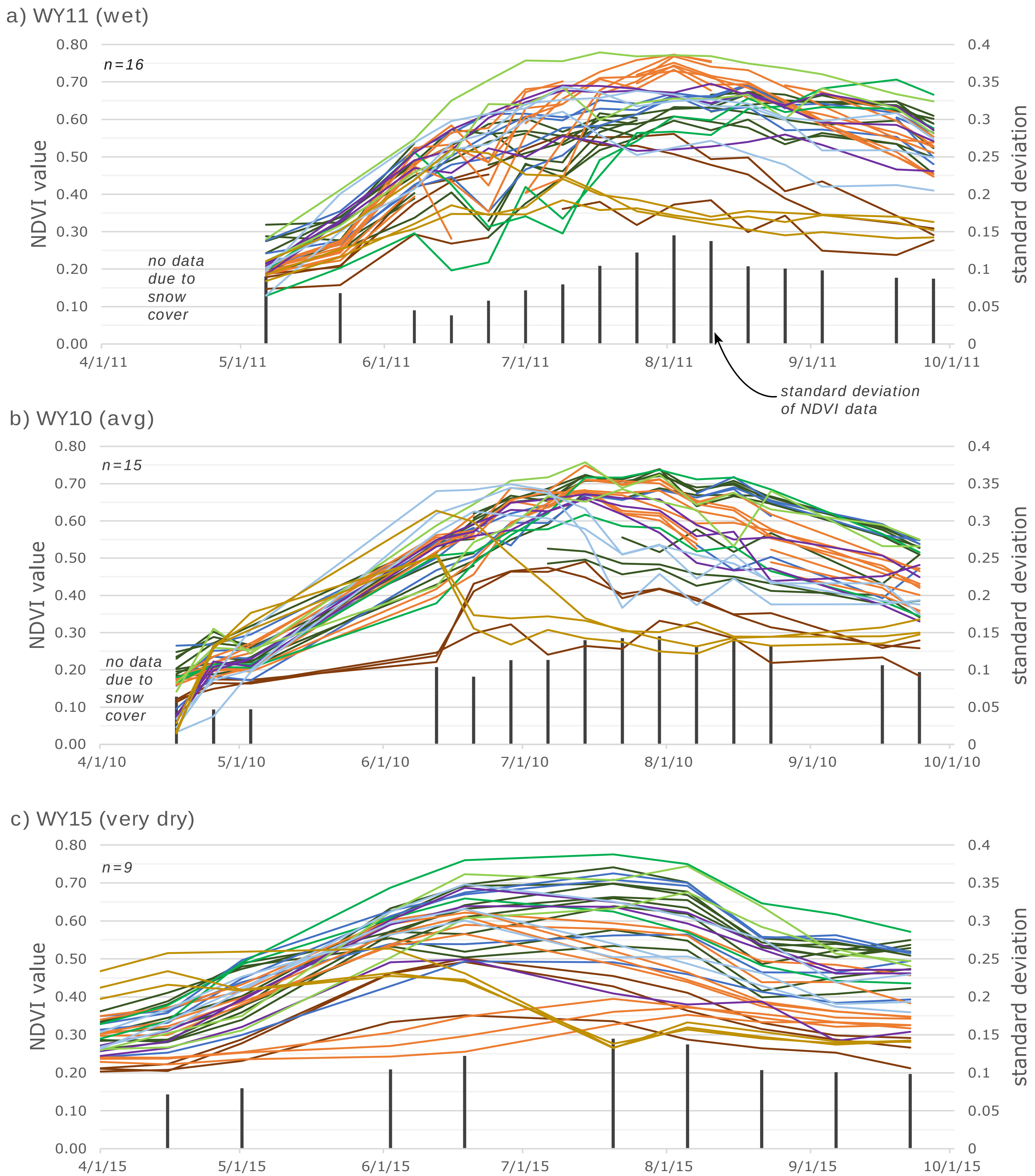


Figure 4 - Conceptual illustration of an NDVI phenology curve and how restoration of the hydro-geomorphic function of a site would theoretically extend the peak vegetation "greenness" later into the season.

To test this hypothesis and to define the optimal timing for sampling NDVI values, we selected 33 individual grid cells at meadow sites in the Tahoe Basin that represent a known range in conditions from wet sites with functional morphology to dry meadow sites adjacent to severely incised stream channels. The NDVI value of each grid cell was sampled for each available, cloud-free Landsat image over the complete growing season (April through September). This was repeated for a wet year (2011), an average year (2010) and a very dry year (2015). The time series phenology curve for each of these test locations is plotted in FIGURE 5 (next page).



33 Landsat pixels selected from a variety of meadow surfaces throughout the Tahoe Basin. Each colored line shows the NDVI values for a single pixel over the couse of a wet (a), average (b) and dry (c) water year. The standard deviation of all NDVI data (all 33 pixels) for each unique sampling date is summarized in lower histogram plots. "n" signifies the number of cloud-free Landsat images that were used to sample NDVI for the 33 test pixels for each example water year.

According to these data, the maximum standard deviation in NDVI values occurs in late July/early August, suggesting that by this time sites in poor condition which are unable to hold water have already "browned-out" while those sites that are in better hydrologic condition and have access to shallow groundwater are able to sustain their "greenness". Late July/early August is therefore an optimal time to sample NDVI values for determining the hydrologic condition, and thus the effectiveness, of wet meadow restoration projects.

4.2 Constraining Annual Variability

Just as the seasonal variation in water availability will influence the greenness of a site as measured by NDVI, so too will annual differences in climate. The amount of precipitation for any given year will have an effect on the intensity and duration of green vegetation at a meadow site. FIGURE 6 shows the NDVI data for an example meadow sampled during the same month of the year over three different water year types. In these three images, the difference in mean NDVI for the site is due exclusively to climate and not to any management actions. Correcting for this interannual climatic variation is therefore important when attempting to isolate the signal from restoration and assess the effectiveness of a management action.

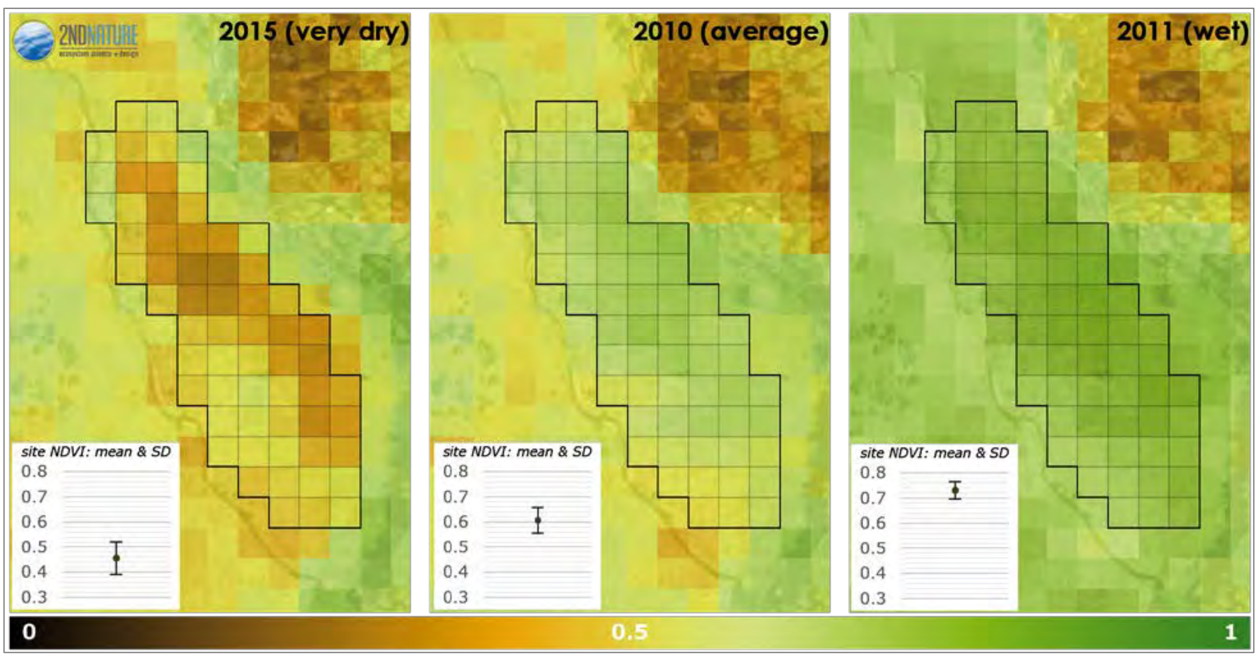
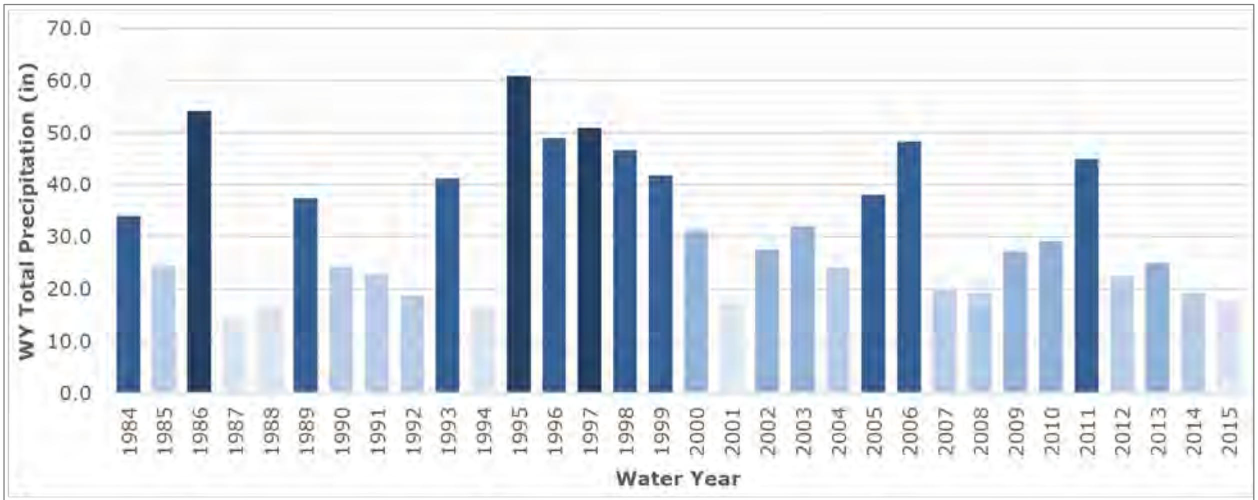


Figure 6 - Example of interannual variability in NDVI values. NDVI data shown was sampled during the same month in late summer for a single, un-managed site, over three years. The three years experienced different levels of precipitation but no other changes occurred at the site from 2010 to 2015.

By incorporating regional and local monthly cumulative precipitation data and plotting sampled NDVI values against them, we can constrain the effect that precipitation has on NDVI and more accurately assess long-term and pre- and post-restoration trends.

FIGURE 7 shows water year types and precipitation amounts in the Tahoe Basin from 1984 to 2015. Through these records we can calculate the cumulative precipitation that fell over the

10 months (or any other defined period) prior to when the NDVI data were sampled. Water year type and 10 month precipitation totals are used to provide climatic context to the NDVI datasets obtained and presented below.



Year Type	WY Type Recurrence Interval (years)	Annual Precip. (in/yr)		Annual PPT Exceedance Probability (%)	n
		Lower (in/yr)	Upper (in/yr)		
Very Dry	10		18.60	> 91	10
Dry	4	18.61	24.63	> 67	26
Average	3	24.64	33.91	> 33	35
Wet	4	33.92	49.00	> 10	24
Very Wet	10	49.01		<10	10
Long-Term Average Annual Precipitation = 31.29 in/yr					
Tahoe City, CA, Water Year Record = 1911 - 2015					

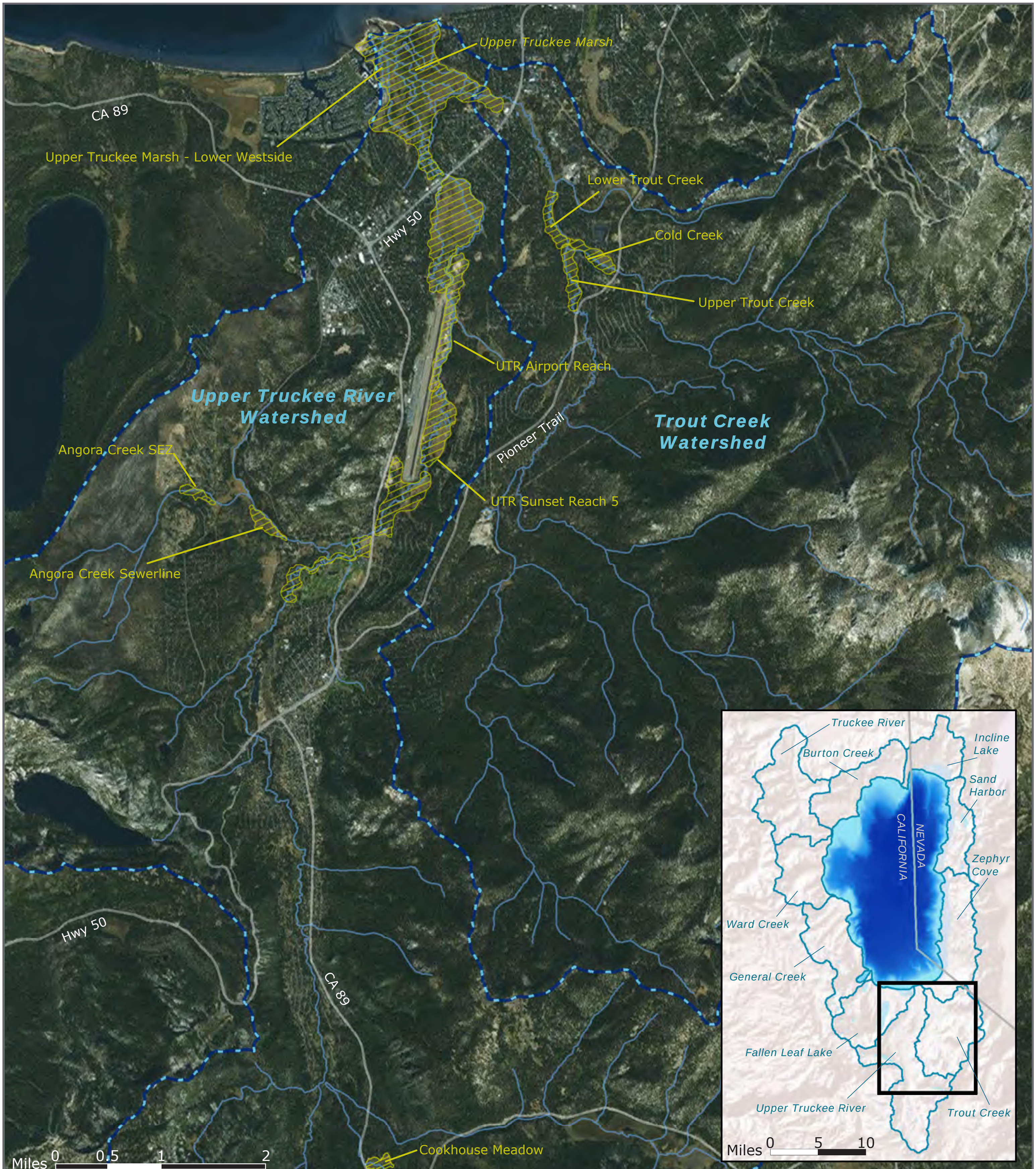
Figure 7 - Water year types and example long-term precipitation data for the Tahoe Basin. These data (and the monthly totals underlying the summary data shown here) can be used in conjunction with NDVI values to constrain annual climatic variability and allow for NDVI analyses independent of precipitation.

5 Study Area

The Upper Truckee River Marsh (UTM) is the largest alpine meadow complex in the Tahoe Basin and is the terminus of the Upper Truckee River (UTR) and Trout Creek (Figure 8, next page). The UTR discharges the greatest runoff volumes and total sediment loads to Lake Tahoe on an average annual basis (LRWQCB and NDEP 2010). Historic land use modifications throughout both watersheds have resulted in significant impairments to the riparian zone. The historic land uses extend beyond the last century and include Basque sheep herding and alpine meadow modifications, the Comstock logging era and more recent urban development. All of these impacts severely degraded the fluvial function of many meadow complexes throughout the UTM drainage. Over the past two decades, Tahoe resource management agencies have designed, implemented and managed several stream and floodplain restoration efforts throughout these two watersheds and there are many more planned in the next decade. Table 1 and Figure 8 show all riparian restoration projects completed to date and included in this analysis. While the results herein are focused on riparian/meadow systems within the Lake Tahoe Basin, the application of these data and this approach potentially extends well beyond the Tahoe Basin to anywhere where riparian restoration includes expected physical, chemical and biological functional improvements that would radiate from the fluvial system outward into an adjacent floodplain complex an acre in size or larger.

Table 1 - Analyzed riparian restoration sites within the Upper Truckee Marsh drainage, South Lake Tahoe, CA.

project name	restoration start	restoration completion	project area analyzed
Angora Creek SEZ	2005	2006	5.3 ac (24 pixels)
Angora Creek Sewerline	2002	2002	16.4 ac (74 pixels)
UTR Sunset Reach 5	2013	2016	54 ac (244 pixels)
UTR Airport Reach	2008	2011	17 ac (77 pixels)
UTR Lower Westside	2001	2001	8.4 ac (38 pixels)
Upper Trout Creek	1999	2001	22.4 ac (101 pixels)
Lower Trout Creek	1999	2001	17.3 ac (78 pixels)
Cold Creek (lower)	1994	1994	5.8 ac (26 pixels)
Cookhouse Meadow	2005	2006	13 ac (59 pixels)



project sites

watershed boundaries

DESIGNED BY
2NDNATURE LLC
TEL: 831.426.9119 FAX: 831.426.7092
www.2ndnaturellc.com

STUDY SITES: UPPER TRUCKEE RIVER & TROUT CREEK WATERSHEDS

FIGURE 8

5.1 Site Delineation

We define specific sampling locations relative to the 30x30 meter grid of the Landsat imagery (using the WGS 1984 UTM Zone 10 N projection), which are consistent over space and time. Restoration areas for analysis were delineated by mapping the length of modified stream and then estimating the anticipated extent of area influenced by the restoration actions. To do this the 30x30 meter Landsat grid was overlaid on aerial imagery of the project area in a GIS and, within project boundaries, individual grid cells were selected that (a) appeared in the imagery to be hydrologically influenced by restoration activities and (b) contained little to no conifers (FIGURE 9a). (Evergreen trees and shrubs can skew NDVI data estimates so those cells are excluded from analyses. Depending on the imagery, distinguishing between conifers and other trees/shrubs such as willows that should *not* be excluded from the analysis was at times difficult. To address this, the grid was viewed in Google Earth and historical/seasonal imagery was used to better assess vegetation type and double check whether or not questionable cells should be included in the analysis).

With project cells first selected for their vegetation and overall imagery qualities, the grid was then overlaid in a GIS on a high resolution DEM and hillshade (FIGURE 9b). Any selected cells that appeared to be topographically disconnected from areas of expected project influence (e.g., cells that were clearly upland compared to the restored floodplain) were identified and excluded from the analysis.

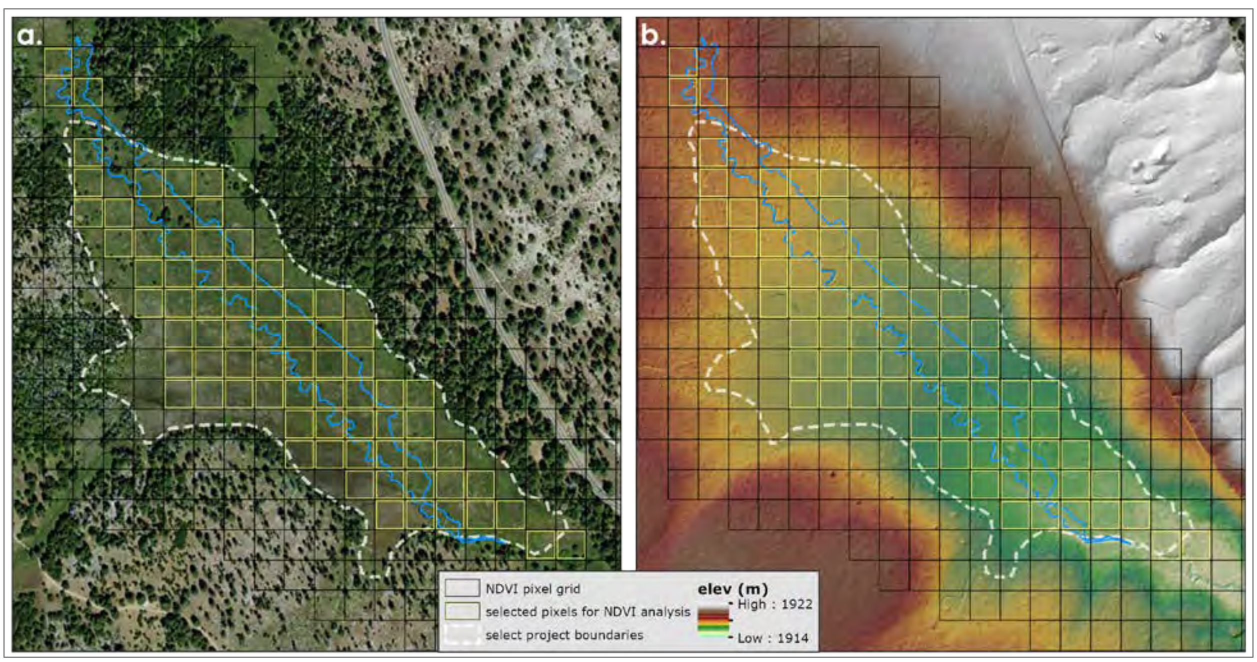


Figure 9 - Example of grid cell selection process for analysis area definition within each restoration project site. (a) *30x30 meter Landsat data collection grid is overlaid on aerial imagery of restoration site with original and restored stream channel, and conifer-free grid cells in anticipated area of restoration influence are selected.* (b) *Selected grid cells are then viewed on top of a high resolution DEM to identify and de-select any cells that are obviously upland of expected restoration influence. The outer boundary of the final selection of grid cells is used to define area of NDVI analysis for each restoration site.*

The resulting selections of 30x30 m cells for each restoration project were vetted by resource management staff from the California Tahoe Conservancy and were finalized with their input. These selected areas were used to spatially define, in terms of Landsat remote sensing data, the best representation of areas of potential vegetation influence from restoration activities, and were used in NDVI analyses. (Specific boundaries for each analysis site are shown with analysis results in FIGURES 10-27).

5.2 LANDSAT Data Management and Analysis Protocols

As stated above in Section 4, we specifically targeted late July/early August as the period to search for quality imagery for this analysis. Using the USGS Earth Explorer (www.earthexplorer.usgs.gov) we searched for all imagery from the Landsat 5, 7 and 8 satellites for path:43/row:33 (the Landsat scene covering the Tahoe Basin), and the dates 1/1/1984 – 12/31/2015. We further specified to only return entries for the months July and August.

Each entry was previewed and qualified for both the north basin and the south basin on a 1-5 scale:

1	image is unusable
2	heavy clouds, snow and/or scan lines exist making some but not all sites visible*
3	minor clouds or other flaws exist, but image is good and warrants correction/masking if possible
4	minor cirrus clouds or other flaws exist, but image is likely OK without correction
5	no issues; image is clean

**In 2003 the Scan Line Corrector aboard Landsat 7 failed, resulting in images with thin lines of missing data.*

The specific dates for all images from this time period, along with additional notes about image quality, were compiled in TABLE A (see appendix). For each water year from 1985 to 2015 we selected the image of the highest overall quality that was closest to the optimal sampling time based on the seasonal variation data presented in FIGURE 5. Pre-processed NDVI raster data for each of these selected images was queried and downloaded using Google Earth Engine. The final selected imagery/NDVI data are summarized in TABLE 2 below:

Table 2 - Table summarizes the Landsat imagery, including specific dates and notes on image quality, that were used in the NDVI analyses presented in this report. In some cases where scan lines in LS7 imagery are present, their effect is localized and can easily be corrected to make the image usable.

Late Growing Season Landsat Imagery for the Lake Tahoe Basin: Scenes Selected for NDVI Analysis

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WY	WY Type	Date	Satellite	QUAL: S. Basin	QUAL: N. Basin	Notes
WY15	Very Dry	7/20/2015	LS8	5	4	
WY14	Dry	8/2/2014	LS8	4	4	
WY13	Average	7/30/2013	LS8	5	5	
WY12	Dry	8/4/2012	LS7	4	3	*scn lines in upper marsh*
WY11	Wet	8/10/2011	LS5	5	5	
WY10	Average	8/7/2010	LS5	5	5	
WY09	Average	8/4/2009	LS5	5	5	
WY08	Dry	8/1/2008	LS5	5	5	
WY07	Dry	7/30/2007	LS5	5	5	
WY06	Wet	7/27/2006	LS5	5	5	
WY05	Wet	8/9/2005	LS5	5	5	
WY04	Dry	8/6/2004	LS5	5	5	
WY03	Average	7/19/2003	LS5	5	5	
WY02	Average	8/1/2002	LS5	5	5	
WY01	Very Dry	7/29/2001	LS5	5	5	
WY00	Average	7/26/2000	LS5	5	5	
WY99	Wet	8/1/1999	LS7	5	5	
WY97	Very Wet	8/3/1997	LS5	5	5	
WY96	Very Wet	7/31/1996	LS5	5	5	
WY95	Very Wet	7/29/1995	LS5	5	5	
WY94	Very Dry	7/26/1994	LS5	4	4	
WY93	Wet	8/8/1993	LS5	5	5	
WY92	Dry	8/5/1992	LS5	5	5	
WY91	Dry	7/18/1991	LS5	5	5	
WY89	Wet	7/28/1989	LS5	5	5	
WY88	Very Dry	8/26/1988	LS5	5	5	*best available; later than desired*
WY87	Very Dry	7/23/1987	LS5	5	5	
WY86	Very Wet	8/5/1986	LS5	5	5	
WY85	Dry	8/2/1985	LS5	5	5	
WY84	Wet	7/30/1984	LS5	5	5	

Data Quality:

1. unusable
2. heavy clouds, snow and/or scan lines; some but not all sites visible
3. minor clouds or other, but warrants correction/masking if possible
4. minor cirrus clouds or other: likely OK without correction
5. no issues, clean image

These NDVI data are stored by 2N in a raster geodatabase and can be shared upon request.

6 NDVI Analysis of Completed Restoration Projects

6.1 Site Results

For each of the completed and active restoration projects described in Table 1, pixels for NDVI site analysis were selected (Figure 9) and mean site NDVI values were calculated annually from the Landsat images specified above in Table 2. These data were organized in a database alongside the prior 10-month cumulative precipitation for each sample year. (For example, 10-month prior cumulative precipitation for a 2012 NDVI sample would be the sum of monthly precipitation, measured at Tahoe City, CA [Figure 7], for water year 2012 through July 31st [e.g. Oct. 2011 – July 2012]).

Figures 10-27 show site selection maps, project details and plotted NDVI and precipitation data for each of nine restoration projects: Upper Truckee River Sunset Reach 5, Upper Trout Creek, Angora Creek SEZ, Cookhouse Meadow, Lower Trout Creek, Upper Truckee River Airport Reach, Lower Cold Creek, Angora Creek Sewerline, and Upper Truckee Marsh Lower Westside. The overview location of each site is mapped in Figure 8.

For each site, analysis results are presented in a two-page figure. The first page shows a regional overview map for project context, provides site acreage, timeline of the restoration actions, and presents a pair of project-scale maps showing the specific area selected for analysis overlaid on high resolution aerial imagery and on a high resolution DEM. (Details of site selection are described above in Section 5.1).

The second page of each site analysis figure presents three graphics communicating the site NDVI results:

(a) The top graphic charts the mean site NDVI value over time from 1984 to 2015 (solid green line) and a center-weighted 3-year moving average of those values (dashed green line). Also graphed are the 10-month cumulative precipitation totals for each year (solid blue line) and a center-weighted 3-year moving average of those values (dashed blue line). The period of time that the site restoration took place is shown on the chart shaded in gray.

Plotted together, these time series data show how late summer NDVI tends to follow general precipitation trends, with higher NDVI values measured during years of greater precipitation and vice versa. While annual pattern of NDVI continues to generally track precipitation, measured NDVI values maintain a higher overall trend, despite fluctuations in precipitation, following restoration than they did prior to restoration, suggesting an improvement in hydrologic connectivity and water availability for vegetation other than precipitation.

(b) In the middle graphic, NDVI values measured before restoration and following restoration are each plotted against 10-month prior cumulative precipitation. A linear regression model is used to define the relationship between precipitation and NDVI both before and following restoration. Years during site construction and 3 years of transition post-restoration are removed from the regression. These plots illustrate the quantitative effect that a restoration action may have had on mean site NDVI, independent of precipitation and climatic variability.

In this graphic, a successful site restoration will be indicated by an upward (greater NDVI) shift of the trend line modeling post-restoration data as compared to the trend line modeling pre-restoration NDVI data. This shift indicates that the site is able to hold on to more water regardless of precipitation conditions, and thus remain greener following restoration than prior to it. The positive shift generally holds across all precipitation levels, though the difference between the pre- and the post-restoration data is less pronounced in wetter years. Note that there is a numeric limit for NDVI values at 1, meaning a functional site can only get so 'green'.

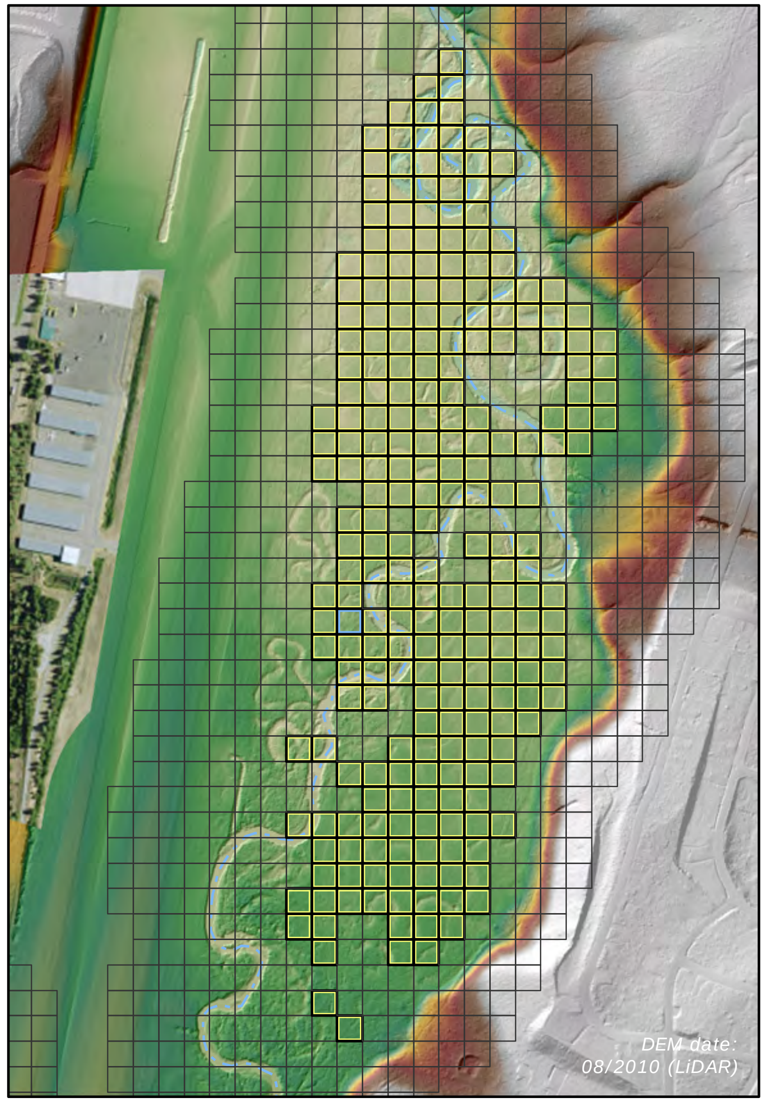
(c) In the bottom graphic, measured mean site NDVI values are plotted from 1984 to 2015 as they were in the top graphic (solid green line). Restoration timing is noted using grey shading as it was in the top graphic. The measured NDVI time series is compared to the predicted NDVI values over time assuming that restoration never occurred (dashed light green line) using the linear regression equation noted in graphic b above and each year's respective 10-month cumulative precipitation.

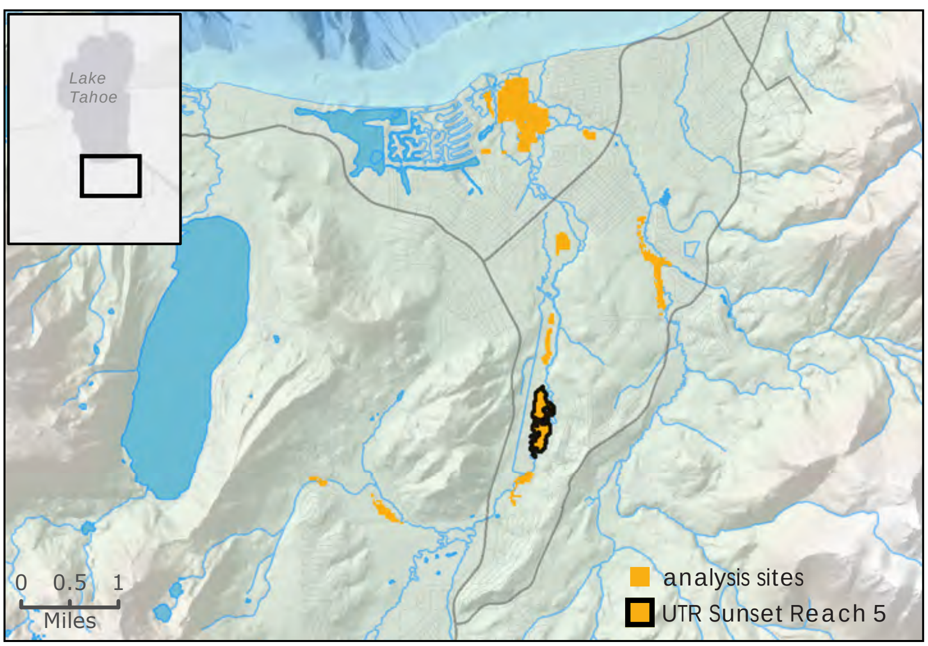
Using this simple model approach, the predicted values reasonably align with the measured NDVI values prior to restoration. Following restoration, a number of sites illustrate an upward divergence of the measured NDVI values (solid green line) from the predicted values. This positive divergence is another means of illustrating a functional improvement in site condition following restoration project completion.

TABLE 3 below summarizes the goodness of fit, confidence and performance of the linear regression model of pre-restoration precipitation as a predictor for NDVI in un-restored meadows.

Table 3 - Summary results for pre-project regression of rainfall on NDVI. The p-value indicates significance of the regression slope coefficient, with values <0.05 indicating greater than 95% confidence that the linear relationship in fact exists. Model performance is quantified by the R-squared, which indicates the amount of variance in NDVI data explained by the rainfall data.

site	observations	slope coefficient	p-value	r-squared
UTR Sunset Reach 5	31	0.0047	< 0.001	0.64
Upper Trout Creek	15	0.0051	< 0.001	0.65
Angora Creek SEZ	21	0.0016	< 0.01	0.32
Cookhouse Meadow	21	0.0039	< 0.001	0.50
Lower Trout Creek	15	0.0038	< 0.005	0.47
UTR Airport Reach	24	0.0024	< 0.001	0.47
Lower Cold Creek	5	0.0027	0.35	0.29
Angora Creek Sewerline	18	0.0037	< 0.001	0.57
UTR Lower Westside	16	0.0004	0.49	0.03





NDVI analysis area
NDVI pixel grid
selected pixels for analysis
pre-restoration
post-restoration

elev (m)
High : 1922
Low : 1904

UTR Sunset Reach 5

NDVI analysis area:
54 acres (244 pixels)

restoration start: 2013
restoration end: 2016

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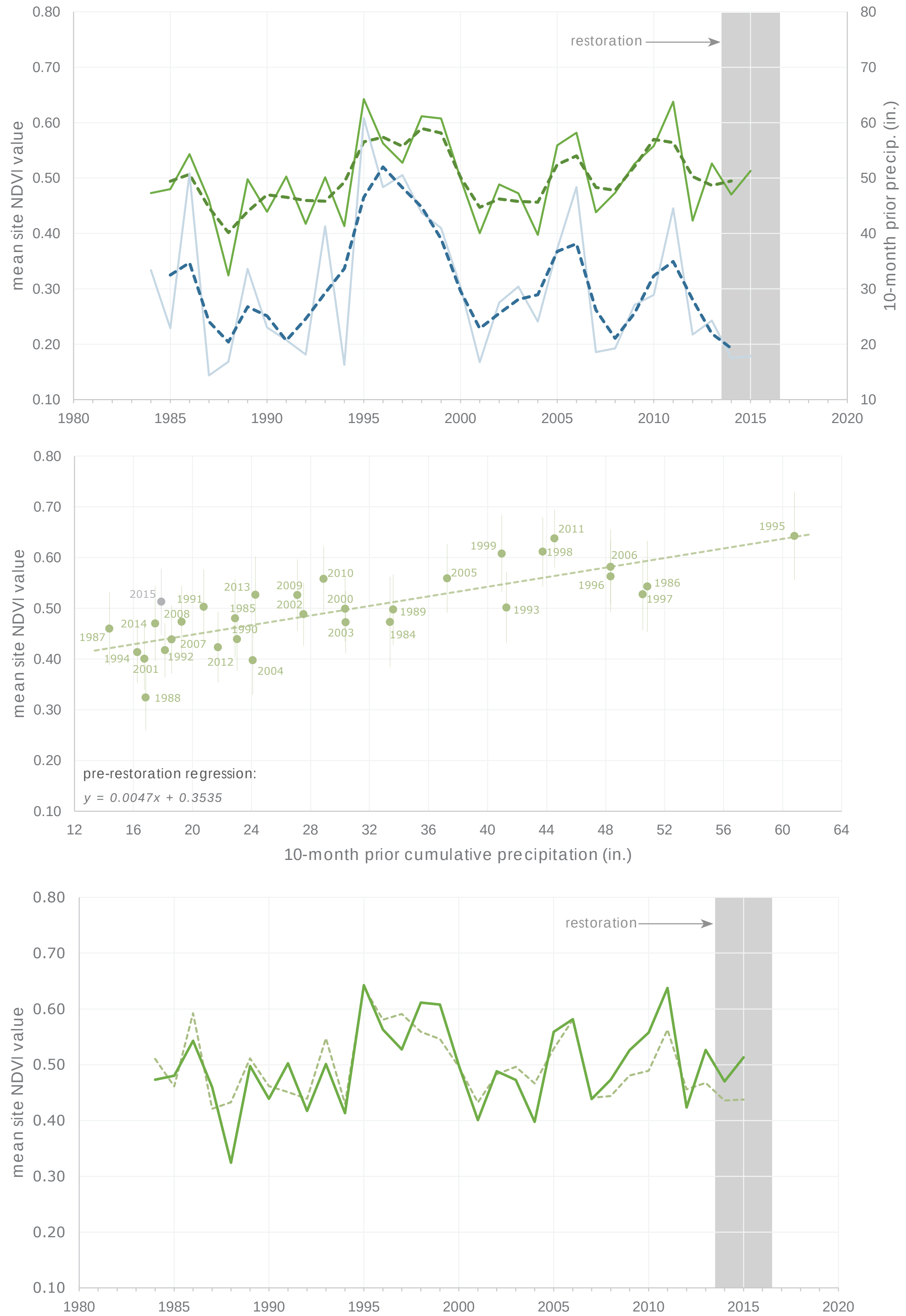


a. Precipitation & NDVI, with 3-year running averages.

NDVI (w/ 3-yr avg)

precipitation (w/ 3-yr avg)

b. Pre- and post-restoration NDVI values plotted against 10-month prior cumulative precipitation.

pre-restoration

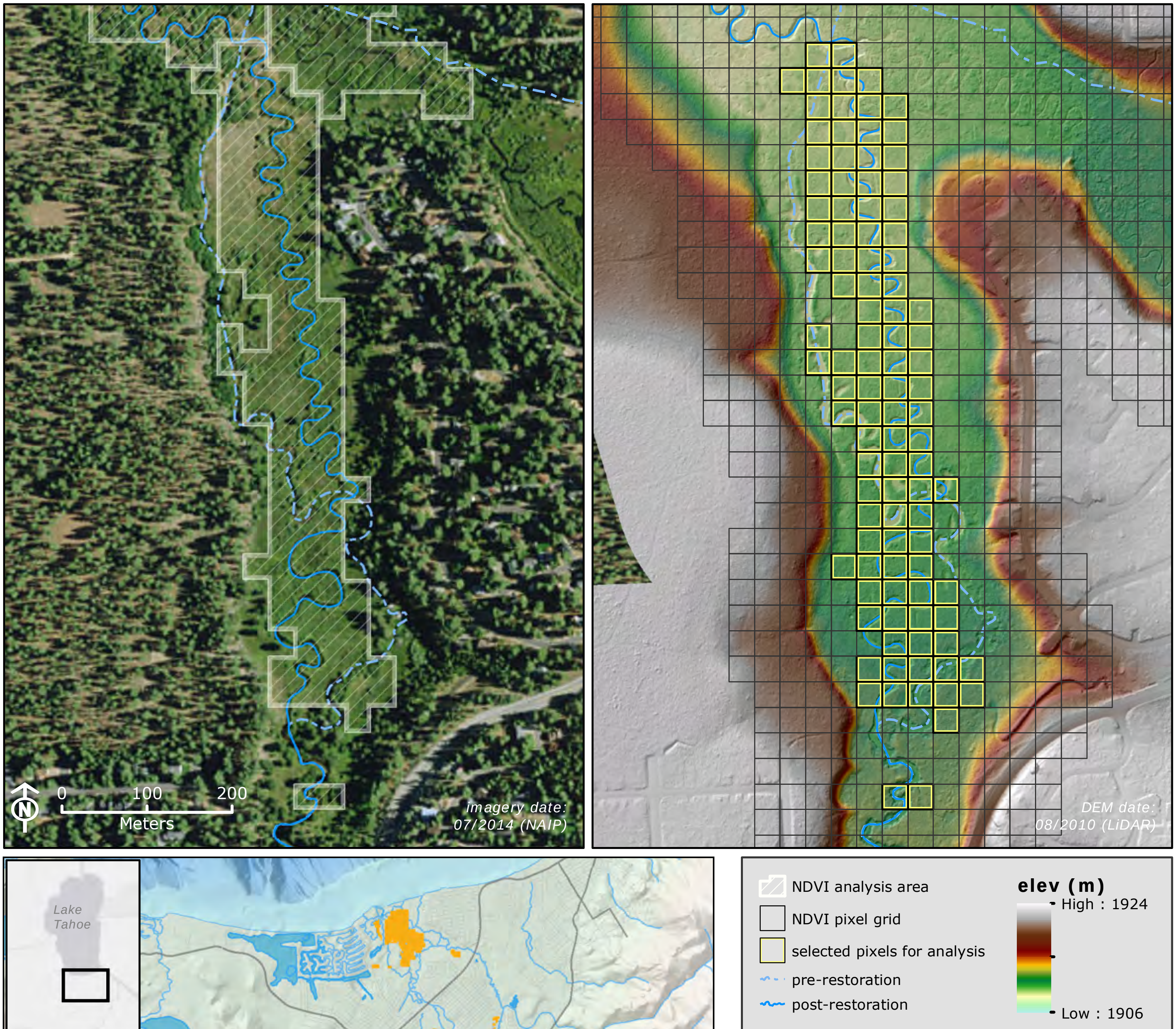
project construction / site transition

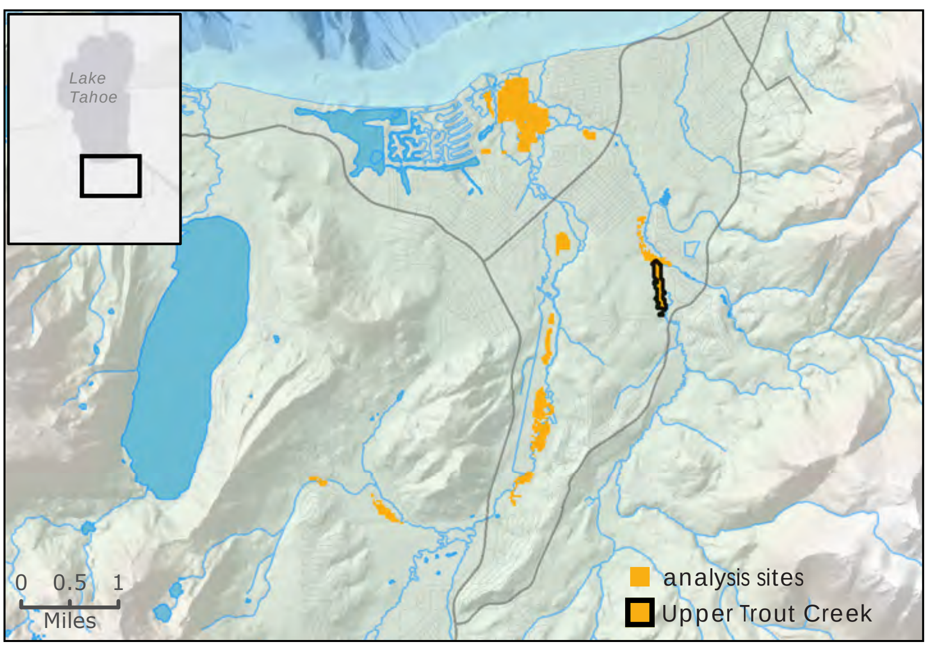
post-restoration

c. Predicted vs. actual NDVI values. (Predicted values are calculated from the pre-restoration regression equation in "b" above).

measured NDVI

predicted NDVI





Upper Trout Creek

NDVI analysis area:
22.4 acres (101 pixels)

restoration start: 1999
restoration end: 2001

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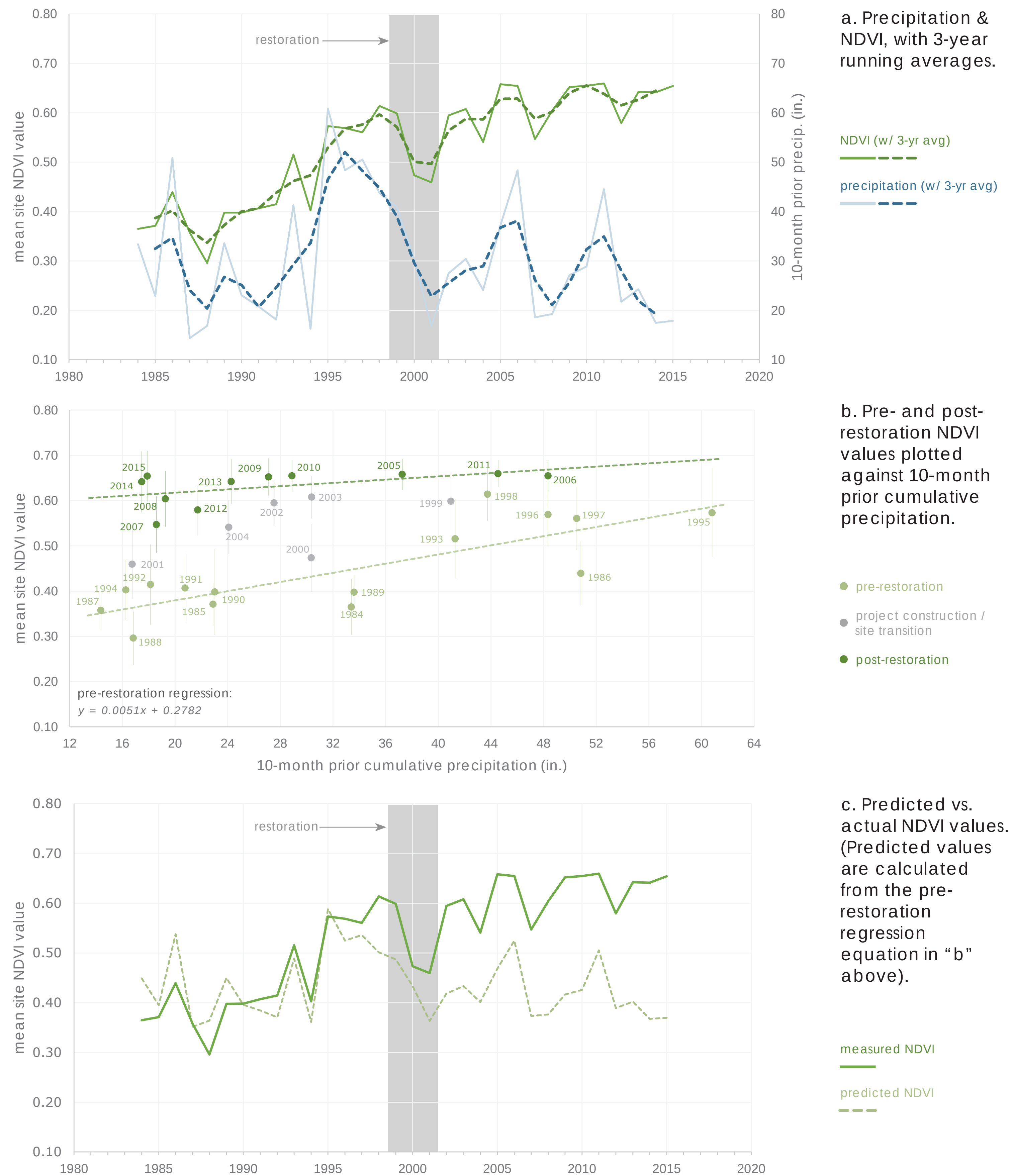

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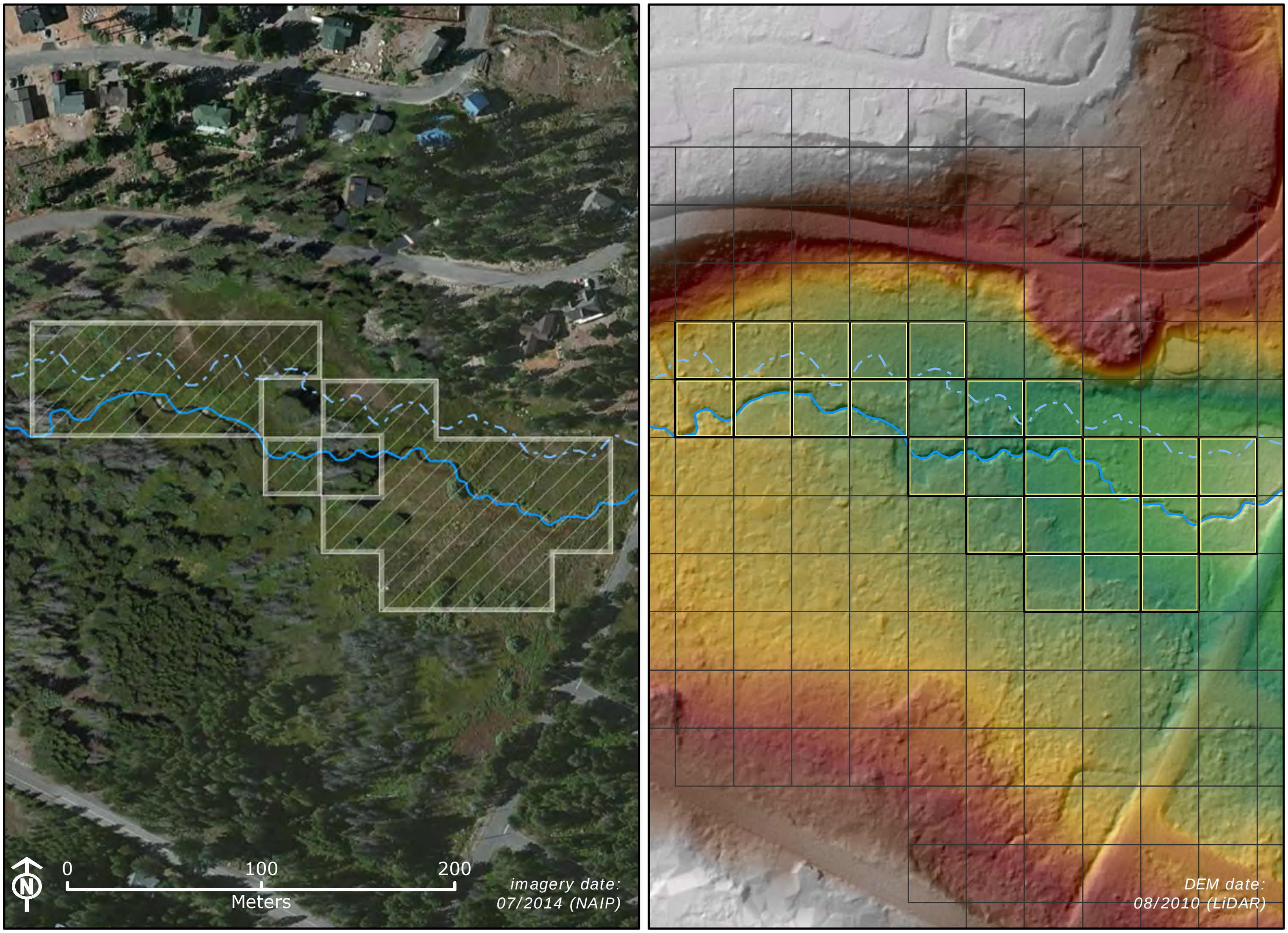
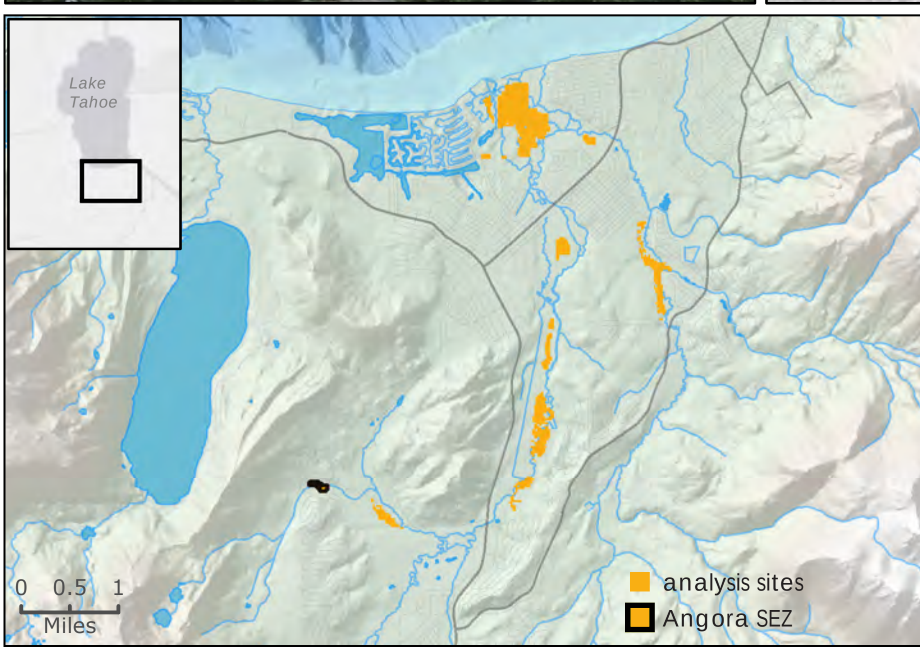
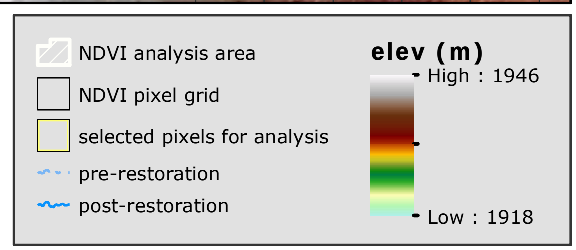
UPPER TROUT CREEK

FIGURE 13







Angora Creek SEZ

NDVI analysis area:
5.3 acres (24 pixels)

restoration start: 2005
restoration end: 2006

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FIGURE 14

FIGURE 15

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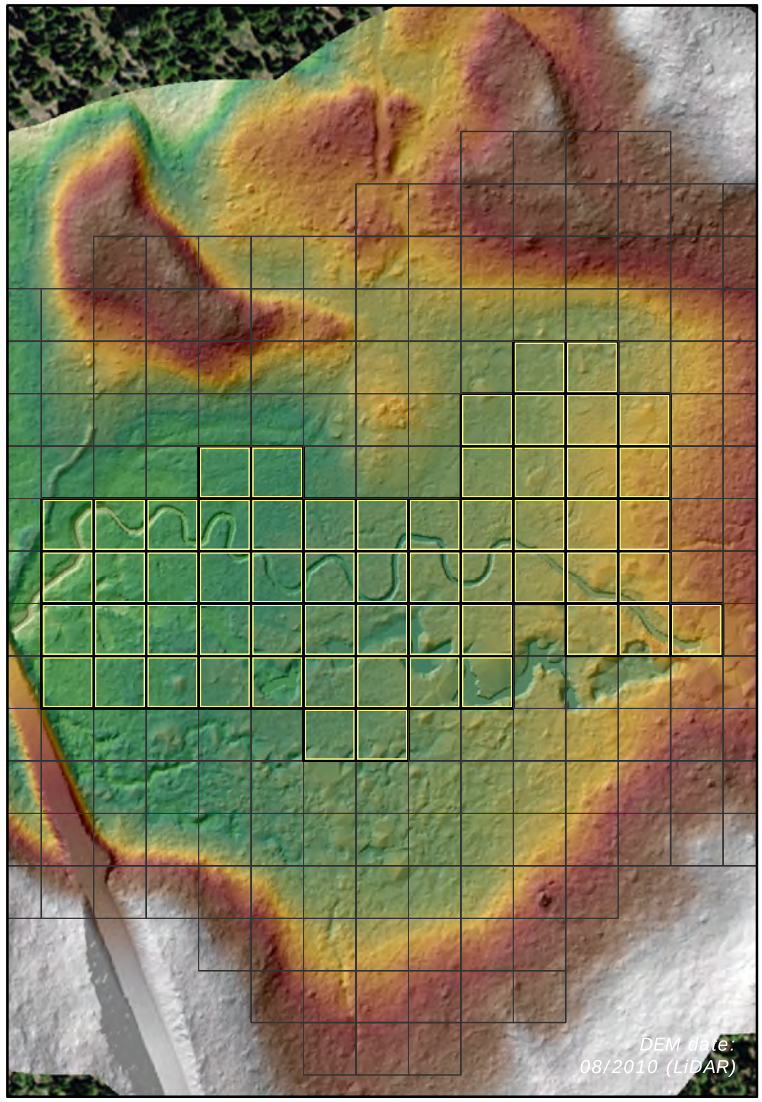

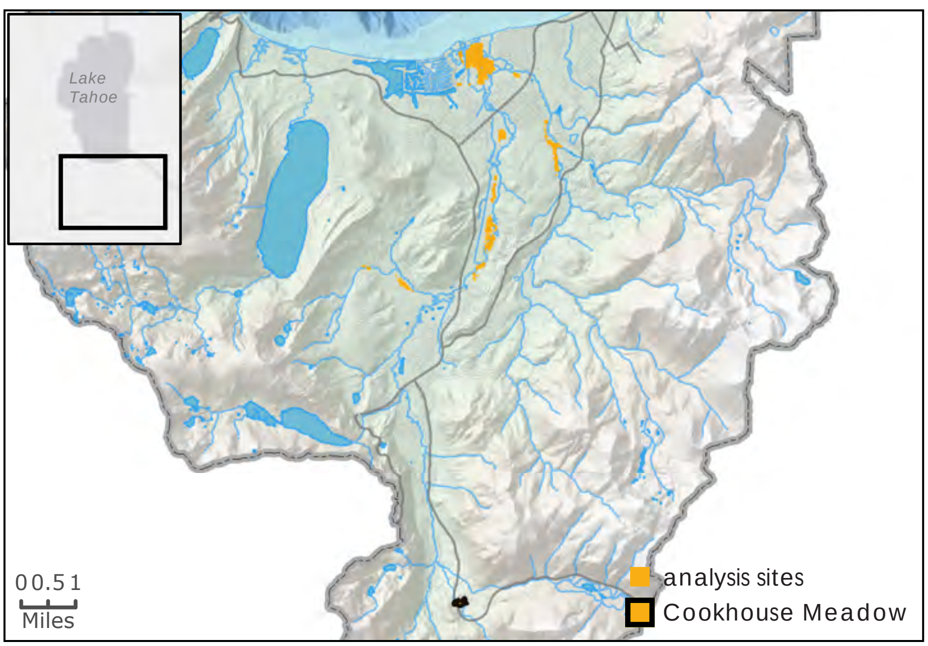

NDVI pixel grid
selected pixels for analysis
pre-restoration
post-restoration

elev (m)
High : 2160
Low : 2140

Cookhouse Meadow

NDVI analysis area:
13 acres (59 pixels)

restoration start: 2005
restoration end: 2006

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a. Precipitation & NDVI, with 3-year running averages.

b. Pre- and post-restoration NDVI values plotted against 10-month prior cumulative precipitation.

c. Predicted vs. actual NDVI values. (Predicted values are calculated from the pre-restoration regression equation in “b” above).

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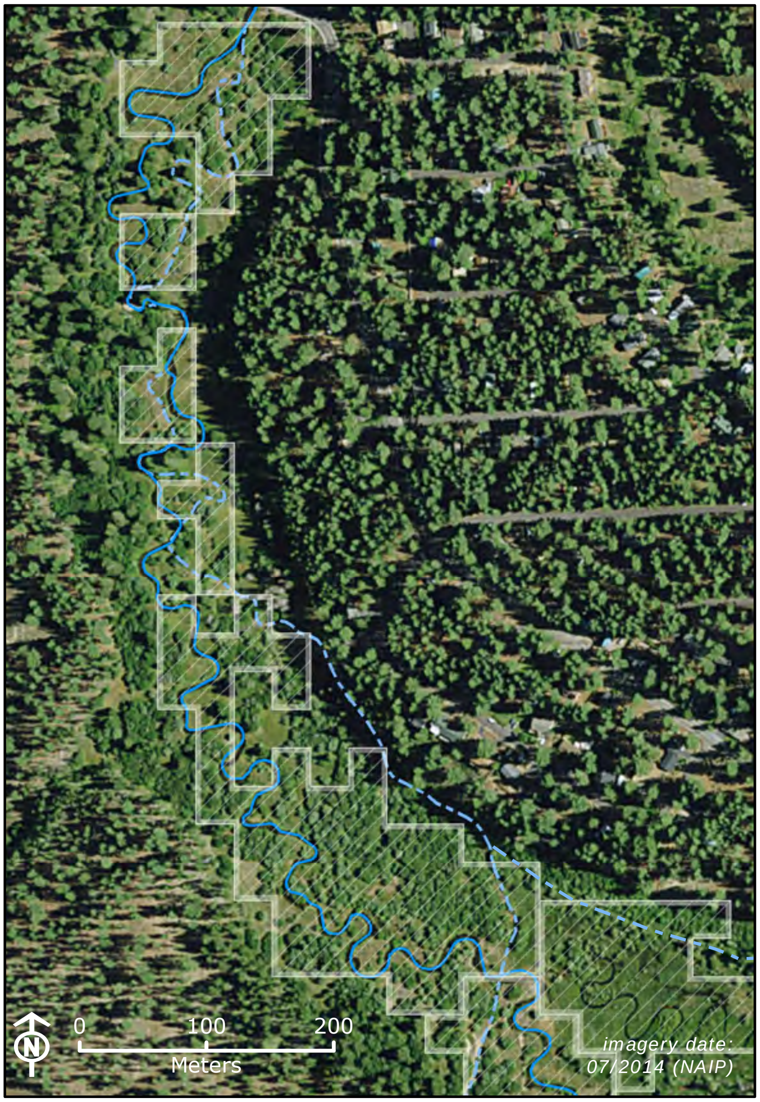
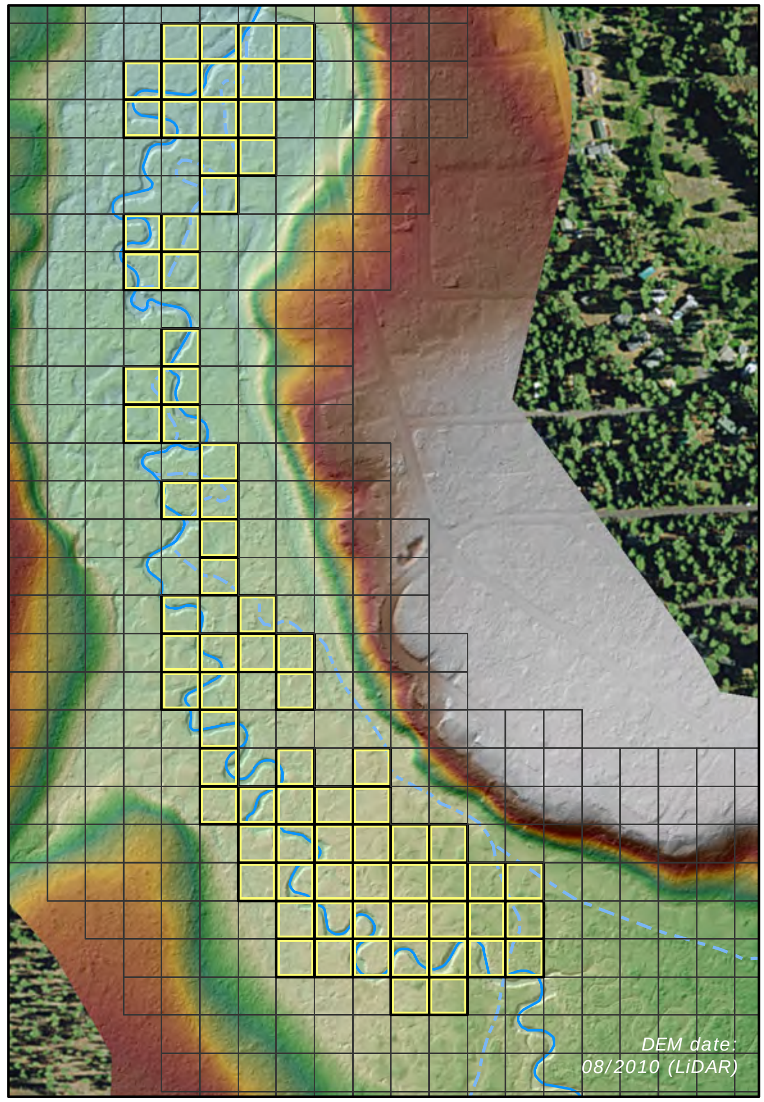
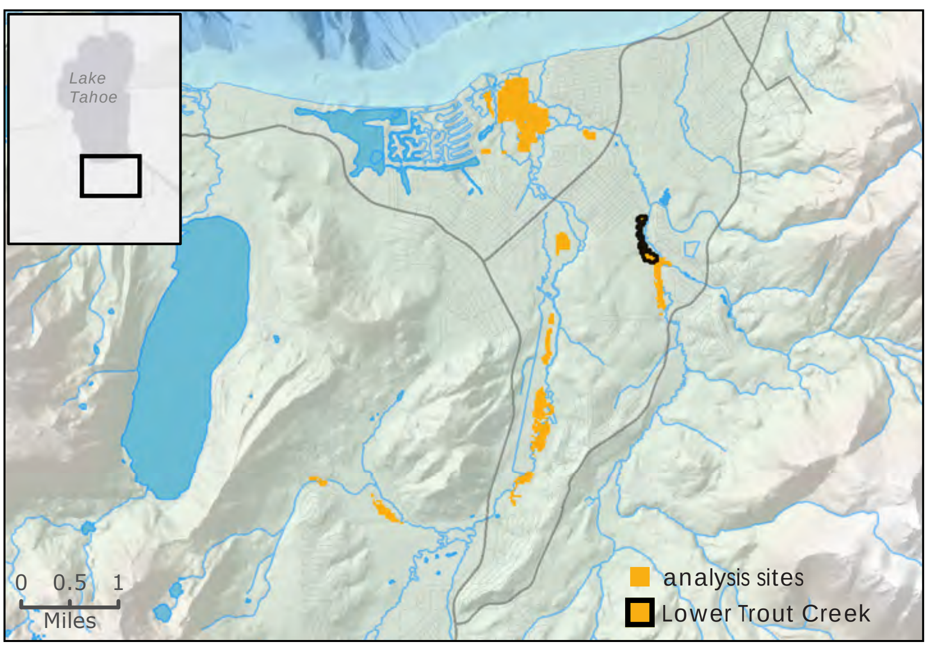
COOKHOUSE MEADOW

FIGURE 17







NDVI analysis area
NDVI pixel grid
selected pixels for analysis
pre-restoration
post-restoration

elev (m)
High : 1924
Low : 1906

Lower Trout Creek

NDVI analysis area:
17.3 acres (78 pixels)

restoration start: 1999
restoration end: 2001

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a. Precipitation & NDVI, with 3-year running averages.

NDVI (w/ 3-yr avg)

precipitation (w/ 3-yr avg)

b. Pre- and post-restoration NDVI values plotted against 10-month prior cumulative precipitation.

pre-restoration

project construction / site transition

post-restoration

c. Predicted vs. actual NDVI values. (Predicted values are calculated from the pre-restoration regression equation in "b" above).

measured NDVI

predicted NDVI

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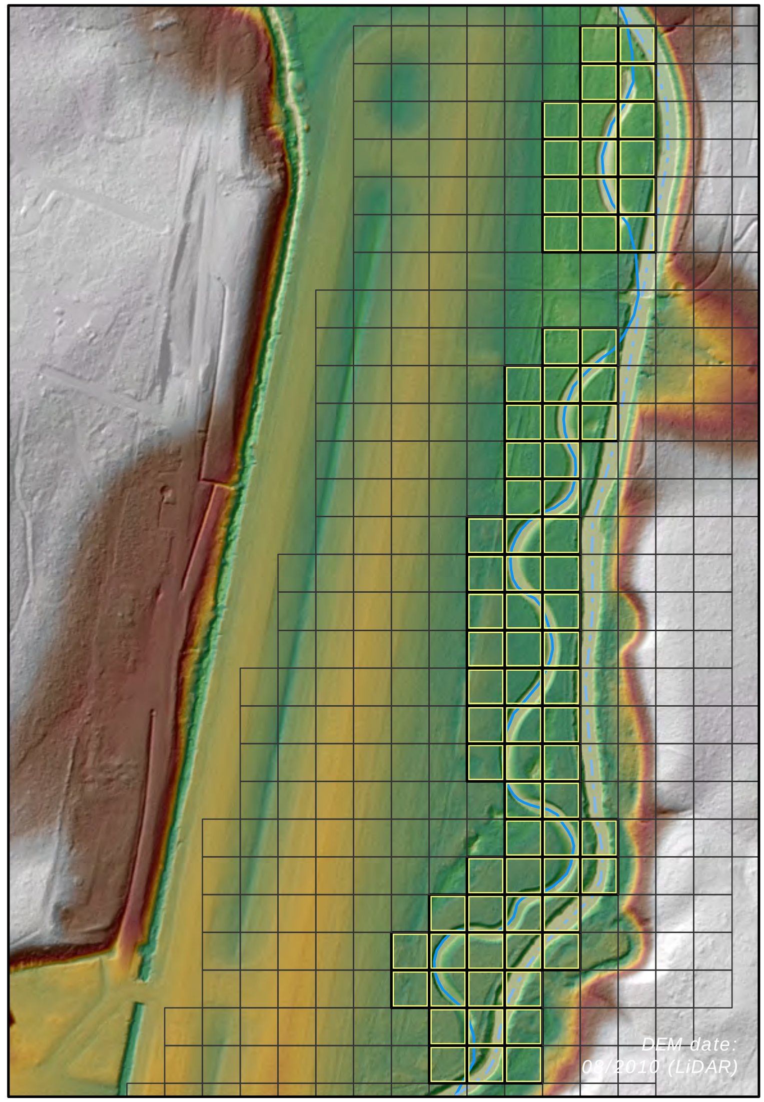

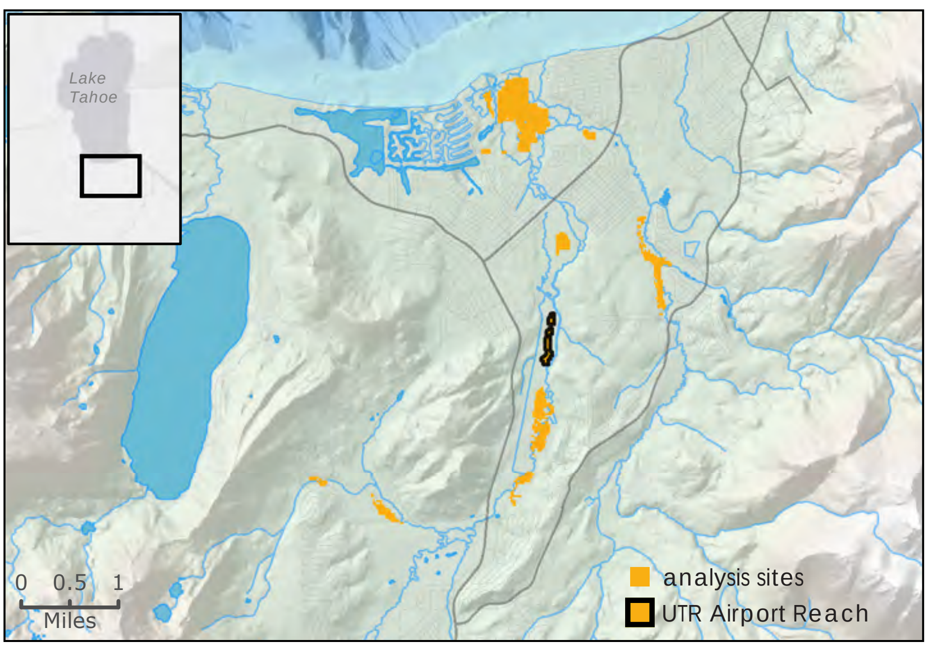

NDVI analysis area

NDVI pixel grid

selected pixels for analysis

pre-restoration

post-restoration

elev (m)

High : 1914

Low : 1902

UTR Airport Reach

NDVI analysis area:
17 acres (77 pixels)

restoration start: 2008
restoration end: 2011

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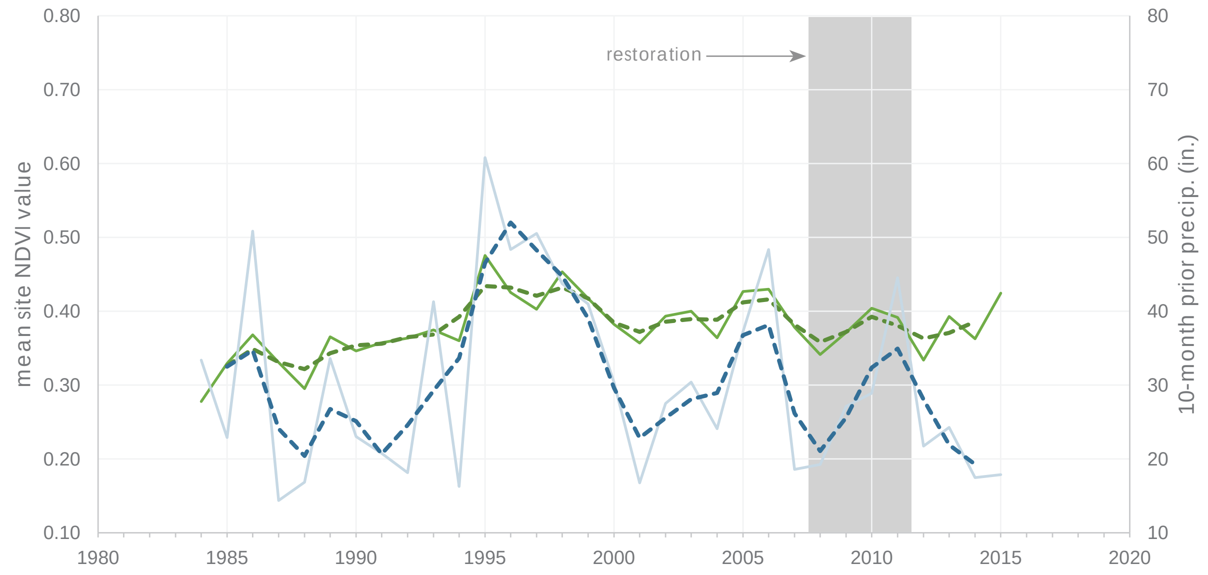
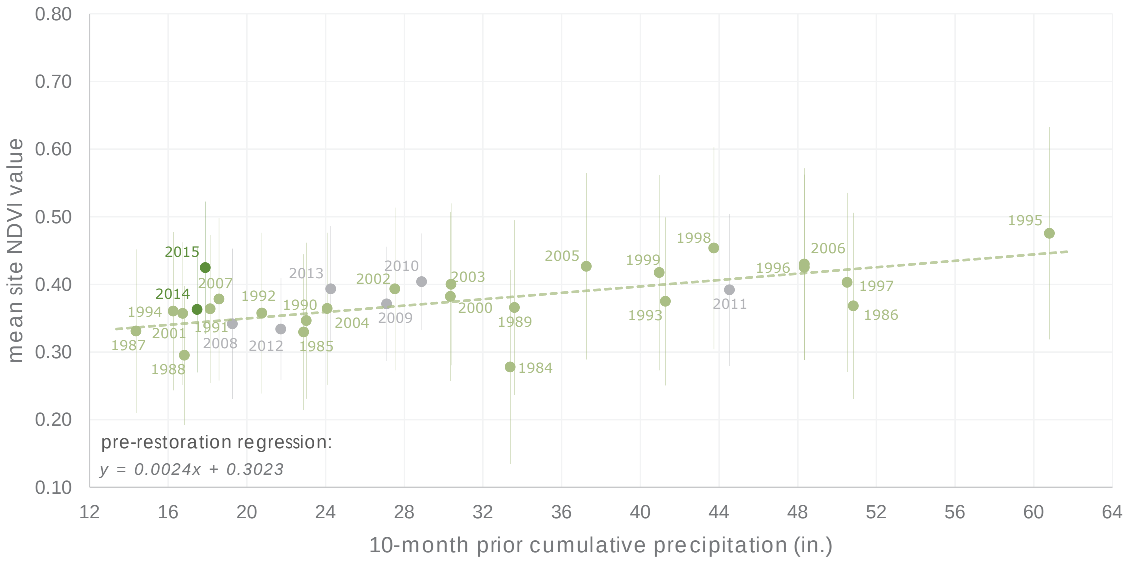


a. Precipitation & NDVI, with 3-year running averages.

NDVI (w/ 3-yr avg)

precipitation (w/ 3-yr avg)

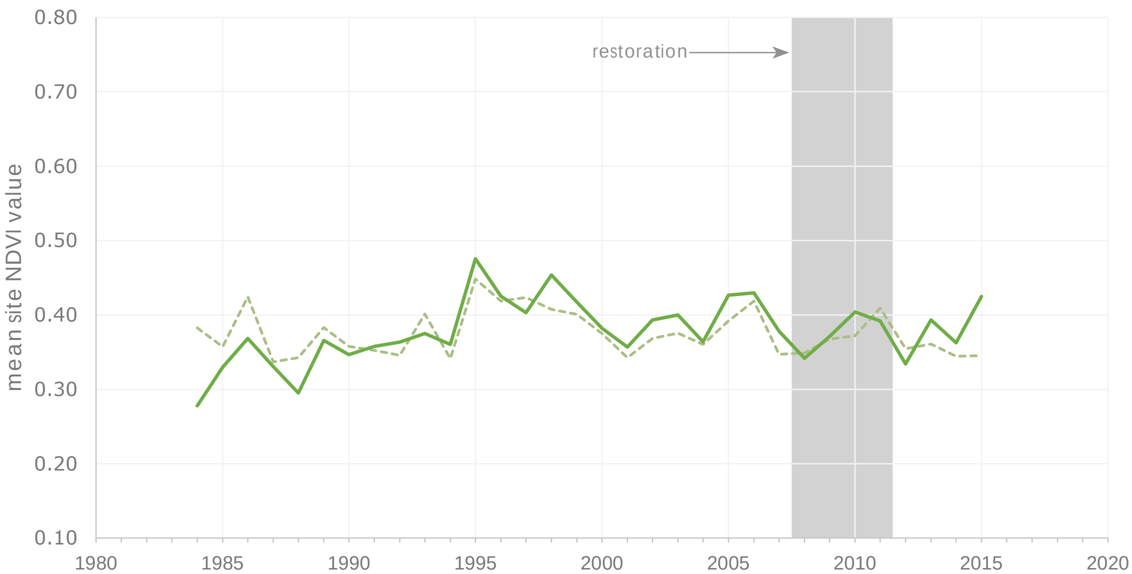


b. Pre- and post-restoration NDVI values plotted against 10-month prior cumulative precipitation.

pre-restoration

project construction / site transition

post-restoration



c. Predicted vs. actual NDVI values. (Predicted values are calculated from the pre-restoration regression equation in “b” above).

measured NDVI

predicted NDVI

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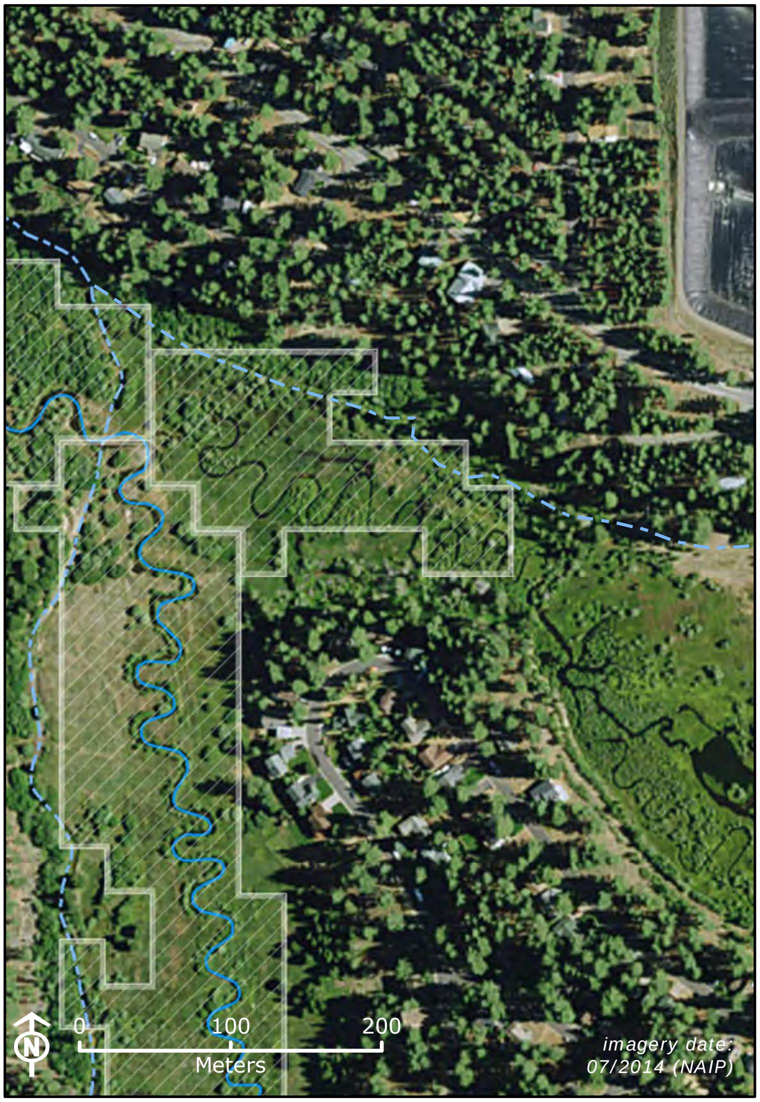

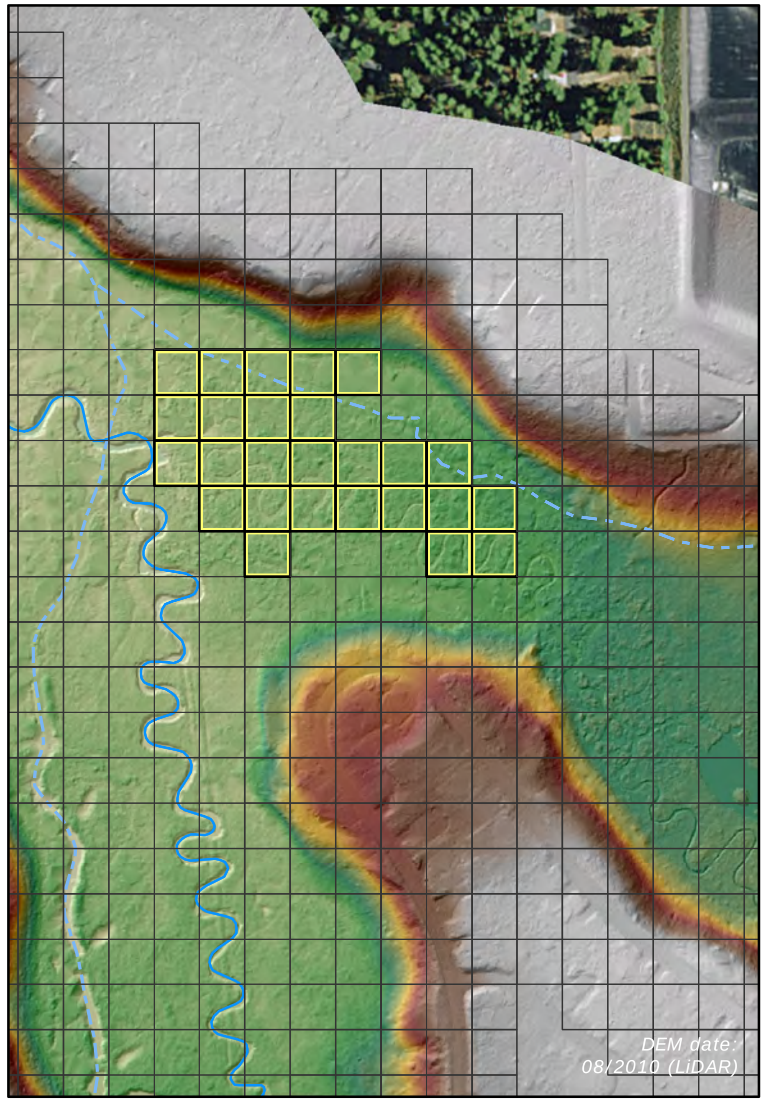

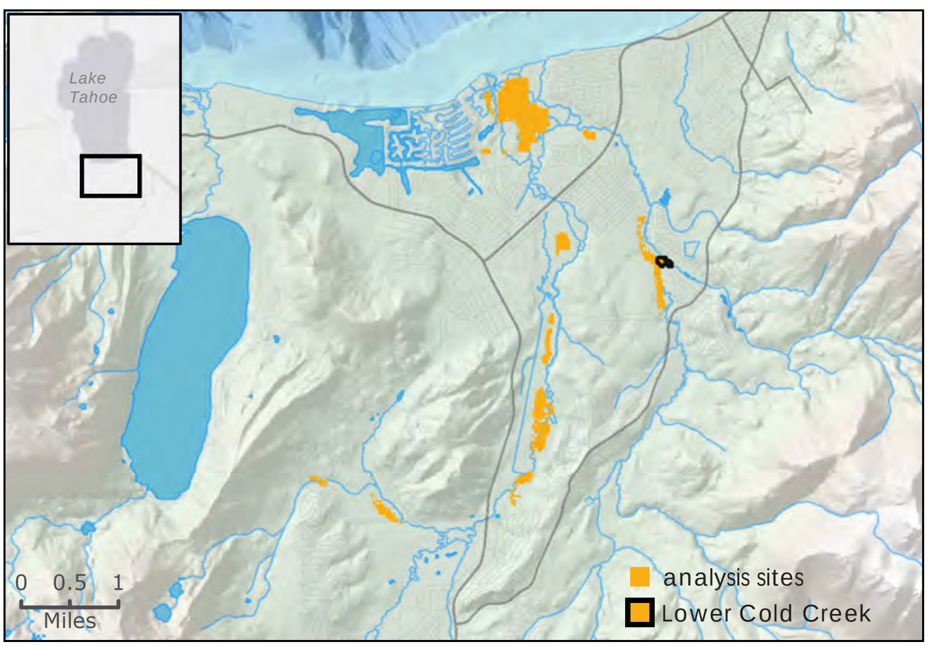

NDVI analysis area
NDVI pixel grid
selected pixels for analysis
pre-restoration
post-restoration

elev (m)
High : 1924
Low : 1906

Lower Cold Creek

NDVI analysis area:
5.77 acres (26 pixels)

restoration start: 1989
restoration end: 1989

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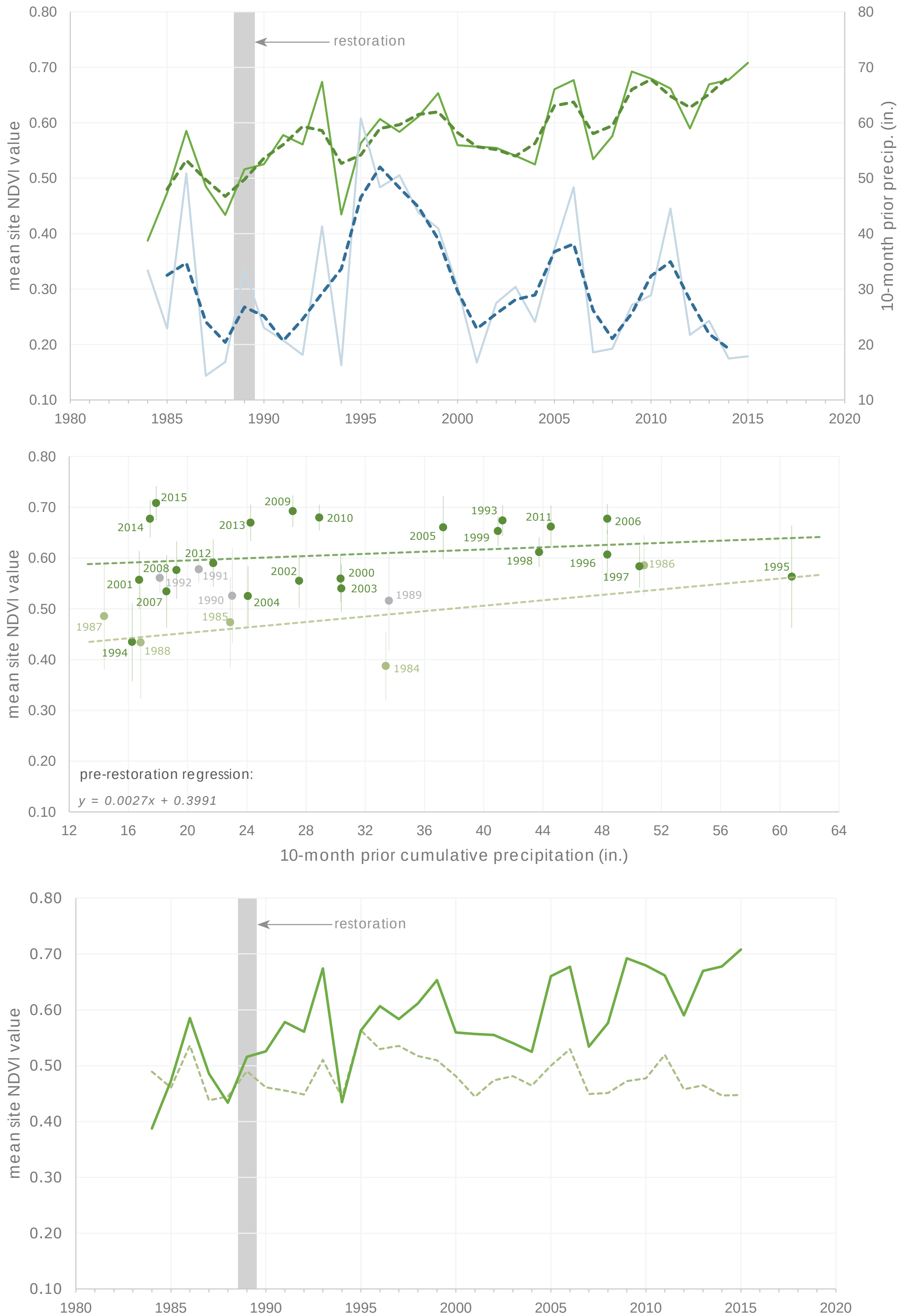

a. Precipitation & NDVI, with 3-year running averages.

b. Pre- and post-restoration NDVI values plotted against 10-month prior cumulative precipitation.

c. Predicted vs. actual NDVI values. (Predicted values are calculated from the pre-restoration regression equation in “b” above).

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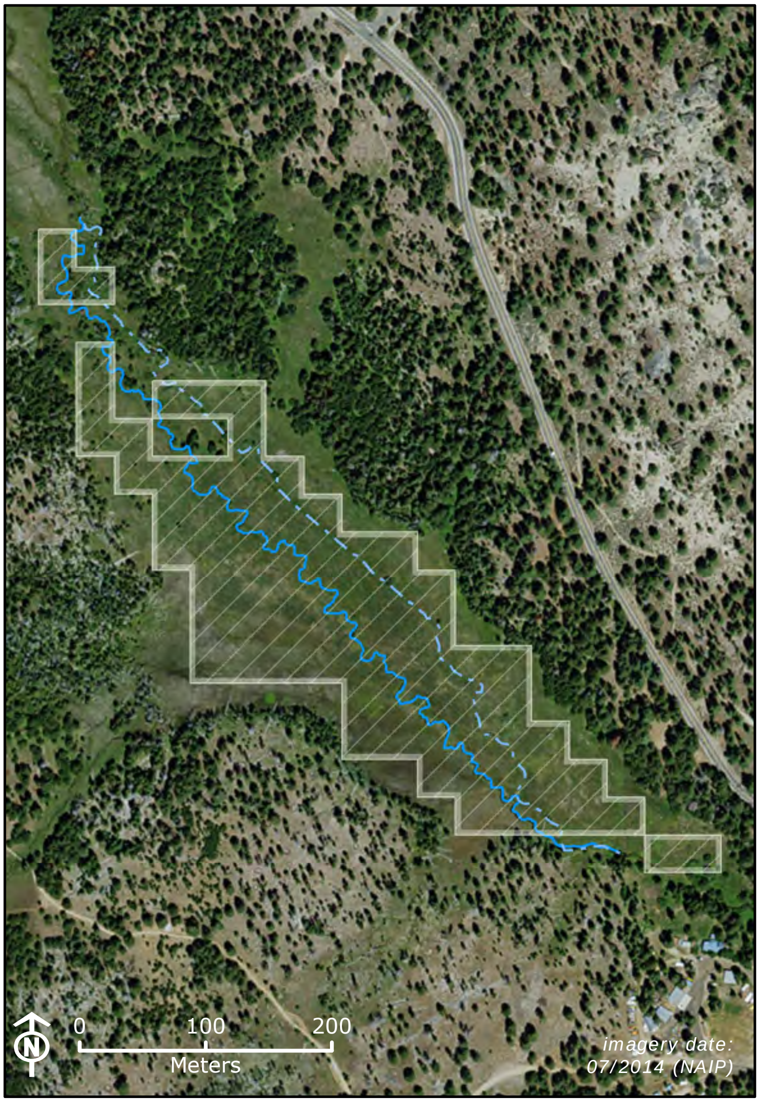
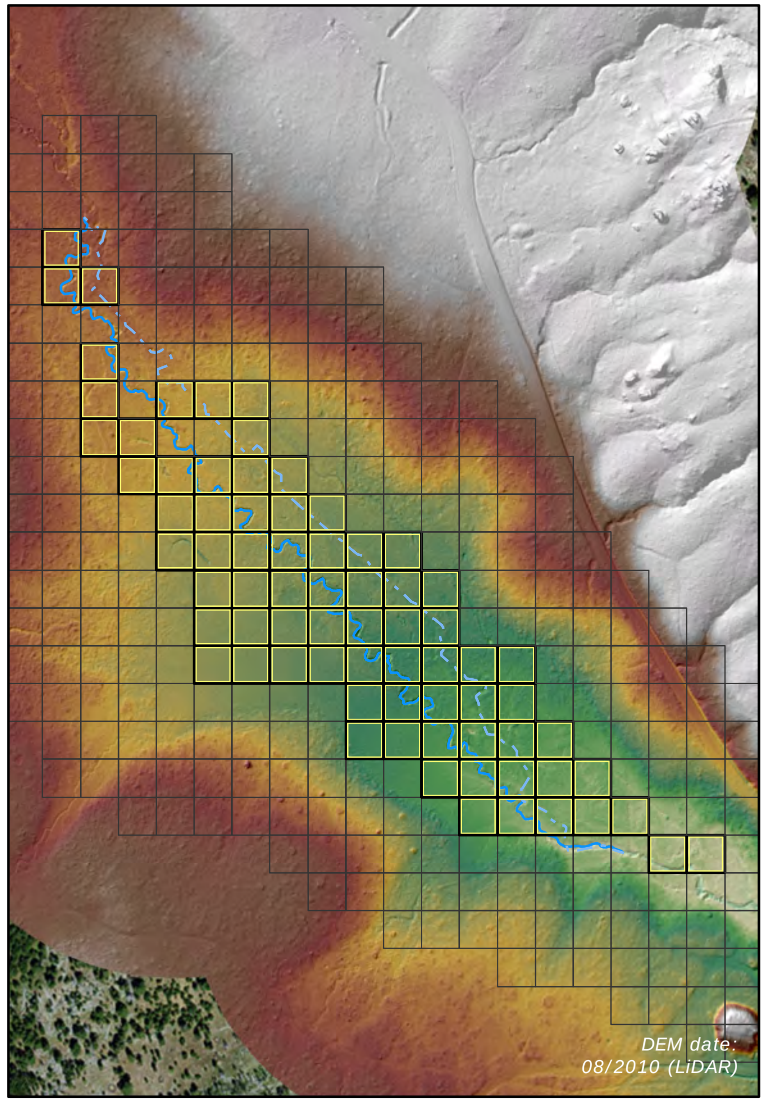
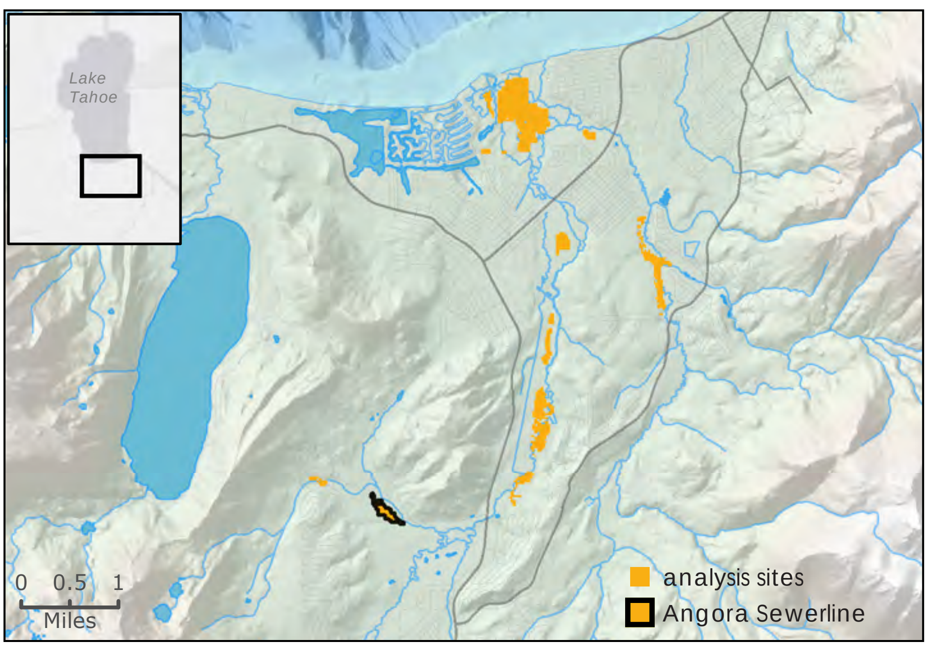
LOWER COLD CREEK

FIGURE 23







NDVI analysis area
NDVI pixel grid
selected pixels for analysis
pre-restoration
post-restoration

elev (m)
High : 1922
Low : 1914

Angora Cr. Sewerline

NDVI analysis area:
16.4 acres (74 pixels)

restoration start: 2002
restoration end: 2002

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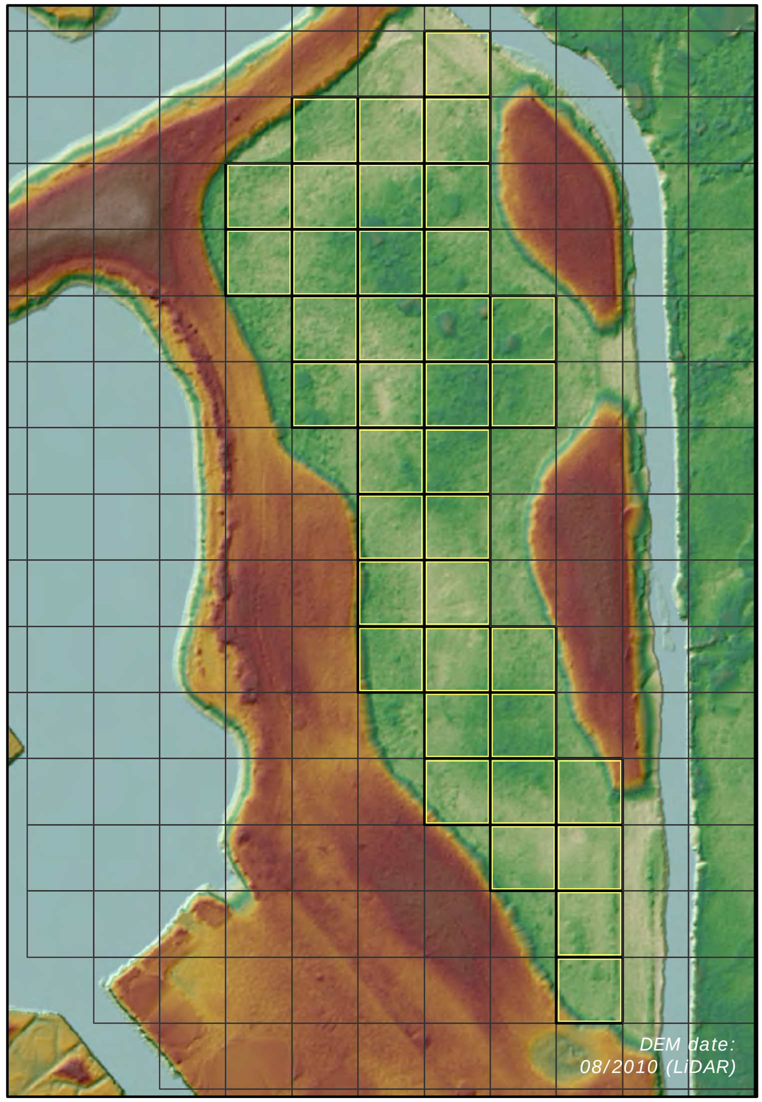
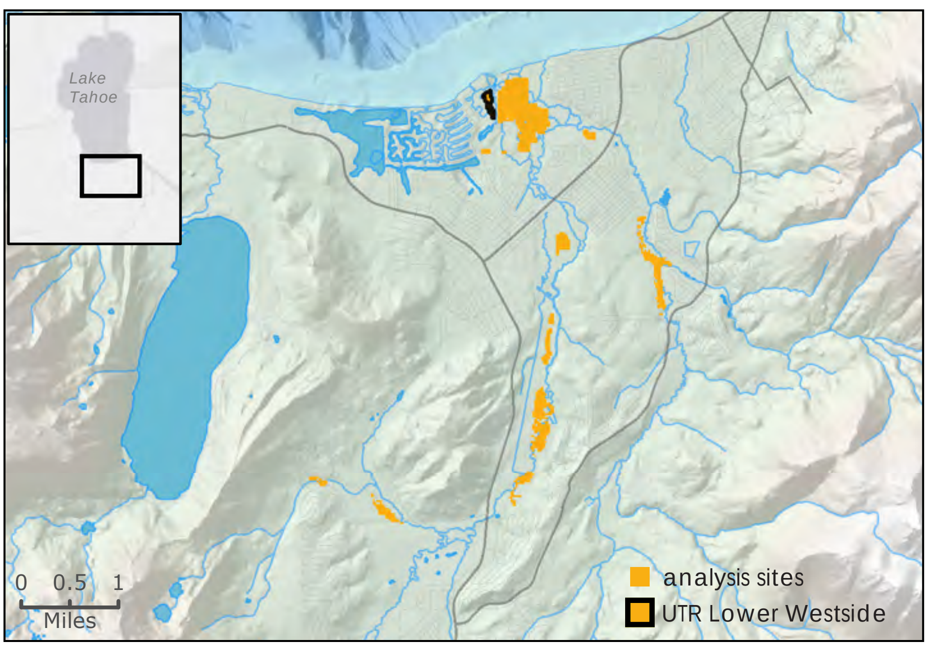
ANGORA CREEK SEWERLINE

FIGURE 25





NDVI analysis area
NDVI pixel grid
selected pixels for analysis
pre-restoration
post-restoration

elev (m)
High : 1903
Low : 1898

UTR Lower Westside

NDVI analysis area:
8.4 acres (38 pixels)

restoration start: 2001
restoration end: 2001

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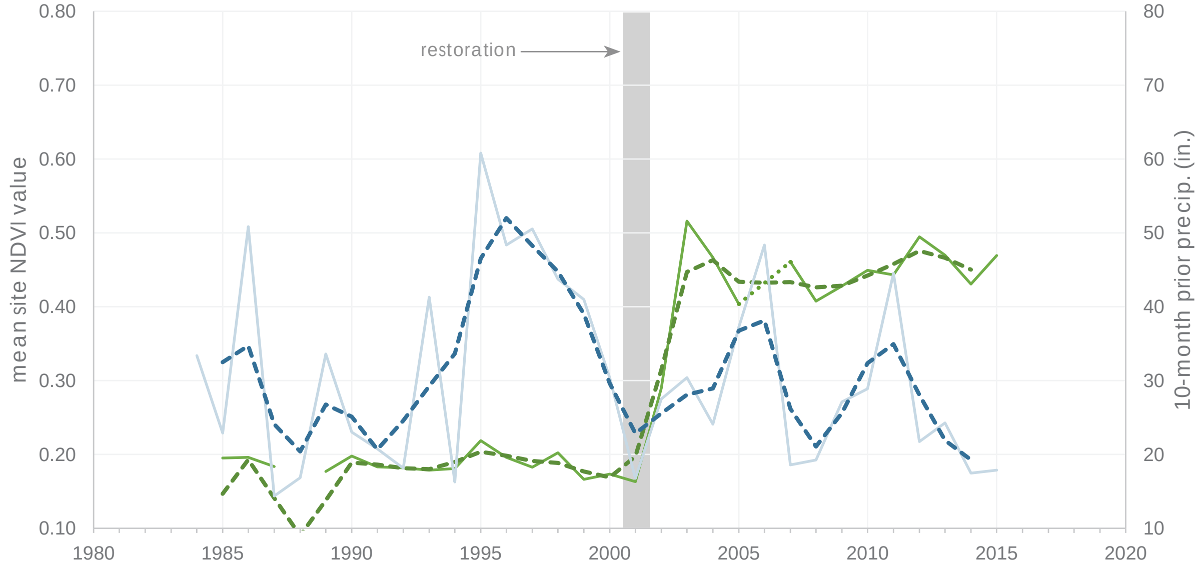
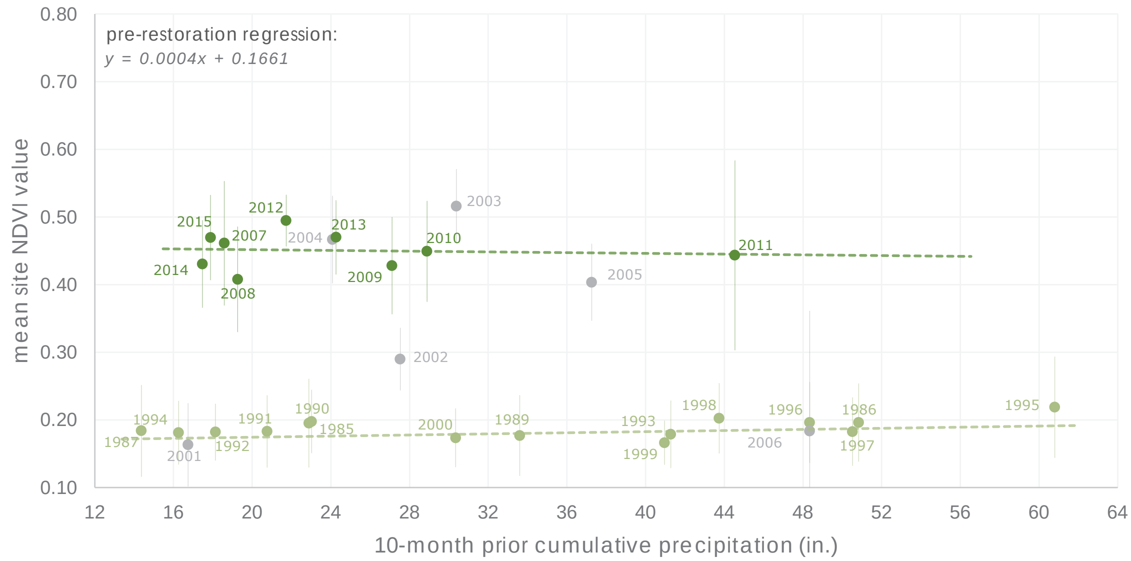


a. Precipitation & NDVI, with 3-year running averages.

NDVI (w/ 3-yr avg)

precipitation (w/ 3-yr avg)

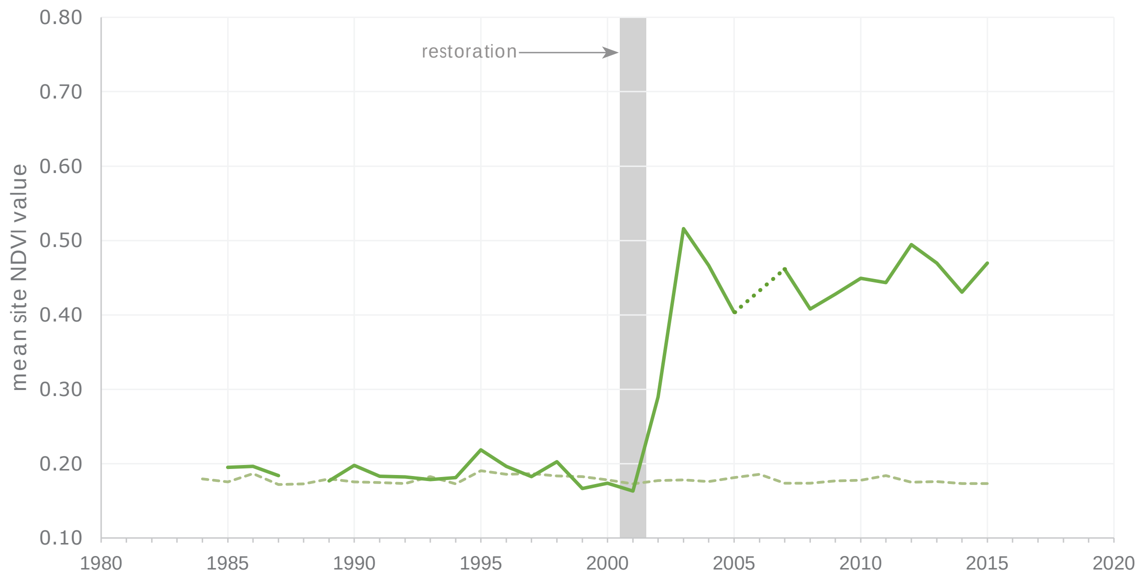


b. Pre- and post-restoration NDVI values plotted against 10-month prior cumulative precipitation.

pre-restoration

project construction / site transition

post-restoration



c. Predicted vs. actual NDVI values. (Predicted values are calculated from the pre-restoration regression equation in "b" above).

measured NDVI

predicted NDVI

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6.2 Analysis and Discussion

The results presented in FIGURES 10-29 tell a unique story for each of the analyzed sites.

Upper Truckee River Sunset Reach 5 project (FIGURES 10 and 11) illustrates how well an impaired site follows precipitation. Restoration began in 2013, so none of the data represent post-restoration conditions. These data show how annual NDVI values at an unrestored site generally track precipitation, with higher NDVI values occurring during years of greater precipitation (FIGURE 11a). Additionally, FIGURE 11c illustrates the relative accuracy of the precipitation-predicted NDVI values based on pre-restoration relationships. Continued annual tracking of this as well as other site NDVI conditions will be telling, but this extended record of pre-restoration NDVI and precipitation data, and the strength of the relationships, reinforces the significance of the comparative post-restoration data presented for the other eight sites. (See TABLE 3 for pre-restoration regression analysis slope coefficients, p-values and r-squared values).

FIGURES 12 and 13 show the results from the analysis of Upper Trout Creek. Upper Trout Creek is continually pointed to as an example of successful wet meadow restoration in the Tahoe Basin, and these results support this claim. While the annual variations of NDVI still follow the trends of annual precipitation, the overall NDVI values post-restoration are significantly greater than those pre-restoration (FIGURE 13a). This is seen in the dramatic upward shift in the post-restoration trend line from as compared to the pre-restoration data (FIGURE 13b), and in the deviation of the measured NDVI values from the predicted values following restoration (FIGURE 13c). Additional resources would allow the testing of other correlations, using the breadth of on the ground hydrology, water quality, vegetation, and biological datasets, with these NDVI findings. Strong responses in NDVI to restoration actions are also seen for Angora Creek SEZ (FIGURES 14 and 15) and Cookhouse Meadow (FIGURES 16 and 17).

Just downstream from Upper Trout Creek, Lower Trout Creek tells a slightly different story (FIGURES 18 and 19). The data as seen in all three charts (FIGURE 19a-c) do in fact show a change in mean site NDVI following restoration, but the change is far less pronounced than it is for Upper Trout Creek. Stream channel instability in Lower Trout Creek and renewed bed incision has occurred during elevated runoff events post restoration, and perhaps this is contributing to a diminished overall change in NDVI benefit from the project as time goes on. The Upper Truckee River Airport Reach (FIGURES 20 and 21) is another site that, so far, does not show a profound response in NDVI following restoration. However, this is likely due to the fact that ample time has not yet passed since the management actions were completed in order to see a response in the site's vegetation. Likewise, the restoration on Lower Cold Creek (FIGURES 22 and 23) was completed in 1989 and there are only 4 years of pre-restoration data. It is therefore difficult to say for this site what the NDVI-response to the restoration action was, given so few data points to which to compare.

Sometimes however the signal from NDVI does not fully capture the site restoration benefits. Angora Creek Sewerline for example is known to be a successful project in that the geomorphology of the stream was dramatically and quantifiably improved. The NDVI analysis for this site (FIGURES 24 and 25) doesn't show the dramatic changes that are seen at some of the other sites. Unlike many other sites, the pre-project NDVI values were relatively high. This site provides us an example and a lesson that a meadow site NDVI does have a ceiling—

even with improved accessibility to water, the site's vegetation may not be able to get any greener. While it is dramatic to see a site's mean NDVI increase from a 0.4 to 0.8 following restoration, if the pre-project condition site NDVI ranges between 0.5-0.6, then absolute restoration benefits as measured by this metric are harder to quantify.

Finally, as will be discussed below in Section 8, there are external elements that can greatly skew measured NDVI values and thus a need to account for these in future analyses. FIGURES 26 and 27 shows the data for the Upper Truckee Marsh Lower Westside project. A localized restoration effort included a plot of upland/infill that was lowered and re-connected to the floodplain. The NDVI data show the very dramatic effect that the site restoration had. However, in 2006 the measured NDVI value was close to 0.1—a dramatic difference from the 2005 and 2007 values of > 0.4. (This "false" data point is not plotted in the figures and instead the NDVI trend from 2005 to 2007 is shown as a dotted line). This low measurement was due to the fact that 2006 was a relatively wet year and at the time of sampling the site was covered in standing water, thereby decreasing the NDVI value significantly. Increasing the prevalence of standing water is a goal for many wet meadow restoration projects, so there needs to be a way to account for these instances when looking at NDVI values and assessing project benefits.

In conclusion:

(1) NDVI does show promise as a cost effective and objective approach to quantifying and reporting riparian restoration effectiveness.

(2) Restoration project effects as measured by NDVI are more pronounced during drier years than they are during wet years. During wet years water is far less of a limiting resource and thus functioning hydrologic connections between the floodplain vegetation and the shallow groundwater are not driving vegetative vigor.

(3) NDVI values have a ceiling where a restored meadow site can only get so green. This suggests that pre-project NDVI value may be useful to consider during restoration prioritization.

(4) There are other site variables that can skew NDVI and lead to low measurements when in fact a site may be in restored and functioning condition. Variables such as the presence of standing water may be an indication of good wet meadow site condition, but they will lead to "false negatives" in an NDVI-based effectiveness assessment.

7 CURRENT NDVI CONDITIONS

A preliminary analysis was conducted to explore if the NDVI data from the projects included could be used to identify other potential high priority areas for meadow restoration in the Upper Truckee River and Trout Creek watersheds. Using a simple approach, all of the pre-restoration mean NDVI values for each of the nine sites were plotted together against cumulative precipitation (FIGURES 28) and used to predict what a pre restoration NDVI threshold may be using minimal effort and resources.

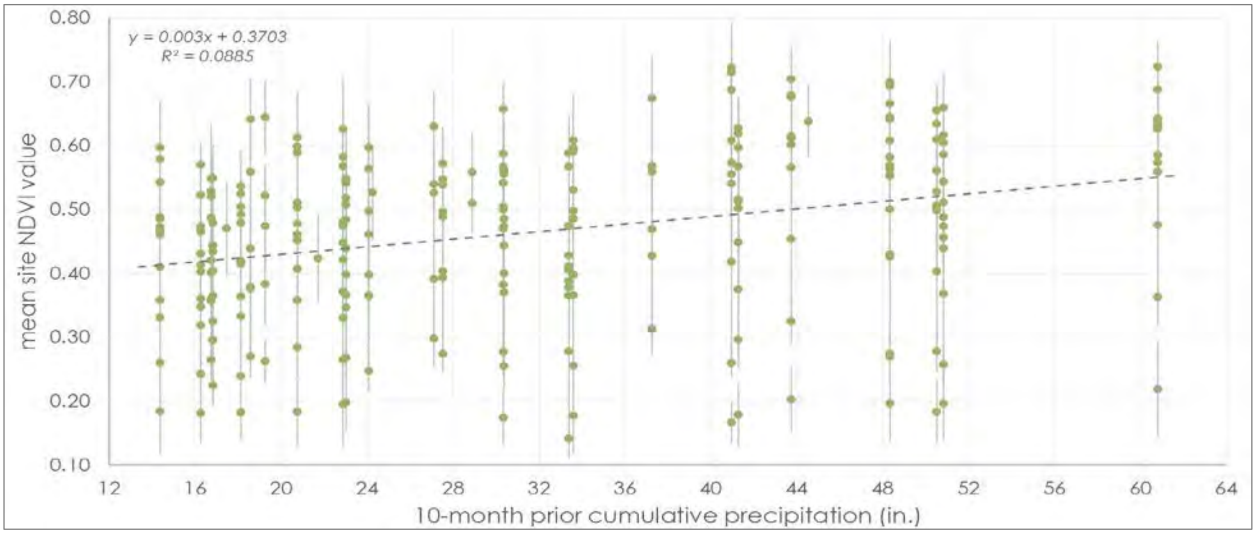
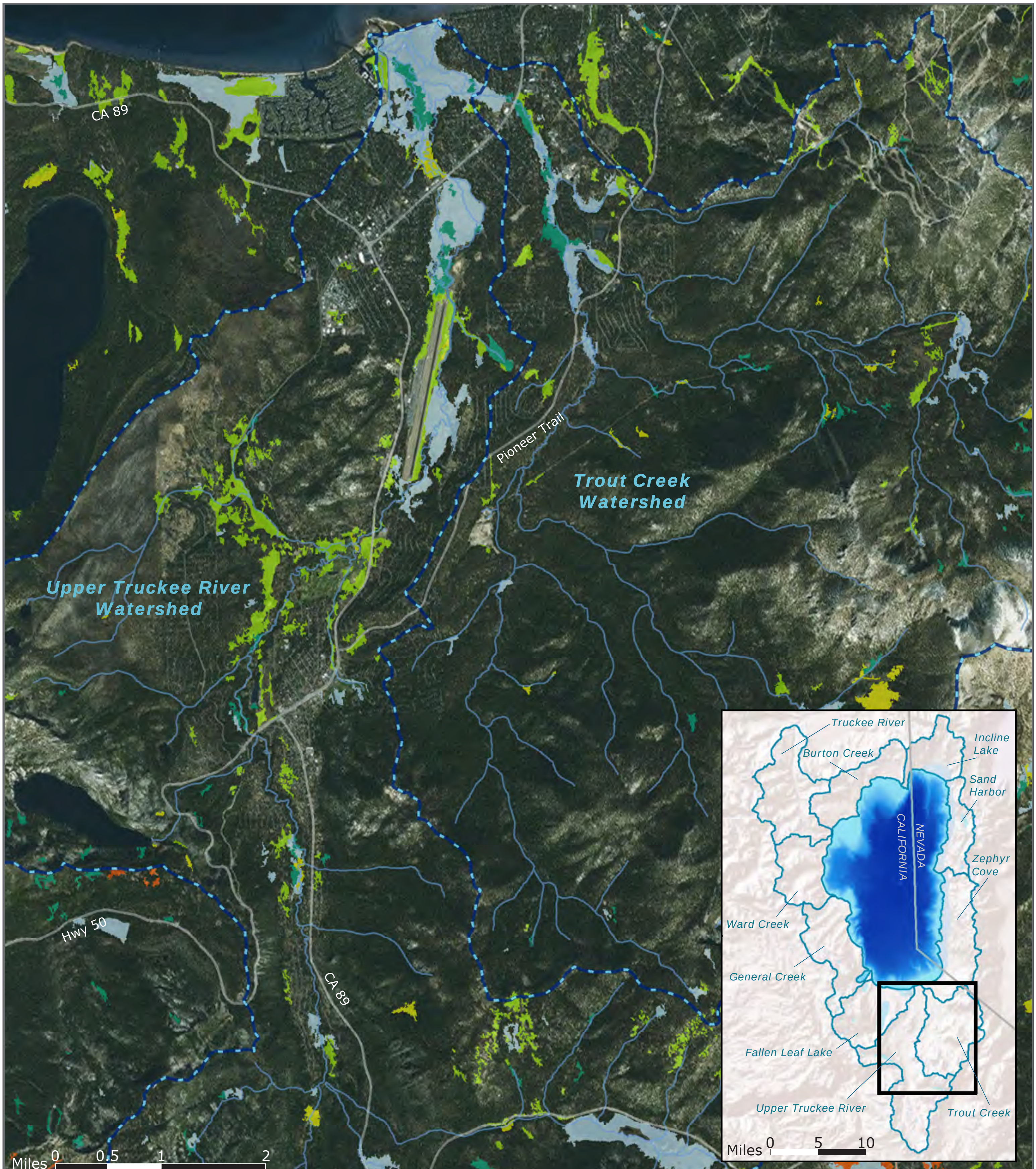


Figure 28 - Pre-restoration NDVI values for all nine sites included in this analysis. Pre-restoration data were fit with a linear regression model and this model was used to calculate expected threshold NDVI values for an example recent wet year and dry year.

A trend line was fit to these data and an equation for the all-sites relationship between pre-restoration NDVI and precipitation was calculated. This equation was then used to identify what a predicted NDVI value would be for an unrestored meadow site in a recent wet year (2011: precipitation = 44.5”, NDVI value = 0.504) and in a recent dry year (2014: precipitation = 17.5”, NDVI value = 0.423).

US Forest Service vegetation cover GIS data was used to identify all wet meadows, riparian areas, and grasslands in the Tahoe Basin to assess for potential future restoration priorities (FIGURE 29). In these wetland and meadow areas, late summer NDVI data from 2011 and 2014 were displayed and filtered to show only those areas that fall below the respective thresholds for pre-restoration NDVI value. These areas, mapped in FIGURE 30, represent sites where the NDVI value during a recent wet year and/or a recent dry year was below the expected value, based on our analysis of nine South Tahoe meadow restoration sites, and thus might be considered priorities for future restoration. Obviously this approach is biased by the condition of the sites that have been selected for restoration within this area. There are a number of improvements that can be made to use NDVI as a pre-project screening approach to consider site prioritization on a regional scale if resources become available. We provide some suggestions below.



Wetland / Meadow Vegetation Types

- annual grassland
- aspen
- montane riparian
- perennial grassland
- wet meadow
- watershed boundaries

Vegetation data sourced from USFS Pacific Southwest Region 5. Vegetation classes by "WHR Type".

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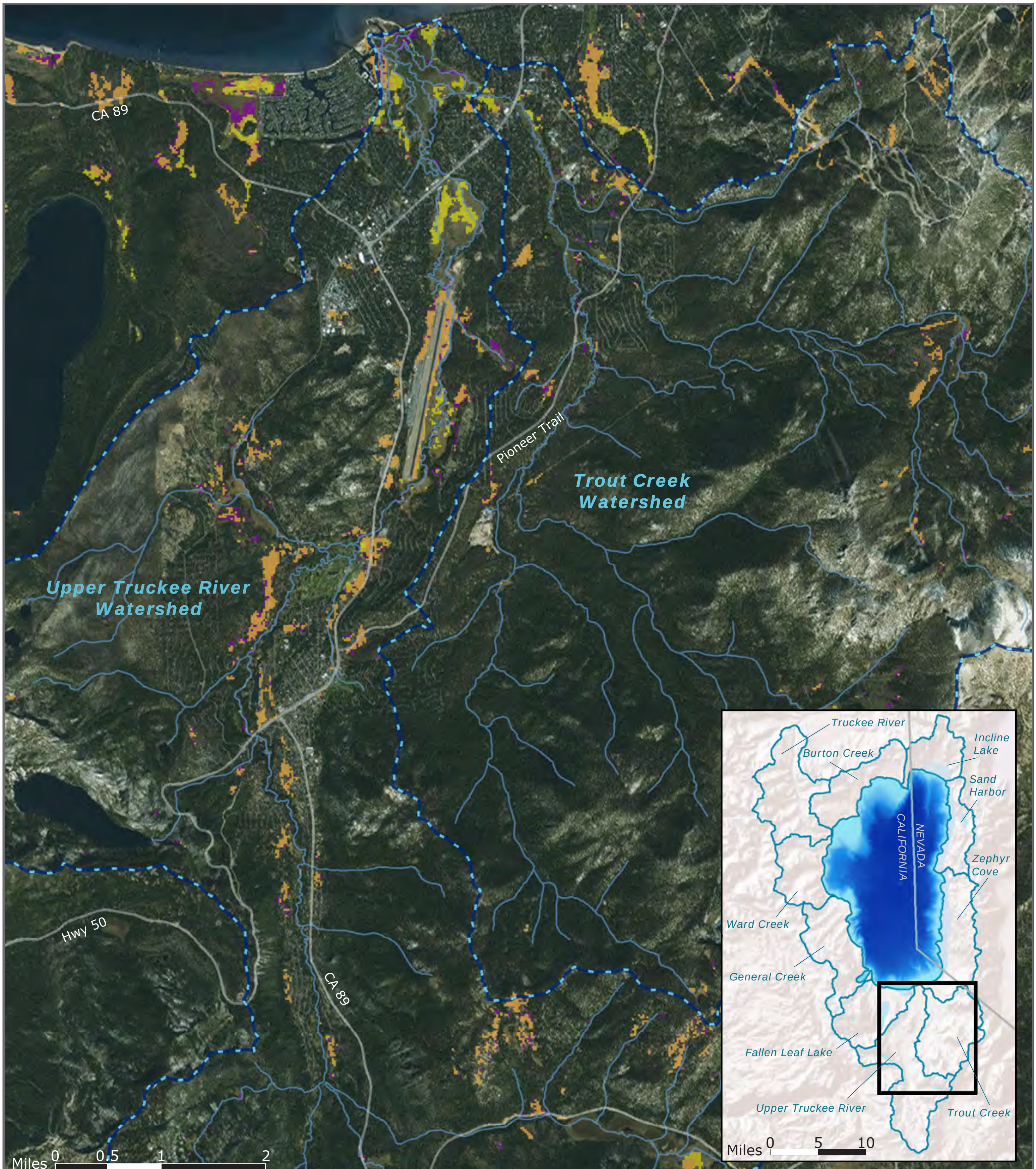
SOUTH TAHOE WETLAND & MEADOW VEGETATION

FIGURE 29



potential priority areas for future restoration

- areas below predicted NDVI value for DRY year
- areas below predicted NDVI value for WET year
- areas below predicted NDVI value for BOTH years
- watershed boundaries

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POTENTIAL AREAS FOR FUTURE WETLAND & MEADOW RESTORATION

FIGURE 30

8 Next Steps and Recommendations

This analysis was conducted with limited resources, yet illustrates great promise of using Landsat and NDVI as a defensible and cost effective approach to assess the relative effectiveness of restoration actions in montane wet meadows. All of the completed sites that were analyzed here illustrate a shift in NDVI values following restoration and additional validation of these data and field verification could allow investigation of the power that NDVI data can provide to prioritize and track restoration benefits. We outline recommended next steps below.

Data Source Precision

Generally speaking, the idea of heritage within an ongoing earth observation program such as the Landsat program ensures that analyses such as NDVI will be comparable across and between sensors and satellites (e.g., Landsat 5 to Landsat 8) (Loveland and Dwyer 2012). That said, there is the potential for radiometric variance between images. An easy next step to test for this would be to check the consistency of reflectance of dark targets both between and within image sources. (Vincente-Serrano et al. 2008 provide a discussion of methods for performing radiometric corrections and considerations for when and when not to do so). Additionally, Landsat imagery for any given year should be screened based on known events (such as major wildfires or volcanic eruptions) that may lead to an elevated presence of fine atmospheric particulates that might influence the spectral reflectance of the landscape as read by a satellite, and thus the measured NDVI values. While it is difficult to correct the images for such particulates, noting the existence of questionable images/dates can help explain outliers when analyzing the data.

Phenology & Timing of Sampling

Section 4.1 discussed the question of when during the year is the optimal time for sampling NDVI in order to capture differences between well-functioning and poorly-functioning sites. The data used to generate Figure 5 came from 33 specific 30x30 meter pixels that were visited during the late summer in 2015. These sites represented the full spectrum of meadow functional condition and we believe are representative and accurately address the question at hand. However, a more in-depth GIS exercise and analysis of more pixels would provide much greater resolution to the seasonal phenology of pixel-specific NDVI across a more complete range of conditions, and could more concretely address the question of data collection timing. This could additionally be accomplished by calculating a set of NDVI difference images for candidate time periods.

Standing Water

As mentioned above in Section 6.2, standing water in montane meadows—particularly during the late summer—can be an indicator of hydrologic connectivity and a functioning wet meadow system. However, NDVI reads water as a negative value and thus the presence of water in an image can dramatically reduce the site's mean NDVI value. Further research is needed on how best to address this issue in regards to the application discussed here. One option would be to plot the full distribution of NDVI values for each site rather than just the mean, and then identify and remove any obvious water-induced outliers. Another option might be to incorporate other remote sensing indices such as the Normalized Difference Water Index (NDWI) to assess the relative "wetness" of pixels and/or sites and use that information in conjunction with NDVI as a measure of site functionality and thus restoration effectiveness.

Additionally, as the availability of VHR imagery (very high spatial resolution, sub-5 meter) grows in the future, that information can be used to help quantify the proportion of each pixel that is vegetation vs. standing water and thus correct for any abnormal NDVI readings. Currently, VHR imagery is temporally rare and prohibitively expensive. However, the prevalence and use of multispectral sensors on drones may help make this technology and these images more accessible and affordable in the near future.

Field Verification and Relative Visual Greenness

With more resources a field verification element could be introduced into this analysis that would have the potential to dramatically improve the precision with which we can interpret relative NDVI values. First, given that NDVI is a remotely sensed measure of "greenness", it would be immensely useful to develop a relative visual greenness scale that could be used to help interpret differences in NDVI measurements and understand the differences between our visual interpretation of greenness and what the satellite sees. Figure 31 is a preliminary attempt at compiling existing photos from the field and ordering them on a scale according to their color, and the density and the height of foliage. A refined output along these lines would be a useful tool for managers to help bridge the academic and technical concepts behind the NDVI analysis and what can actually be seen on the ground at the site.

Finally, this analysis is based on a theoretical interpretation of plant phenology, meadow geomorphology and ecological condition, how these elements combine under different restoration conditions and how they are viewed through the lens of NDVI. There is a trove of valuable datasets that describe the hydrological, geomorphological and vegetative conditions of numerous sites throughout the Lake Tahoe Basin. These data have the potential to synergistically combine with this NDVI methodology to provide an incredibly rich tool that can be used to assess far more than just what we addressed in this analysis. Additional resources would allow these data to be explored and analyzed, and then complimented with rapid field assessments to create a robust tool with the ability to remotely assess not only vegetative condition, but perhaps soil carbon storage and hydro-geomorphology as well.

NDVI Analysis

In this study, we used a 10-month precipitation metric to adjust NDVI values, knowing that this time period was likely to have a substantial influence on the health of the vegetation. However, wetness conditions over longer and shorter time periods may also have a substantial

90-100% green: little to zero bare ground, little to zero dry/dead material, relatively dense/thick cover.

25-75% green: some bare ground, some dry/dead material, dense/thick cover in some places, but others not.

0-10% green: lots of bare ground, majority dry/dead material, thin/sparse/low cover.

★ *photos for which we have corresponding NDVI values*

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DRAFT VISUAL GREENNESS SCALE

FIGURE 31

influence on the NDVI. Better representation of the wetness conditions before each satellite image was captured would improve our ability to separate NDVI changes that are due to restoration actions from those that are due to the climate variability. This work would focus on creating a composite precipitation metric that includes precipitation totals for all relevant timeframes and calculating a metric to represent potential evapotranspiration for the period prior image capture.

Modeling of the effects of differing wetness conditions can be improved by incorporating more sophisticated techniques. Pixel data tends to be spatially autocorrelated and time series data often exhibit temporal autocorrelation. This can cause the residuals of linear models to be non-normal, making the corresponding equation unreliable. By including terms to model these sources of error within the models, we can generate more robust statistical relationships between the NDVI and rainfall.

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Inventory of Late Growing Season Landsat Imagery for the Lake Tahoe Basin

WY	WY Type	Date	Satellite	QUAL: S. Basin	QUAL: N. Basin	Notes
WY15	Very Dry	8/21/2015	LS8	4	4	
WY15	Very Dry	8/5/2015	LS8	4	4	
WY15	**Very Dry**	**7/20/2015**	**LS8**	**5**	**4**	
WY15	Very Dry	7/4/2015	LS8	1	1	
WY14	Dry	8/18/2014	LS8	5	5	
WY14	Dry	8/10/2014	LS7	3	5	
WY14	**Dry**	**8/2/2014**	**LS8**	**4**	**4**	
WY14	Dry	7/17/2014	LS8	4	2	
WY14	Dry	7/1/2014	LS8	5	5	
WY13	Average	8/31/2013	LS8	4	3	
WY13	Average	8/15/2013	LS8	5	5	
WY13	**Average**	**7/30/2013**	**LS8**	**5**	**5**	
WY13	Average	7/25/2013	LS7	5	5	*scn lines in upper marsh*
WY13	Average	7/14/2013	LS8	4	5	
WY12	**Dry**	**8/20/2012**	**LS7**	**4**	**5**	*scn lines in upper marsh*
WY12	Dry	8/4/2012	LS7	3	3	*scn lines in upper marsh; clouds*
WY12	Dry	7/19/2012	LS7	1	1	
WY11	Wet	8/26/2011	LS5	5	5	
WY11	Wet	8/18/2011	LS7	3	5	*scn lines in upper marsh*
WY11	**Wet**	**8/10/2011**	**LS5**	**5**	**5**	
WY11	Wet	8/2/2011	LS7	3	4	*scn lines in upper marsh*
WY11	Wet	7/25/2011	LS5	5	5	
WY11	Wet	7/17/2011	LS7	3	4	*scn lines in upper marsh*
WY11	Wet	7/9/2011	LS5	4	4	
WY10	Average	8/23/2010	LS5	4	4	
WY10	Average	8/15/2010	LS7	3	5	*scn lines in upper marsh*
WY10	**Average**	**8/7/2010**	**LS5**	**5**	**5**	
WY10	Average	7/30/2010	LS7	3	5	*scn lines in upper marsh*
WY10	Average	7/22/2010	LS5	5	5	
WY10	Average	7/14/2010	LS7	3	4	*scn lines in upper marsh*
WY10	Average	7/6/2010	LS5	5	5	
WY09	Average	8/12/2009	LS7	4	4	*scn lines in upper marsh*
WY09	**Average**	**8/4/2009**	**LS5**	**5**	**5**	
WY09	Average	7/27/2009	LS7	5	5	*scn lines in upper marsh*
WY09	Average	7/19/2009	LS5	4	5	
WY09	Average	7/11/2009	LS7	1	1	
WY08	Dry	8/17/2008	LS5	5	5	
WY08	Dry	8/9/2008	LS7	5	5	*scn lines in upper marsh*
WY08	**Dry**	**8/1/2008**	**LS5**	**5**	**5**	
WY08	Dry	7/24/2008	LS7	5	5	*scn lines in upper marsh*
WY08	Dry	7/16/2008	LS5	5	5	

Data Quality:

1. unusable
2. heavy clouds, snow and/or scan lines; some but not all sites visible
3. minor clouds or other, but warrants correction/masking if possible
4. minor cirrus clouds or other; likely OK without correction
5. no issues, clean image

** bold entries indicate the scenes that were selected for this analysis*

***In many cases where scan lines in LS7 imagery are present, their effect is localized and can easily be corrected to make the image usable*

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WY	WY Type	Date	Satellite	QUAL: S. Basin	QUAL: N. Basin	Notes
WY07	Dry	8/15/2007	LS5	5	5	
WY07	Dry	8/7/2007	LS7	5	5	*scn lines in upper marsh (quite bad)*
WY07	**Dry**	**7/30/2007**	**LS5**	**5**	**5**	
WY07	Dry	7/22/2007	LS7	5	5	*scn lines in upper marsh (quite bad)*
WY07	Dry	7/14/2007	LS5	5	5	
WY06	Wet	8/12/2006	LS5	5	5	
WY06	Wet	8/4/2006	LS7	3	5	*scn lines in upper marsh*
WY06	**Wet**	**7/27/2006**	**LS5**	**5**	**5**	
WY06	Wet	7/19/2006	LS7	3	5	*scn lines in upper marsh*
WY05	Wet	8/17/2005	LS7	3	5	*scn lines in upper marsh*
WY05	**Wet**	**8/9/2005**	**LS5**	**5**	**5**	
WY05	Wet	8/1/2005	LS7	3	5	*scn lines in upper marsh*
WY05	Wet	7/24/2005	LS5	5	5	
WY05	Wet	7/16/2005	LS7	3	5	*scn lines in upper marsh*
WY04	Dry	8/14/2004	LS7	3	5	*scn lines in upper marsh*
WY04	**Dry**	**8/6/2004**	**LS5**	**5**	**5**	
WY04	Dry	7/29/2004	LS7	3	5	*scn lines in upper marsh*
WY04	Dry	7/21/2004	LS5	5	5	
WY04	Dry	7/13/2004	LS7	3	5	*scn lines in upper marsh*
WY03	Average	8/12/2003	LS7	3	5	*scn lines in upper marsh*
WY03	Average	8/4/2003	LS5	3	5	
WY03	Average	7/27/2003	LS7	3	5	*scn lines in upper marsh*
WY03	**Average**	**7/19/2003**	**LS5**	**5**	**5**	
WY02	Average	8/9/2002	LS7	5	5	
WY02	**Average**	**8/1/2002**	**LS5**	**5**	**5**	
WY02	Average	7/24/2002	LS7	4	5	
WY02	Average	7/16/2002	LS5	5	5	
WY01	Very Dry	8/14/2001	LS5	5	5	
WY01	Very Dry	8/6/2001	LS7	4	5	
WY01	**Very Dry**	**7/29/2001**	**LS5**	**5**	**5**	
WY01	Very Dry	7/21/2001	LS7	5	5	
WY00	Average	8/11/2000	LS5	5	5	
WY00	Average	8/3/2000	LS7	2	1	
WY00	**Average**	**7/26/2000**	**LS5**	**5**	**5**	
WY00	Average	7/18/2000	LS7	5	5	
WY99	Wet	8/17/1999	LS7	5	5	
WY99	**Wet**	**8/1/1999**	**LS7**	**5**	**5**	
WY99	Wet	7/24/1999	LS5	5	5	
WY99	Wet	7/16/1999	LS7	5	5	
WY98	**Wet**	**8/6/1998**	**LS5**	**5**	**5**	
WY98	Wet	7/21/1998	LS5	4	5	
WY97	Very Wet	8/19/1997	LS5	1	1	
WY97	**Very Wet**	**8/3/1997**	**LS5**	**5**	**5**	
WY97	Very Wet	7/18/1997	LS5	5	5	

Data Quality:

1. unusable
2. heavy clouds, snow and/or scan lines; some but not all sites visible
3. minor clouds or other, but warrants correction/masking if possible
4. minor cirrus clouds or other; likely OK without correction
5. no issues, clean image

** bold entries indicate the scenes that were selected for this analysis*

***In many cases where scan lines in LS7 imagery are present, their effect is localized and can easily be corrected to make the image usable*

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WY	WY Type	Date	Satellite	QUAL: S. Basin	QUAL: N. Basin	Notes
WY96	**Very Wet**	**7/31/1996**	**LS5**	**5**	**5**	
WY95	Very Wet	8/14/1995	LS5	5	5	
WY95	**Very Wet**	**7/29/1995**	**LS5**	**5**	**5**	
WY94	Very Dry	8/11/1994	LS5	3	5	
WY94	**Very Dry**	**7/26/1994**	**LS5**	**4**	**4**	
WY93	**Wet**	**8/8/1993**	**LS5**	**5**	**5**	
WY93	Wet	7/23/1993	LS5	1	1	
WY92	Dry	8/21/1992	LS5	5	5	
WY92	**Dry**	**8/5/1992**	**LS5**	**5**	**5**	
WY92	Dry	7/20/1992	LS5	5	5	
WY91	Dry	8/3/1991	LS5	2	2	
WY91	**Dry**	**7/18/1991**	**LS5**	**5**	**5**	
WY90	**Dry**	**8/16/1990**	**LS5**	**5**	**5**	
WY89	Wet	8/13/1989	LS5	5	5	
WY89	**Wet**	**7/28/1989**	**LS5**	**5**	**5**	
WY88	**Very Dry**	**8/26/1988**	**LS5**	**5**	**5**	*best available; later than desired*
WY88	Very Dry	7/25/1988	LS5	2	2	
WY87	Very Dry	8/8/1987	LS5	5	5	
WY87	**Very Dry**	**7/23/1987**	**LS5**	**5**	**5**	
WY86	**Very Wet**	**8/5/1986**	**LS5**	**5**	**5**	
WY86	Very Wet	7/20/1986	LS5	5	5	
WY85	**Dry**	**8/2/1985**	**LS5**	**5**	**5**	
WY85	Dry	7/17/1985	LS5	5	5	
WY84	**Wet**	**7/30/1984**	**LS5**	**5**	**5**	

Data Quality:

1. unusable
2. heavy clouds, snow and/or scan lines; some but not all sites visible
3. minor clouds or other, but warrants correction/masking if possible
4. minor cirrus clouds or other; likely OK without correction
5. no issues, clean image

** bold entries indicate the scenes that were selected for this analysis*

***In many cases where scan lines in LS7 imagery are present, their effect is localized and can easily be corrected to make the image usable*