SOUTHERN ROCKIES
Landscape Conservation Cooperative

Remote Sensing Time Series Approaches for Assessing Vegetation Changes on Abandoned Oil and Gas Pads of the Colorado Plateau

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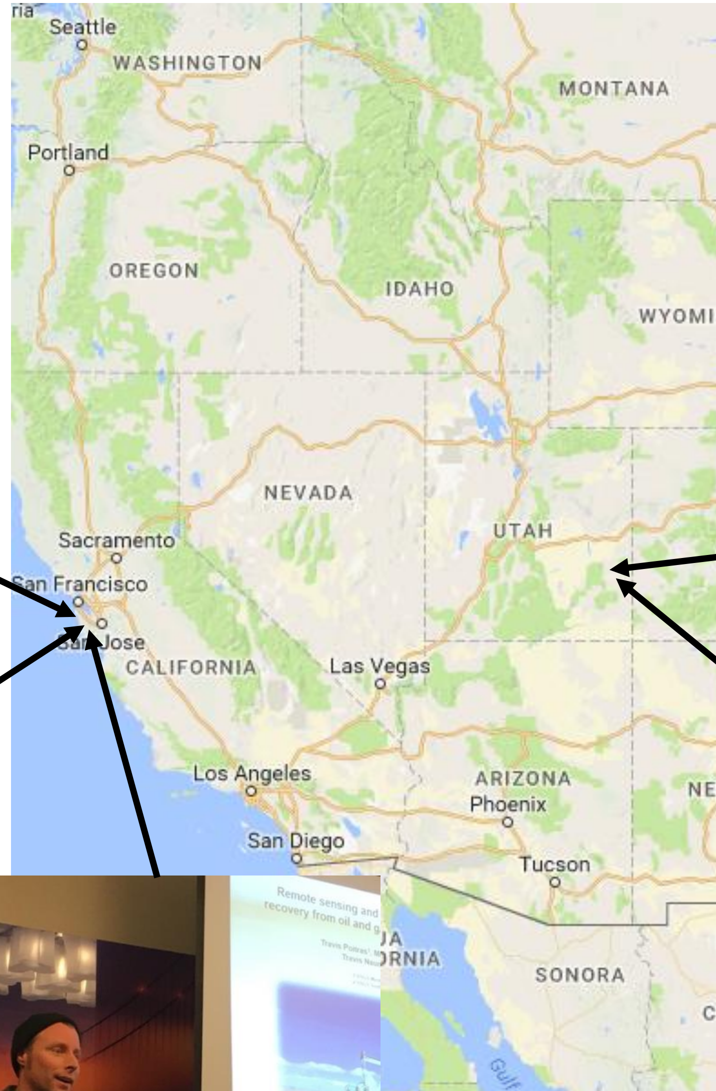

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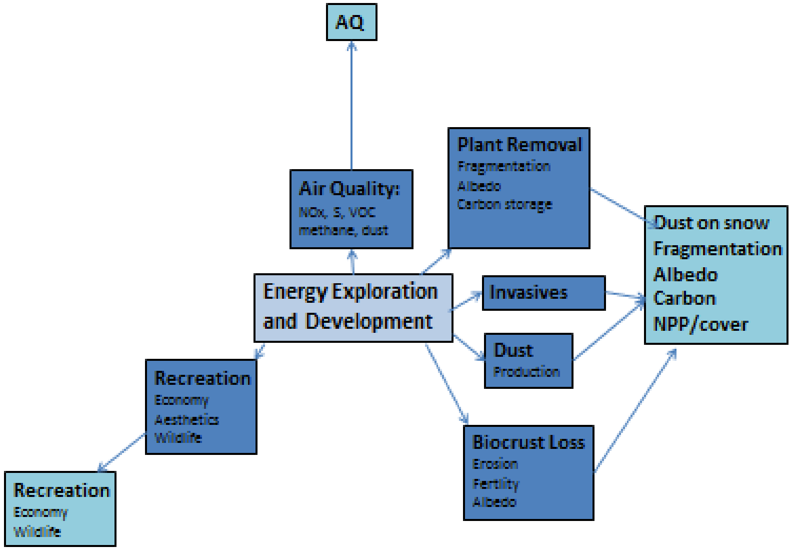
Southwest Energy Development & Drought (SWEDD)

- New multi-center USGS project
  - Southwest Biological Science Center
  - Western Geographic Science Center
  - Western Ecological Research Center
  - Fort Collins Science Center
- Initial efforts focused on the impacts of and restoration from traditional oil and gas activities.
  - Impacts to social-ecological systems at the plot to regional scale
  - Rehabilitation of roads and pads
  - Integrated analysis and scenario development

Priority Ecosystems Science



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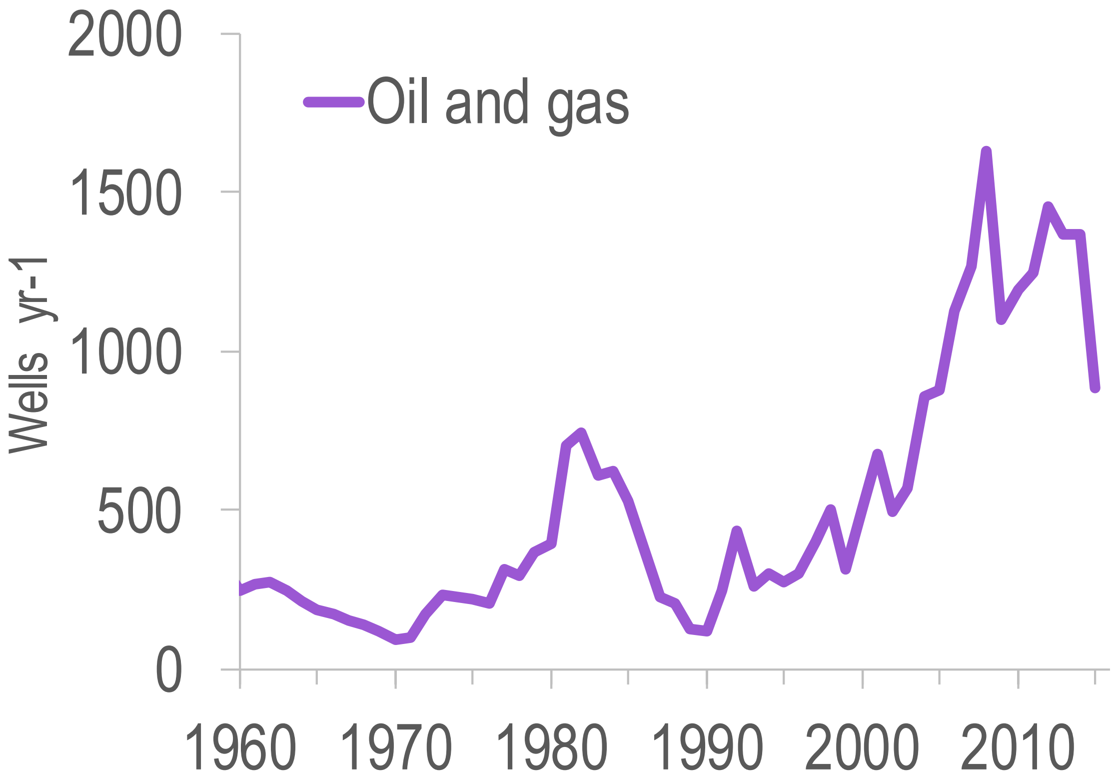
Recent Trends in Oil & Gas Development in Utah



Shown are total annual oil and/or gas wells drilled per year in Utah.

Utah Department of Natural Resources. Oil and Gas GIS Data Layer: Oil and Gas Wells http://gis.utah.gov/data/energy/oil-gas/. Accessed: (7/1/2015).


6/1/2013
Google Earth
Tour Guide
1997
Imagery Date: 6/1/2013   40°00'31.28" N 109°22'10.13" W elev 0 ft eye alt 12302 ft

The Need for Assessment Tools

- Vegetation and soil are removed to level the areas for drilling and other operations.
- Active management intervention of vegetation and soils at abandoned well pads
- Timely assessments to assist land managers and industry with implementation


Photo: Tim Peterson

Reclamation objectives

- The long-term objective of final reclamation is to set the course for eventual ecosystem restoration, including the restoration of the natural vegetation community, hydrology, and wildlife habitats.
- In most cases, this means returning the land to a condition approximating or equal to that which existed prior to the disturbance.
- The operator is generally not responsible for achieving full ecological restoration of the site. Instead, the operator must achieve the short-term stability, visual, hydrological, and productivity objectives of the surface management agency and take the steps necessary to ensure that long-term objectives will be reached through natural processes

From: SURFACE OPERATING STANDARDS AND GUIDELINES FOR OIL AND GAS EXPLORATION AND DEVELOPMENT "Gold Book" 2007, BLM

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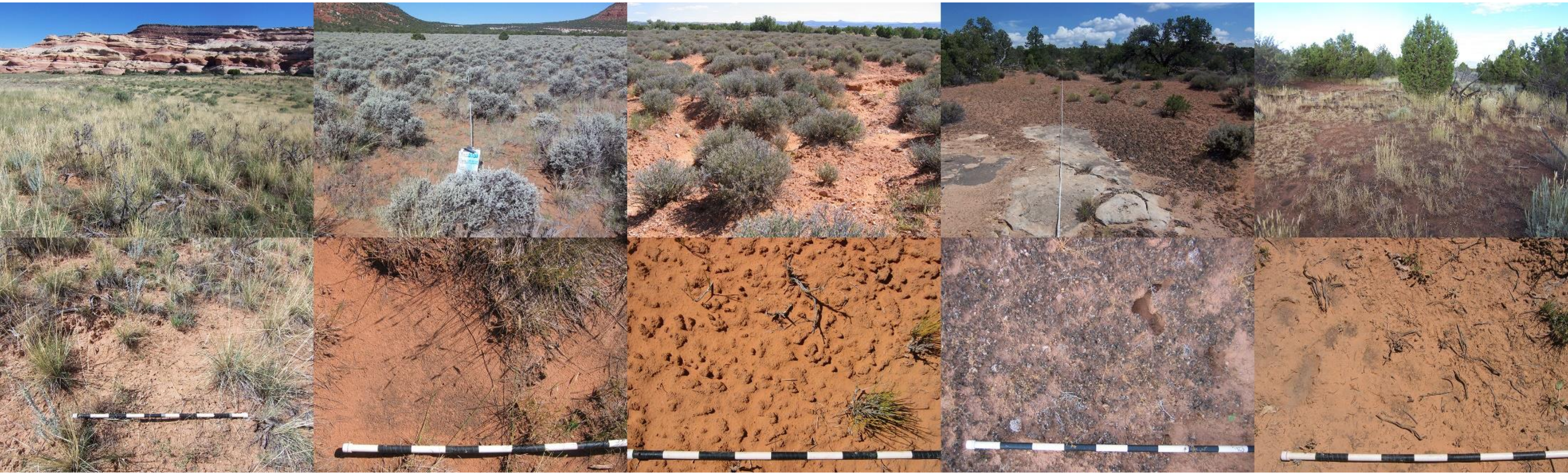
Research objectives

1) Identify best multispectral satellite variables for monitoring temporal changes in vegetation and bare ground in Colorado Plateau drylands

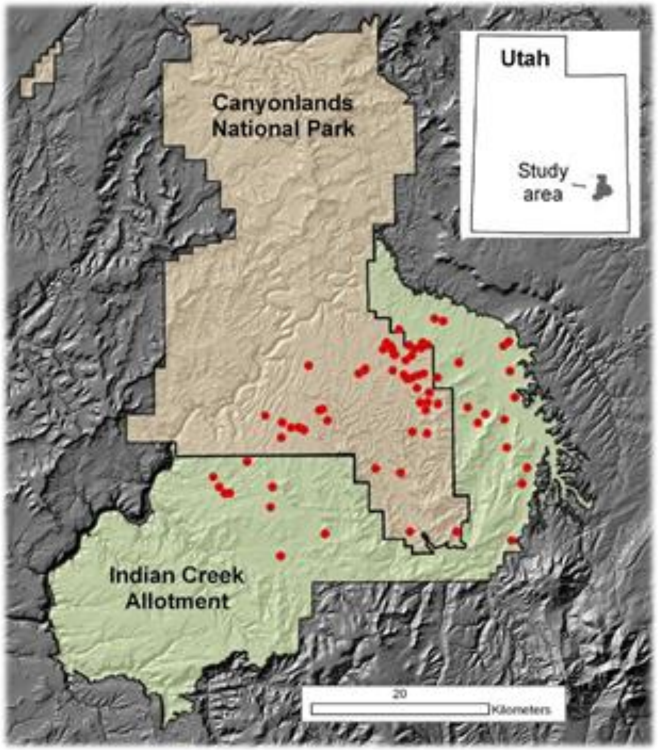
2) Analyze temporal and spatial trends of well-pad recovery using Landsat time series, Google Earth Engine and R (BFAST)

3) Examine potential role of temporal/episodic drought and climate on recovery trajectories and reclamation success

Identifying Optimal Remotely-sensed Variables for Ecosystem Monitoring in Colorado Plateau Drylands



USGS/NPS Vegetation monitoring plots



map: Mark E. Miller et al.

Photo: Erik Mohr

Surveys from Canyonlands National Park & Indian Creek grazing allotment of Dugout Ranch

- **315 plots sampled in 2006, 2007 & 2008**
- **52 plots sampled in 2014**

- **Each plot:**
  - **Three parallel 52 meter transects**
  - **Separated by 25 meters**
  - **Parallel to hillslope contour**

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Exploratory analysis of Landsat spectral data

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Approach:

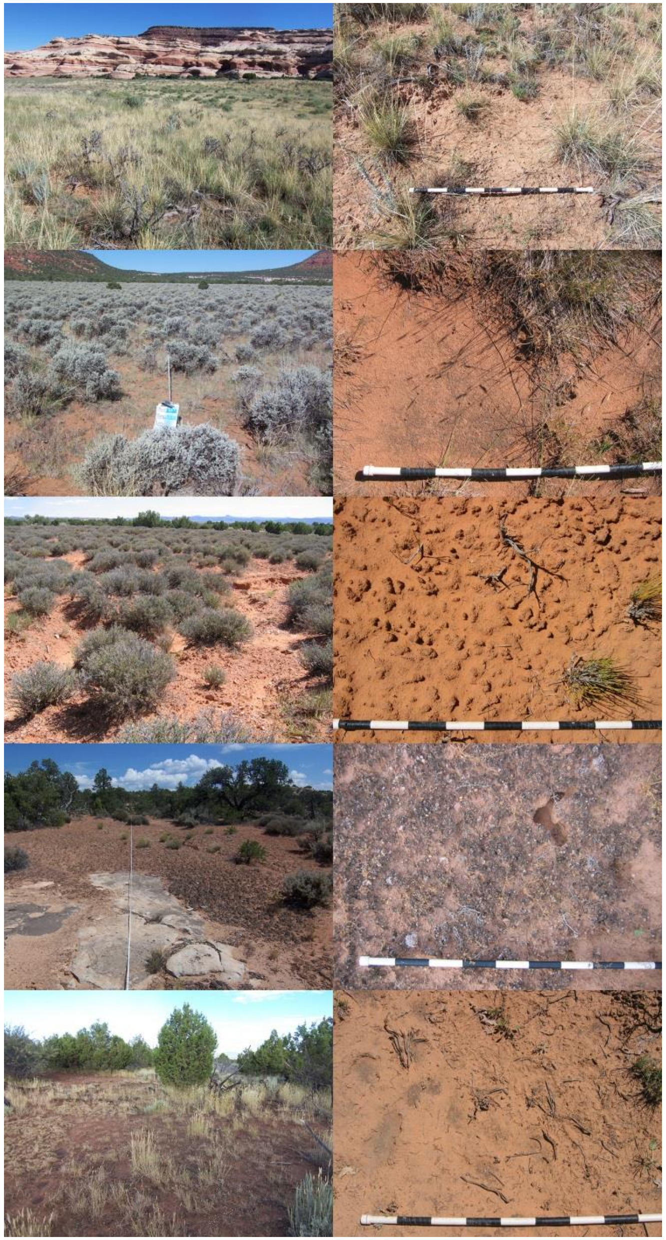
- Use Google Earth Engine Landsat data to calculate 12 different spectral variables (indices) that account for green vegetation, non-photosynthetic vegetation and soil

- Develop remote sensing estimates of surface cover from 315 monitoring plots near Canyonlands NP:

  % cover models:

  - Total live vegetation cover
  - Bare ground
  - Biological soil crust
  - Exotic Vegetation
  - Native Vegetation
  - Perennial Vegetation
  - Tree cover

- Created model sets for 5 major vegetation communities



Models:

- Create linear regression models of total vegetation, bare ground, exotic species and biological soil crust cover
- Developed multiple regression models, using cross-validation to assess improvement over single variables

Table 1. Landsat bands, spectral indices, and transformations selected for this study based on their known (and hypothesized) ability to capture three basic surface properties of drylands: photosynthetic vegetation (surface property = PV), non-photosynthetic vegetation (surface property = NPV), and bare ground (surface property = Soil).

Index	Acronym	Surface Property	Formula	Reference
Normalized Difference Vegetation Index	NDVI	PV	$\frac{(NIR - Red)}{(NIR + Red)}$	Tucker, 1979
Soil Adjusted Vegetation Index	SAVI	PV	$\frac{(NIR - Red)}{(NIR + Red + L)}(1 + L)$	Huete, 1988
Tasseled Cap Transformation (greenness)	TCG	PV		Kauth and Thomas, 1976
Soil Adjusted Total Vegetation Index	SATVI	PV/NPV*	$\frac{(SWIR1 - Red)}{(SWIR1 + Red + L)}(1 + L) - \frac{SWIR2}{2}$	Marsett et al., 2006
Non-Photosynthetic Vegetation Normalized Difference	NPVND	NPV	$\frac{SWIR1 - (Red + NIR)}{SWIR1 + (Red + NIR)}$	
Tasseled Cap Transformation (wetness)	TCW	NPV		Kauth and Thomas, 1976
Soil Normalized Difference Index	SNDI	Soil	$\frac{Red - (NIR + SWIR1)}{Red + (NIR + SWIR1)}$	
Tasseled Cap Transformation (brightness)	TCB	Soil		Kauth and Thomas, 1976
Landsat TM band 3 (0.63-0.69 µm)	Red	Soil		

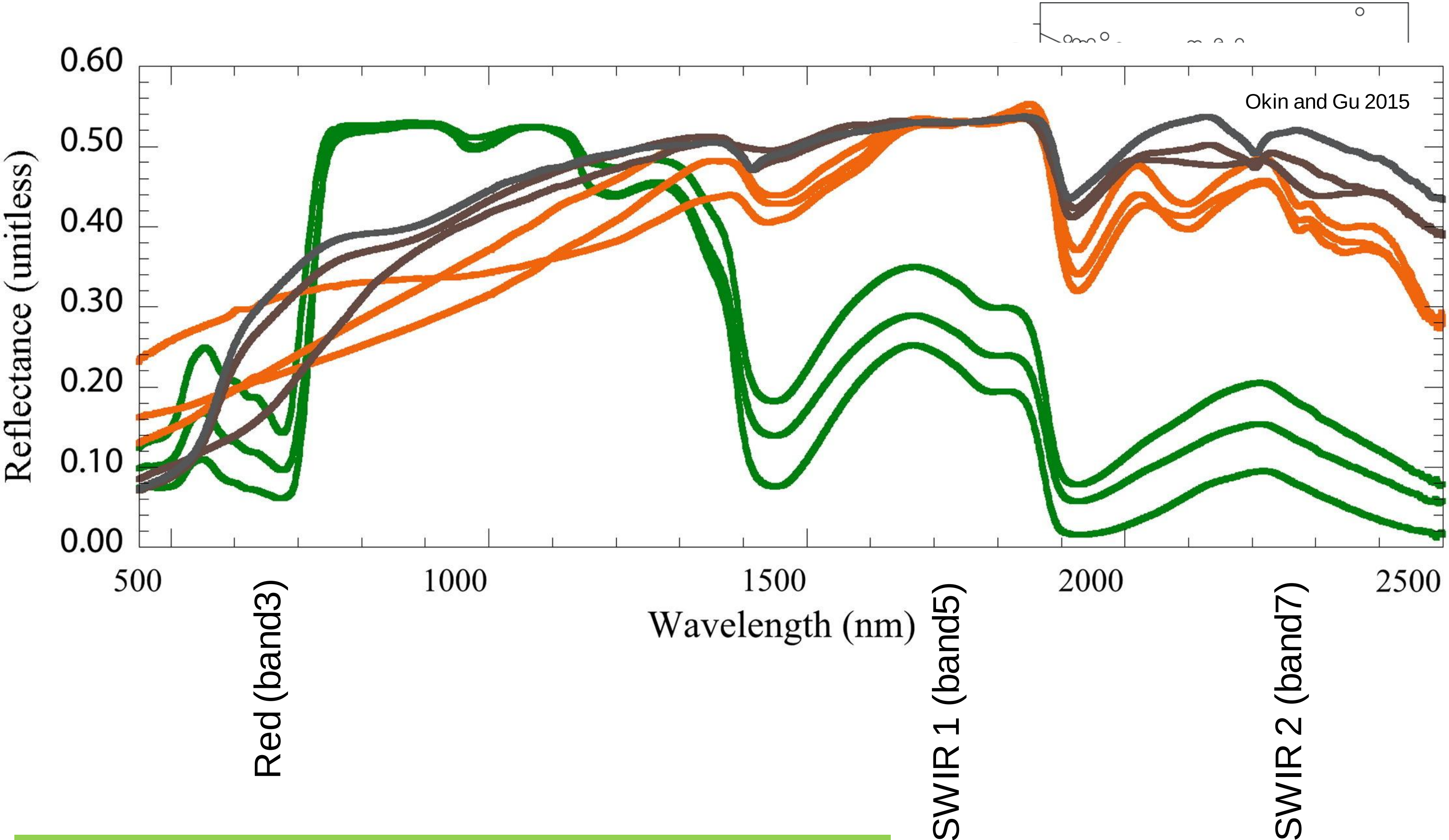
Results:

- We found that for all vegetation types, percent cover bare ground could be accurately modeled with single indices that included a combination of **red** and **shortwave infrared (SWIR) bands**

	Regression Model	Grasslands (G)	Sagebrush (S)	Blackbrush (B)	Juniper-Blackbrush (JB)	Pinyon-Juniper (PJ)
Bare Ground (BG)	Linear	SATVI ** (R^2=0.55) (RMSE=11.60)	SATVI** (R^2=0.35) (RMSE=9.78)	SATVI** (R^2=0.78) (RMSE=6.20)	SATVI** (R^2=0.45) (RMSE=12.40)	SNDI** (R_2=0.58) (RMSE=6.95)
	Multiple	SATVI+NPVND+TCG** (R^2=0.57) (RMSE=11.30)	SATVI+SNDI+SAVI** (R_2=0.40) (RMSE=9.41)	SATVI+TCW** (R^2=0.76) (RMSE=6.04)	SATVI+TCG+Red** (R^2=0.57) (RMSE=11.03)	SNDI+TCB** (R^2=0.63) (RMSE=6.58)
Total Vegetation (TV)	Linear	SATVI** (R^2=0.34) (RMSE=16.80)	SATVI** (R^2=0.38) (RMSE=9.66)	Red* (R^2=0.37) (RMSE=5.04)	Red (R^2=0.07) (RMSE=9.75)	NDVI** (R^2=0.69) (RMSE=7.38)
	Multiple	SATVI+NDVI+SNDI** (R^2=0.37) (RMSE=16.10)	SATVI+SNDI** (R^2=0.40) (RMSE=9.46)	Red+SATVI* (R^2=0.42) (RMSE=4.81)	Red+TCG (R^2=0.096) (RMSE=9.61)	NDVI+SATVI** (R^2=0.71) (RMSE=7.05)
Biological Soil Crust (BSC)	Linear	Red*** (R^2=0.22) (RMSE=12.20)		SATVI** (R^2=0.70) (RMSE=5.21)	SATVI** (R^2=0.60) (RMSE=7.63)	SATVI* (R^2=0.21) (RMSE=5.53)
	Multiple	TCG+NPVND+SNDI** (R^2=0.30) (RMSE=11.50)		SATVI** (R^2=0.70) (RMSE=5.21)	SATVI+SAVI+TCB** (R^2=0.74) (RMSE=6.20)	SATVI+TCG+SNDI** (R^2=0.40) (RMSE=4.81)
Exotic Vegetation (EX)	Linear	NDVI** (R^2=0.32) (RMSE=11.60)				NPVND*** (R^2=0.46) (RMSE=7.86)
	Multiple	SATVI+TCG+SNDI** (R^2=0.47) (RMSE=9.77)				NPVND+TCG+SAVI** (R^2=0.67) (RMSE=6.51)

Table 2. Comparison of cross-validated simple linear and multiple regression model adjusted R^2 and RMSE values and model significance. Each column represents a vegetation community type and each pair of rows represents a cover type. For each combination of vegetation community and surface cover type, the best single variable model is on the top row and multiple regression below them. Cover types with no plots exceeding 10% within a community type were not modeled and are left blank (e.g. BSC in Sagebrush and EX in Blackbrush). *p>0.01, **p<0.001

Exploratory analysis of Landsat spectral data



$$SATVI = \frac{\rho\text{band5} - \rho\text{band3}}{\rho\text{band5} + \rho\text{band3} + \text{L}}(1+\text{L}) - \frac{\rho\text{band7}}{2}$$

Landsat time series analysis of fractional plant cover on abandoned energy development sites

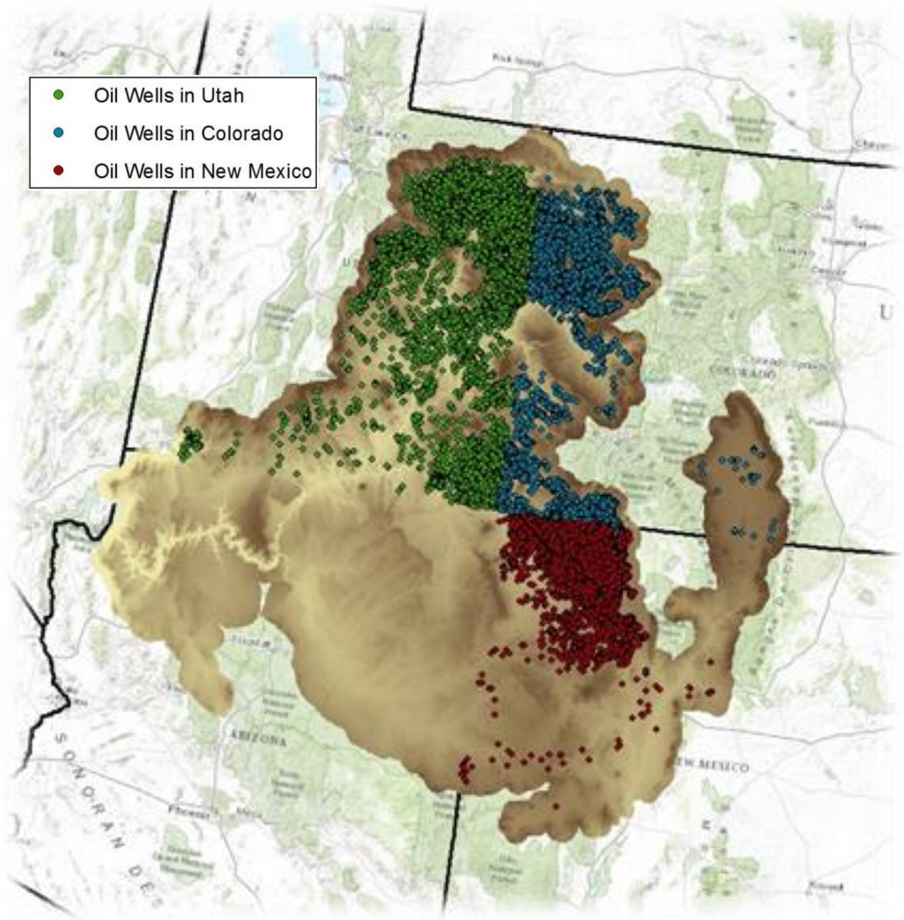
Methods: data validation

Geospatial data sets used:

- Utah Automated Geographic Reference Center (UAGRC, 2015)
- Colorado Oil and Gas Conservation Commission (COCG, 2015)
- New Mexico Institute of Mining and Technology's Petroleum Recovery Research Center (GO-TECH, 2015)

Inconsistent records but each contain, at the very least, information on spud date, abandonment date, and ownership

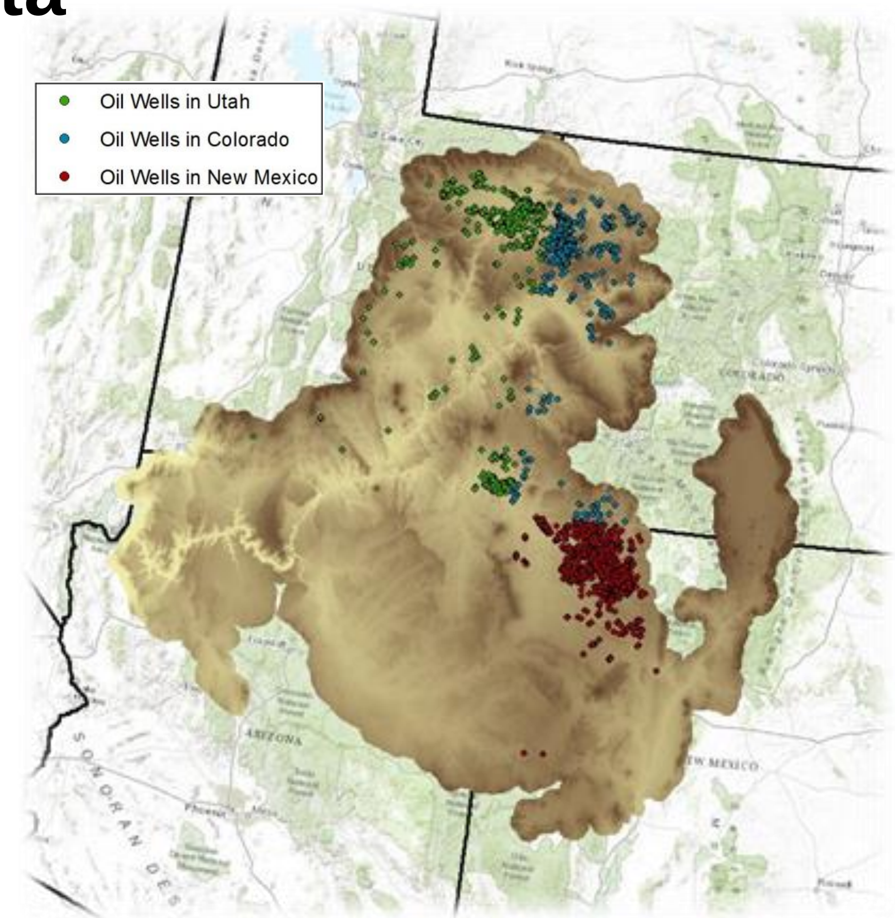
Many errors – both spatial and attribute



All active and abandoned wells: 90,000

Validation of geospatial data

- **Well locations filtered by year, status and land cover type**
- **Only kept locations with a status of "plugged and abandoned (PA)"**
- **Removed all PA wells pre-1997 and post-2005**
- **Remaining wells visually inspected with Google Earth time-line imagery**
- **Removed all locations that were either duplicates, still active, or non-existent**
- **Repositioned point locations with obvious GPS error**



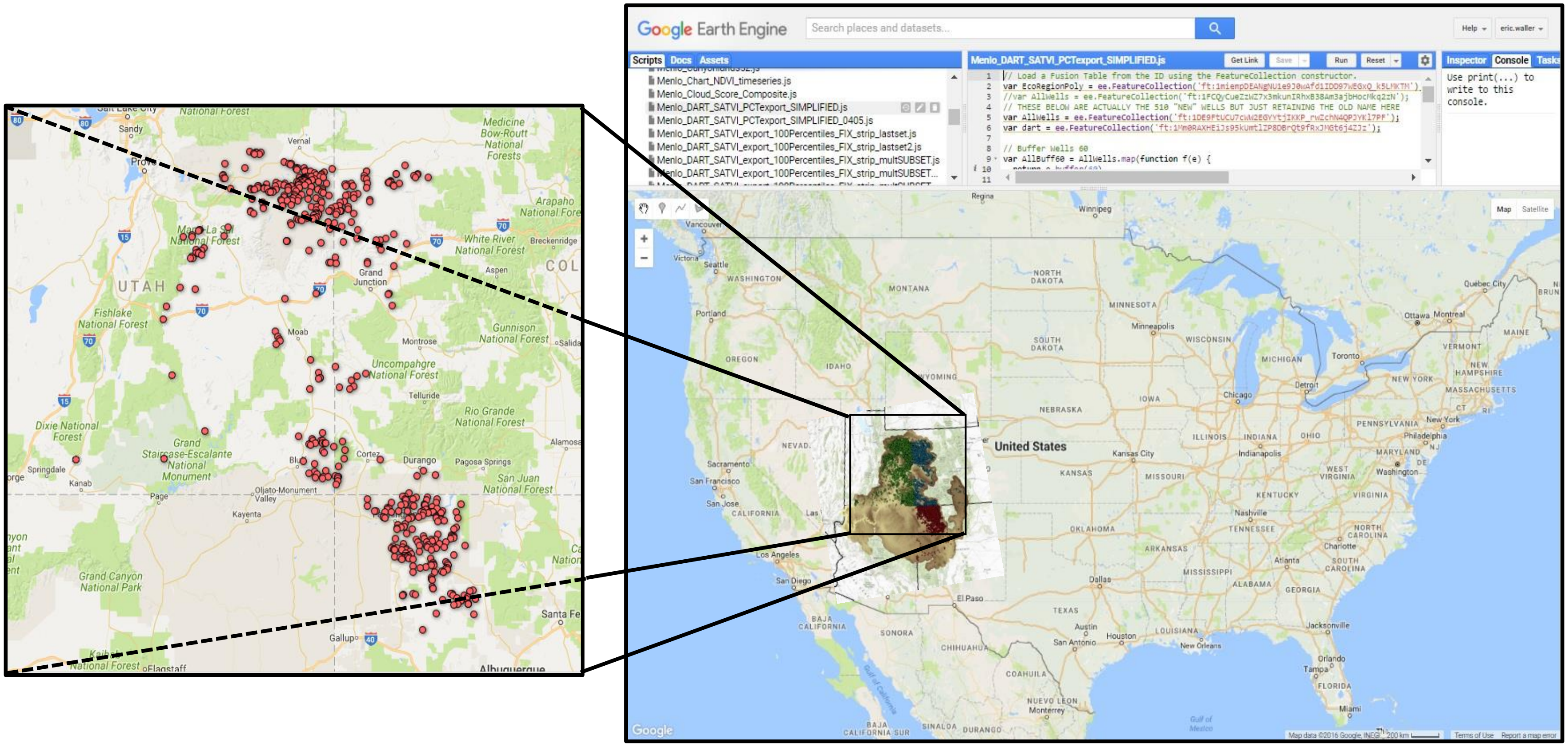
Validated as abandoned pad: 1,866

(plugged & abandoned between 1997-2005)

Methods: time series

Further refined to focus time series analysis on 510 sites

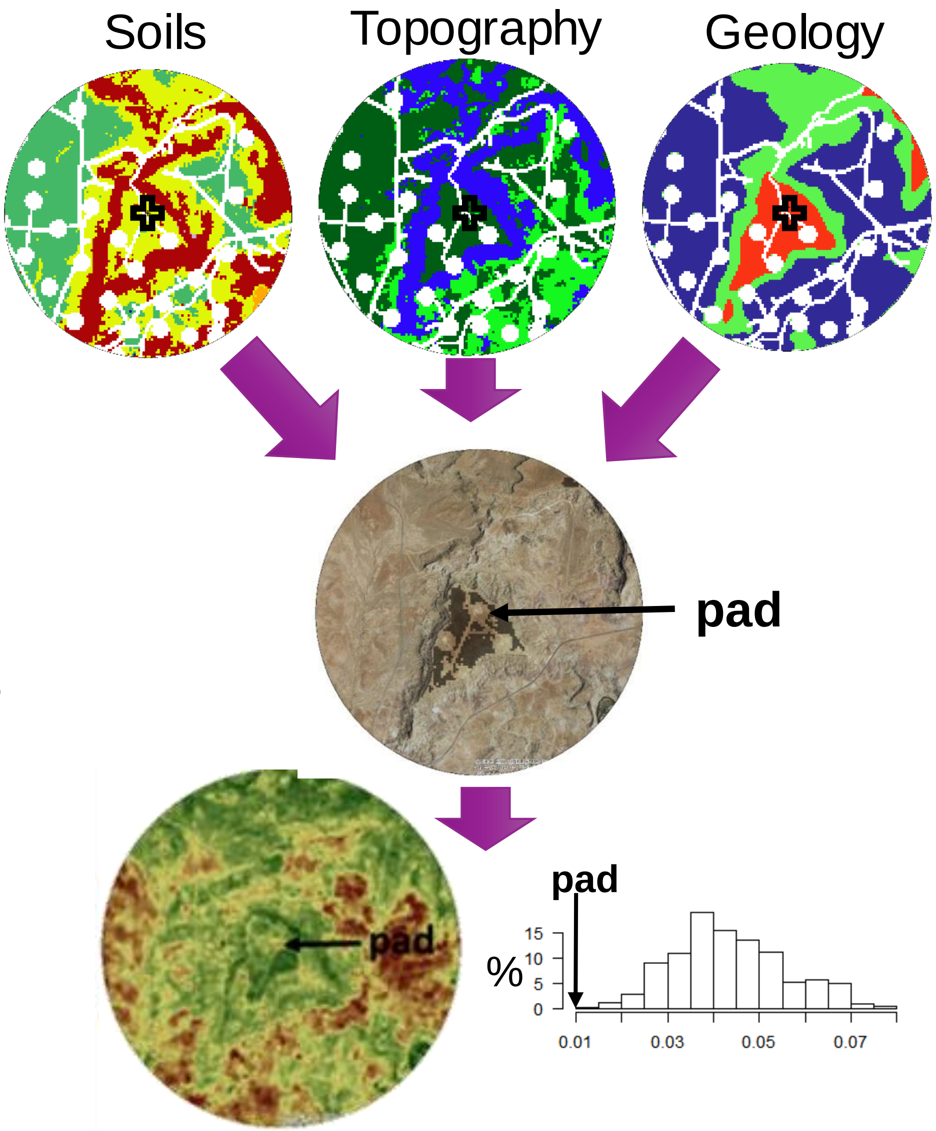
- Drilled after 1984 (allows pre-drill comparison: Landsat 5, 1984-2011)
- Abandoned between 1997 and 2005 (adequate time for any recovery)



Calculated a Landsat SATVI time series (1984-2011) for each well pad and the surrounding DART reference pixels

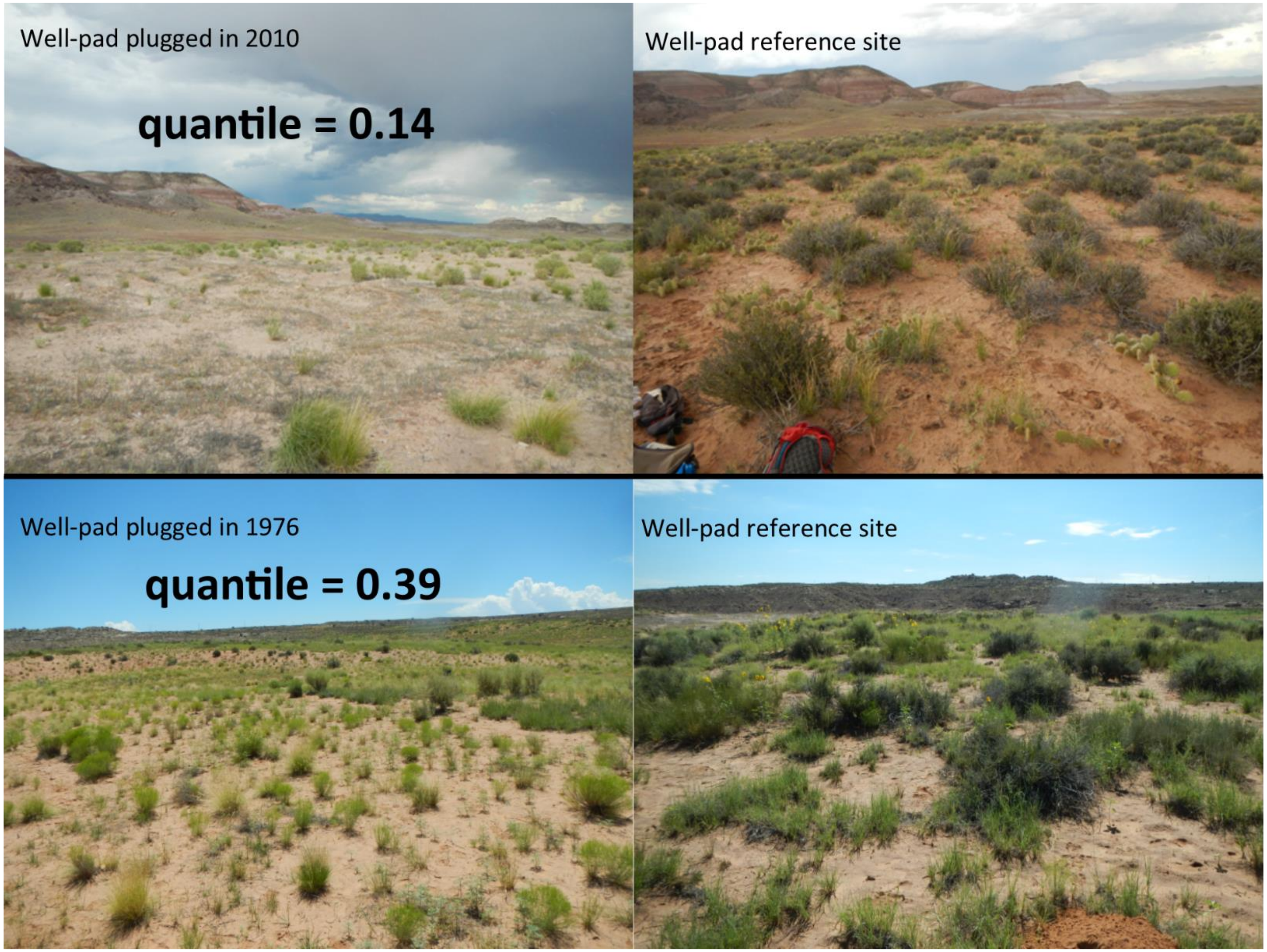
The Disturbance Automated Reference Toolset (DART)

1. Combine digital soil mapping, topography, and geology
2. Identify undisturbed reference sites
3. Compare well pad to vegetation cover at reference sites
4. Score each well pad on a 0 to 1 recovery scale



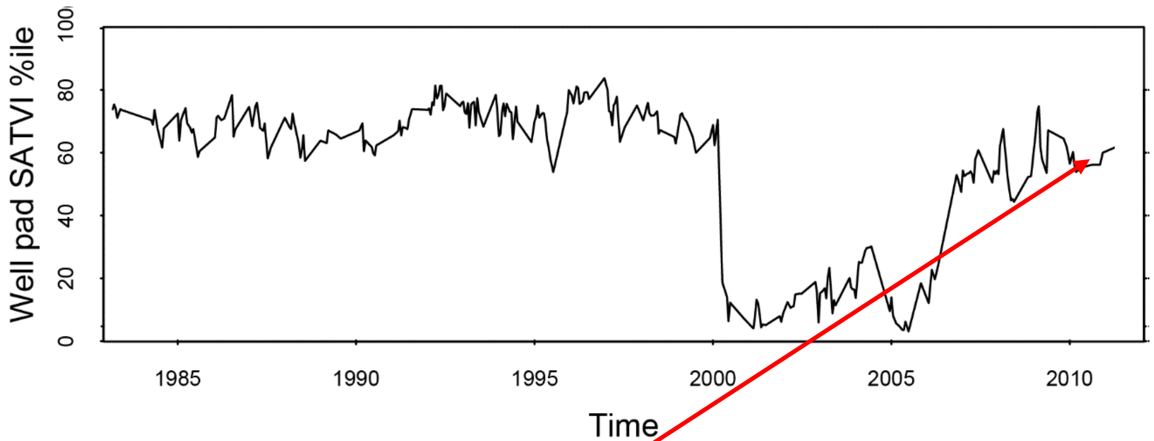
Nauman, T. W., Duniway, M. C., Villarreal, M. L., & Poitras, T. B. (2017). Disturbance automated reference toolset (DART): Assessing patterns in ecological recovery from energy development on the Colorado Plateau. Science of The Total Environment, 584, 476-488.

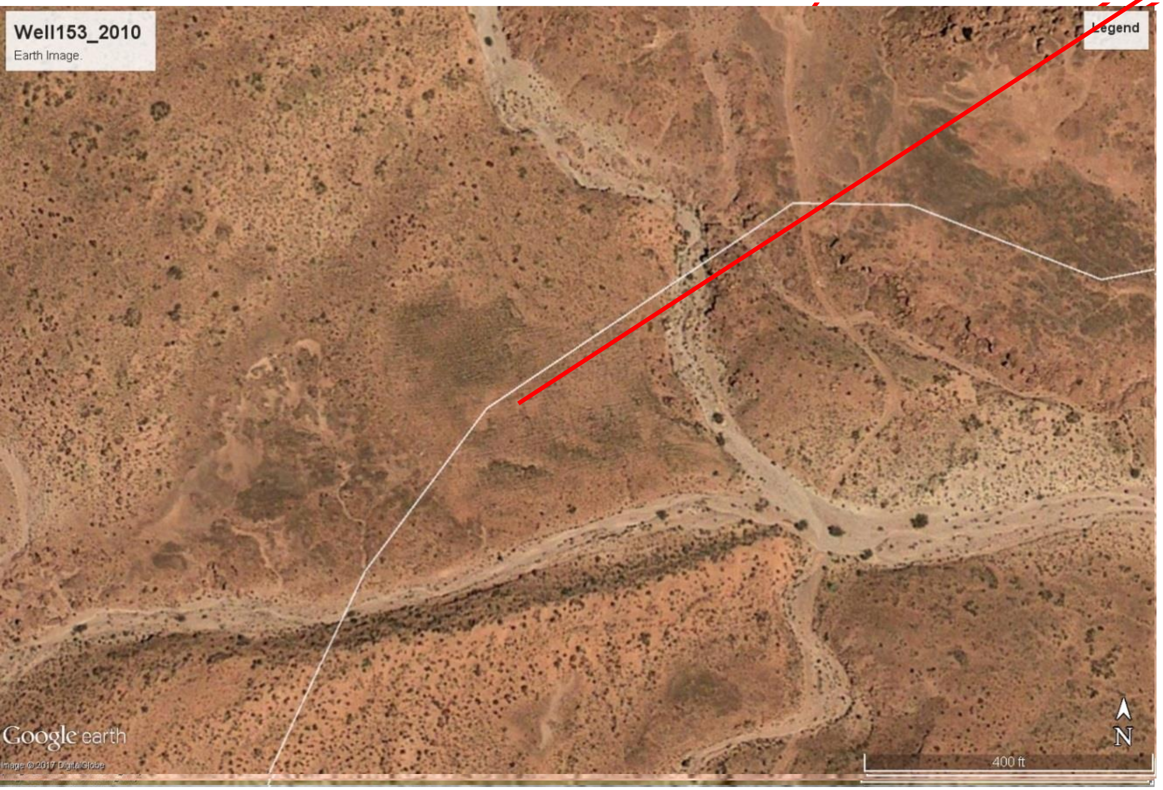
Example DART Quantiles



Methods: time series

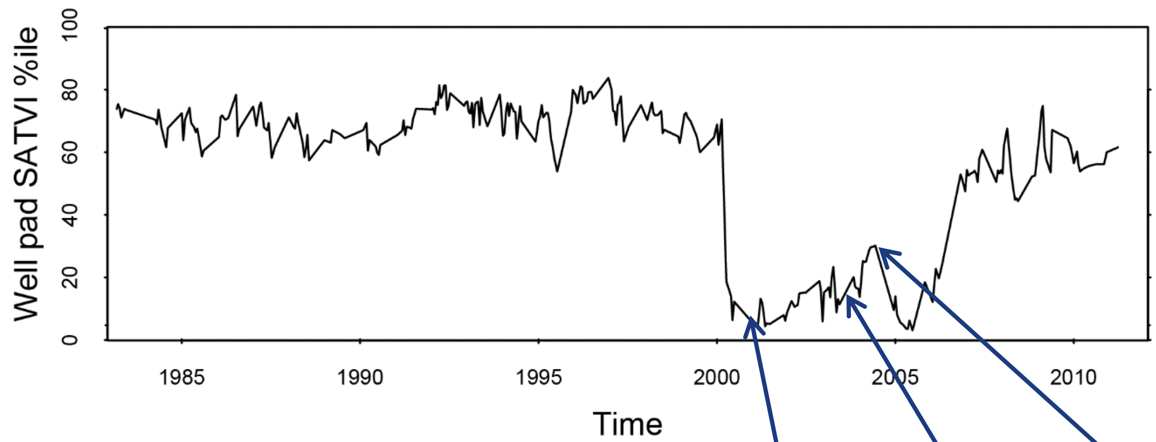
SATVI
Time series:

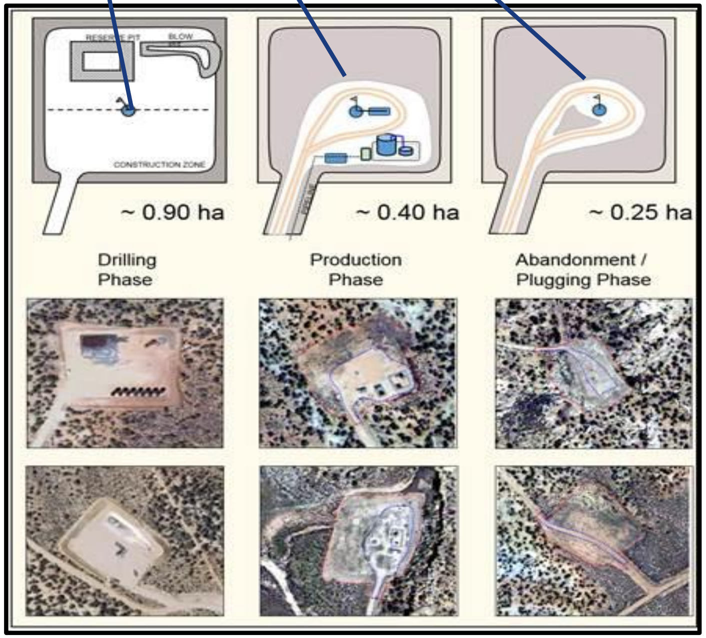




Target pad surrounded by DART reference pixels

Methods: time series





Methods: Bfast

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Estimating revegetation:

Relative fractional vegetation cover (RFVC) = (A/B)

Change rate (CR) = RFVC/T

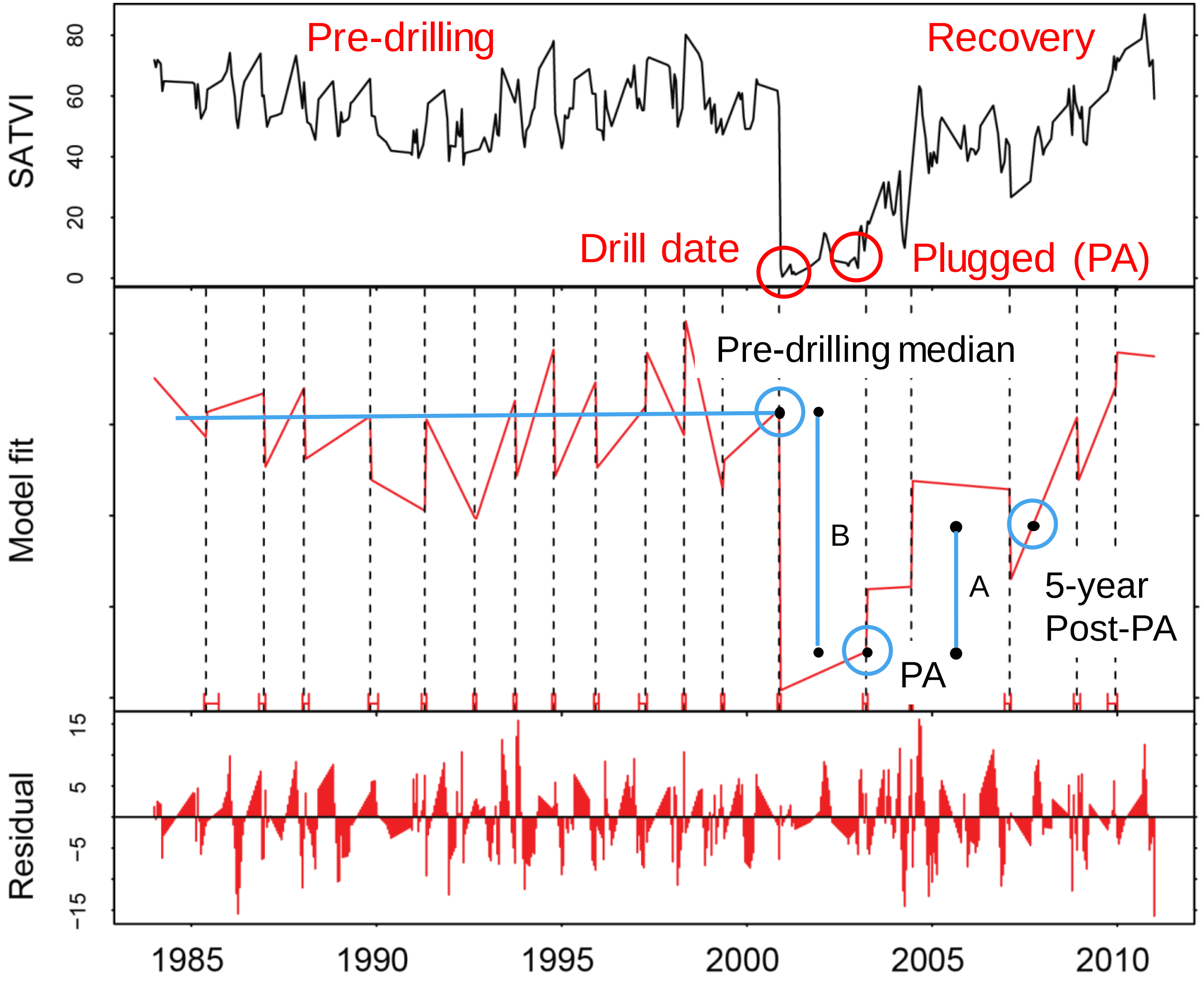
Based on Bfast model fit

Where
A = T_{yr} post-PA_{median} - PA_{min}
B = pre-$drill_{median}$ - PA_{min}
T = years since PA

Example:
A = 30
B = 50
T = 5

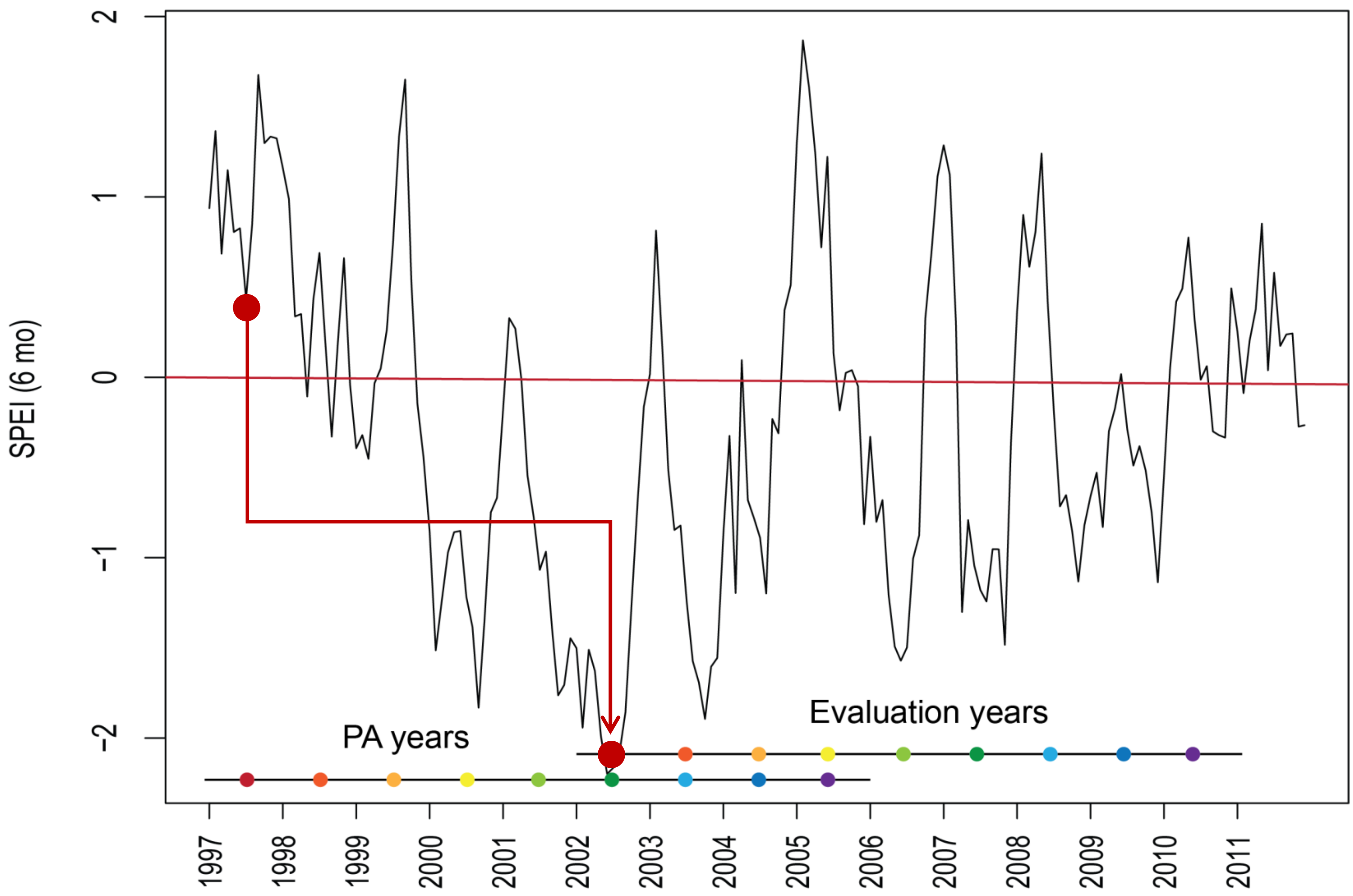
RFVC = (30/50)
RFVC = 0.6
CR = 0.12

Developing a Bfast time series model with SATVI percentile:



Methods: climate trends

Is climate during year of abandonment or evaluation important for recovery?

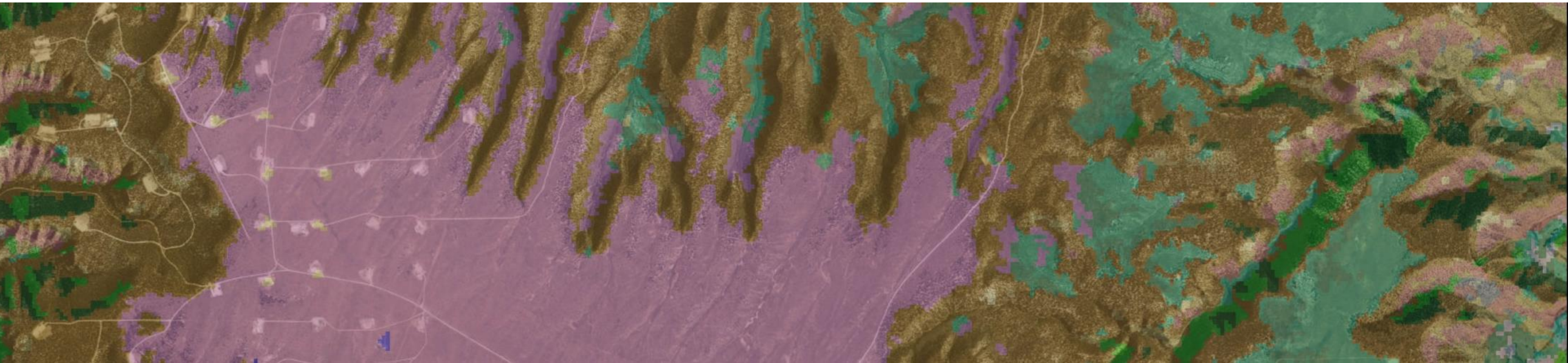


Methods: random forest

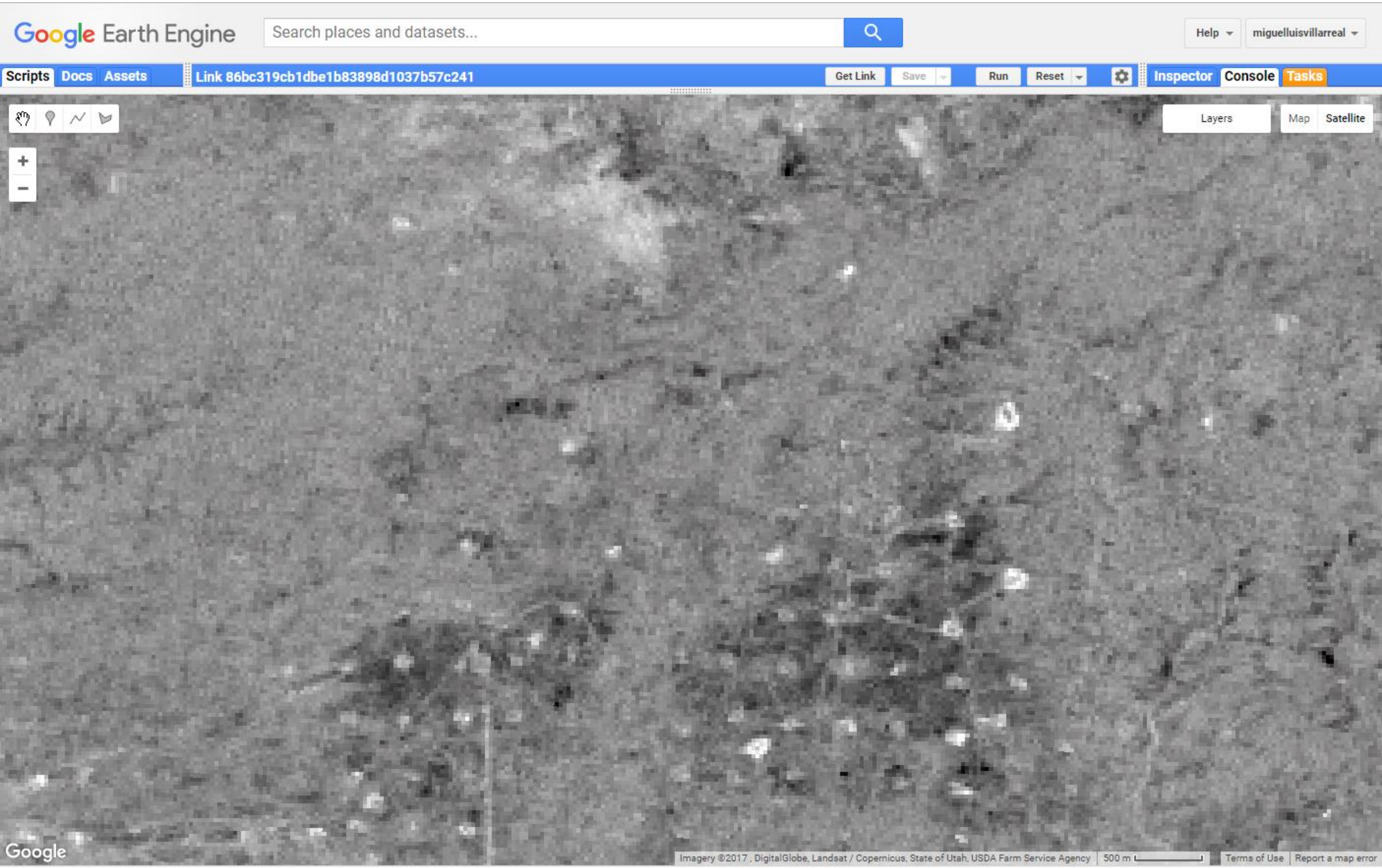
Evaluation of factors contributing to recovery

- Vegetation, soils, climate, land ownership
- Random Forest models
- 5 year relative fractional vegetation cover values

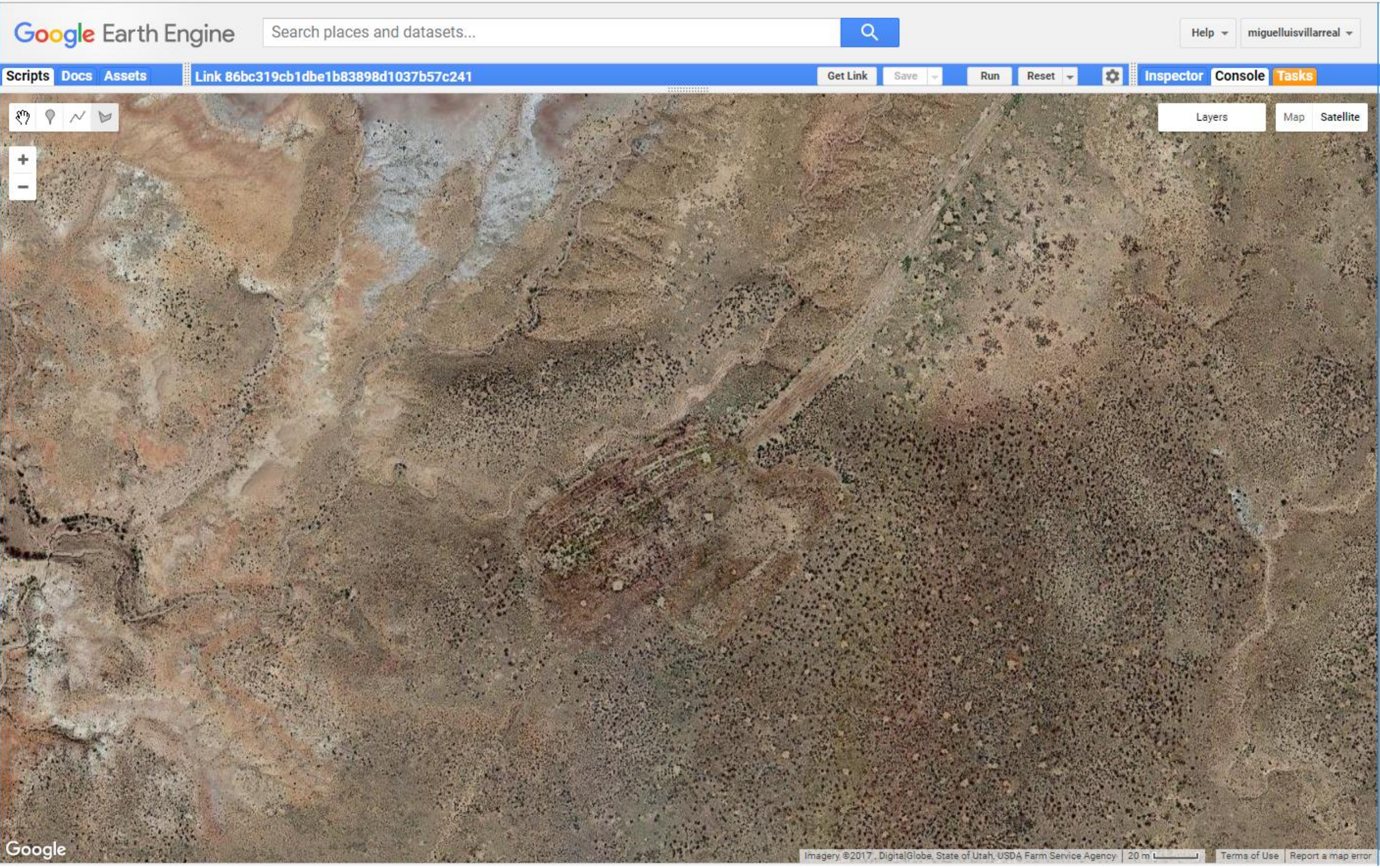
List of Variables	Details
Plug Year	1997-2005
Soils (Soilgrids.org)	79 Vars: soil classes, texture, nutrient content, salinity etc.
SWReGAP Land Cover reclass	5 class: Grassland, Short shrub, Tall shrub, Evergreen woodland, Deciduous woodland
Cheatgrass Index	Landsat 2009->11, March->May greenest (Max NDVI composite) - Median June NDVI
Salsola Index	Landsat 2009->11, (Avg of June-July & Aug-Sept Max NDVI composites) - (March->May Max NDVI composite)
DESI (Year 5)	MODIS, Spring NDVI - Summer NDVI (250m)
Land Ownership	4 class: Federal, State, Tribal, Private
Elevation	30m DEM
Latitude	
Longitude	
SPEI (Standardized Precipitation Evaporation Index)	(1,3,6,9,12,18,24 month windows) June & October, Years 0,1,5
PDSI (Palmer Drought Severity Index)	(March-June & July-October & January-October), Years 0,1,5
Precipitation	(March-June & July-October & January-October), Years 0,1,5



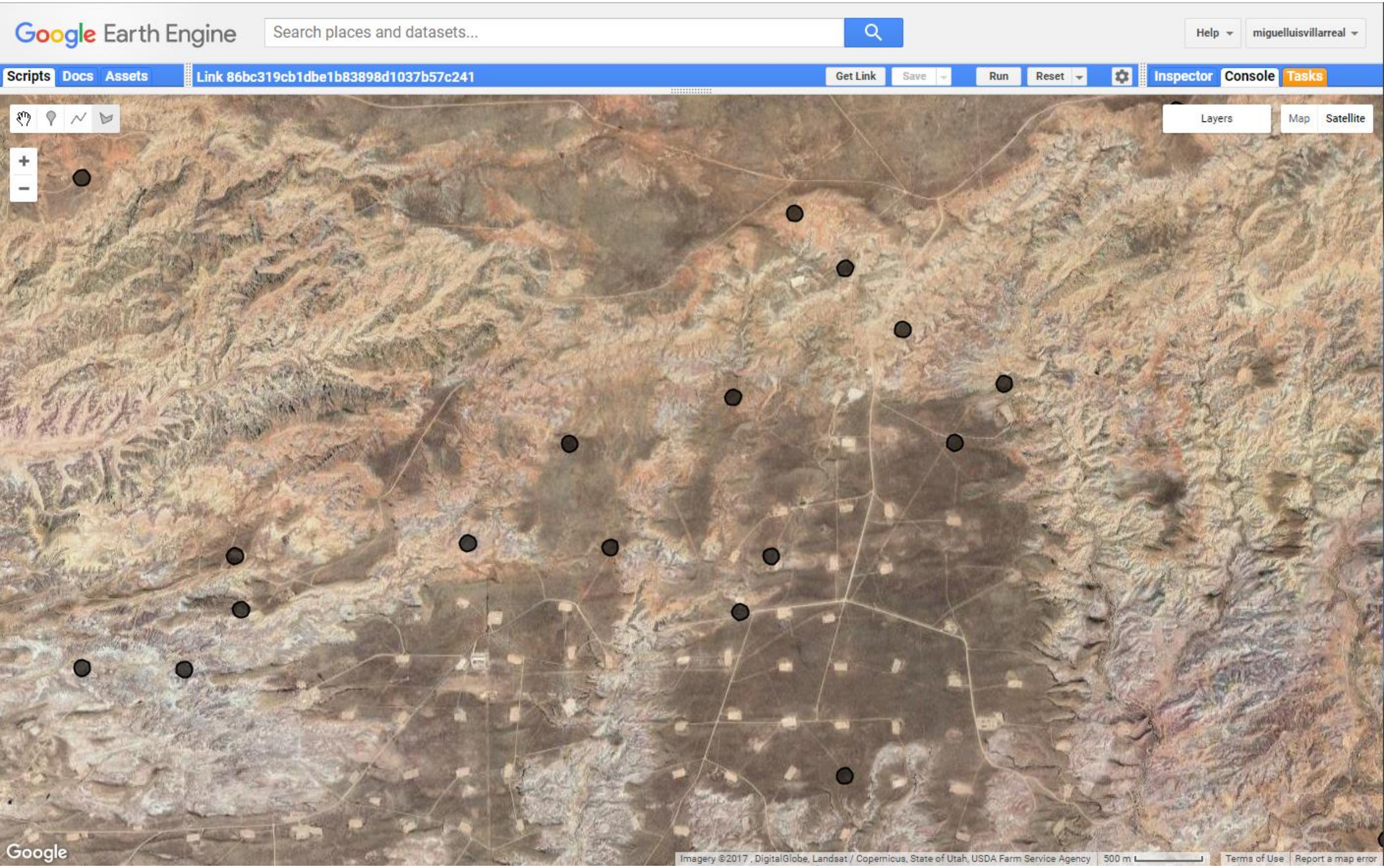
Methods: Salsola and Bromus indices



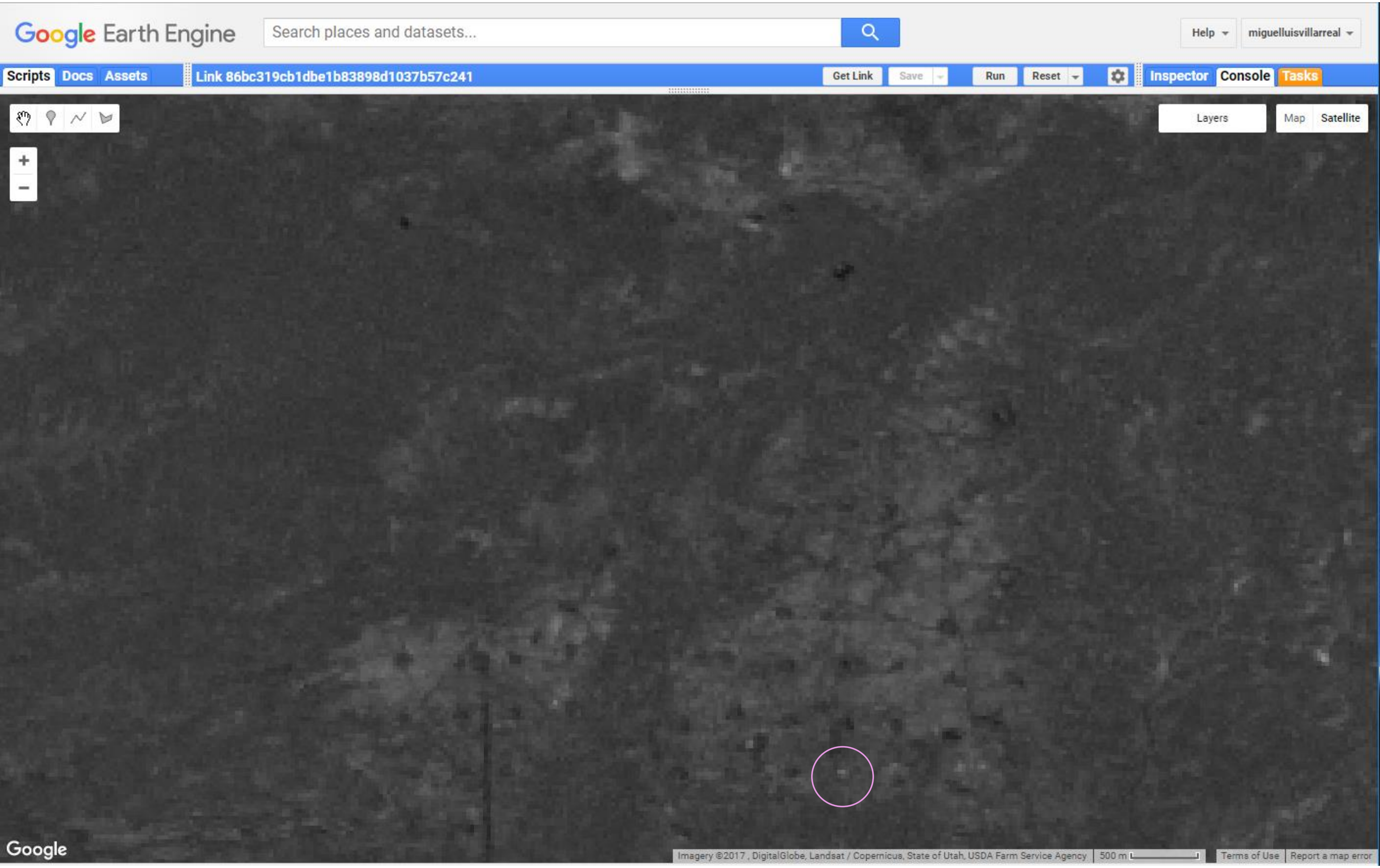
Methods: Salsola index



Methods: Salsola and Bromus indices



Methods: Salsola and Bromus indices



Methods: Cheat index

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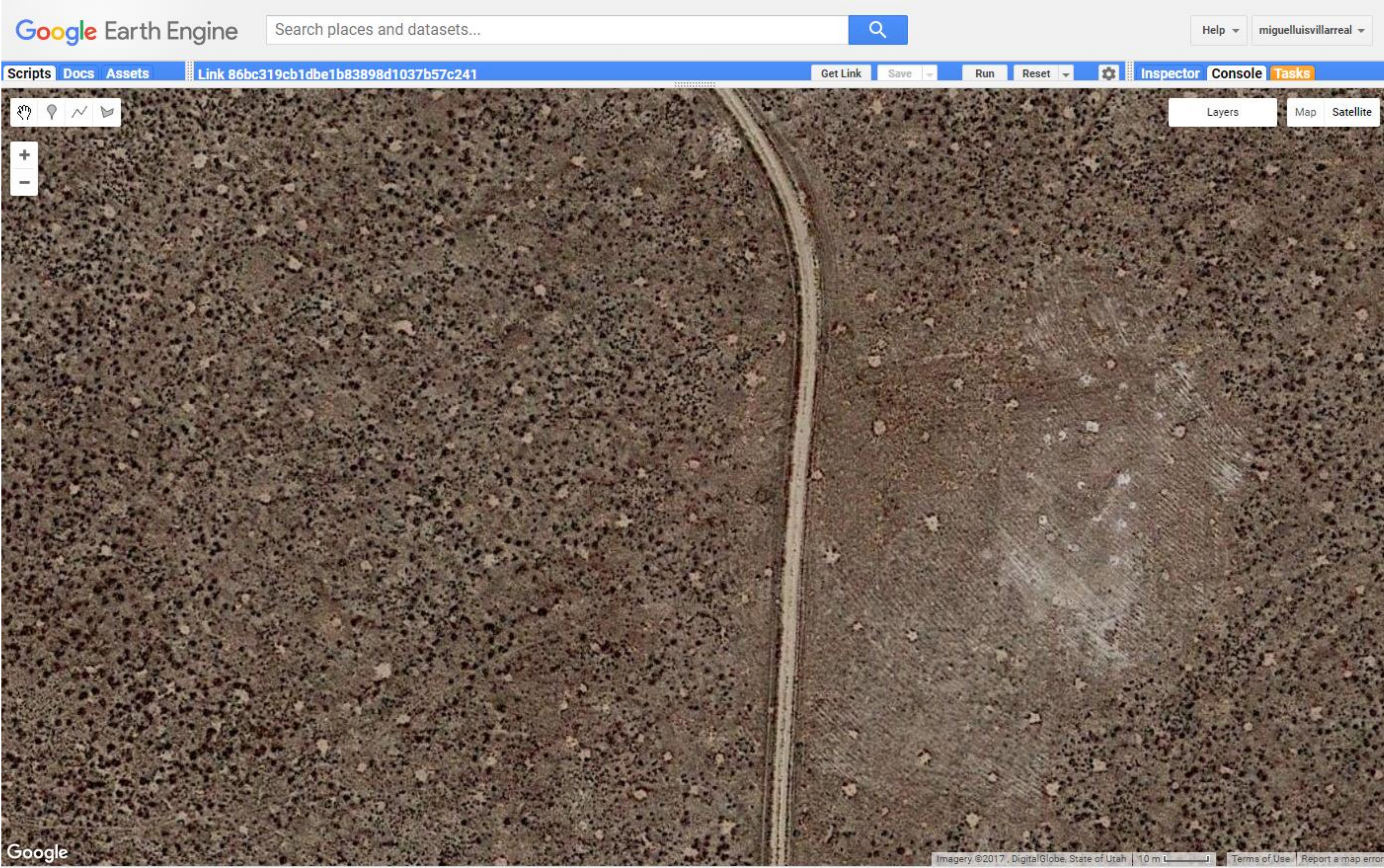
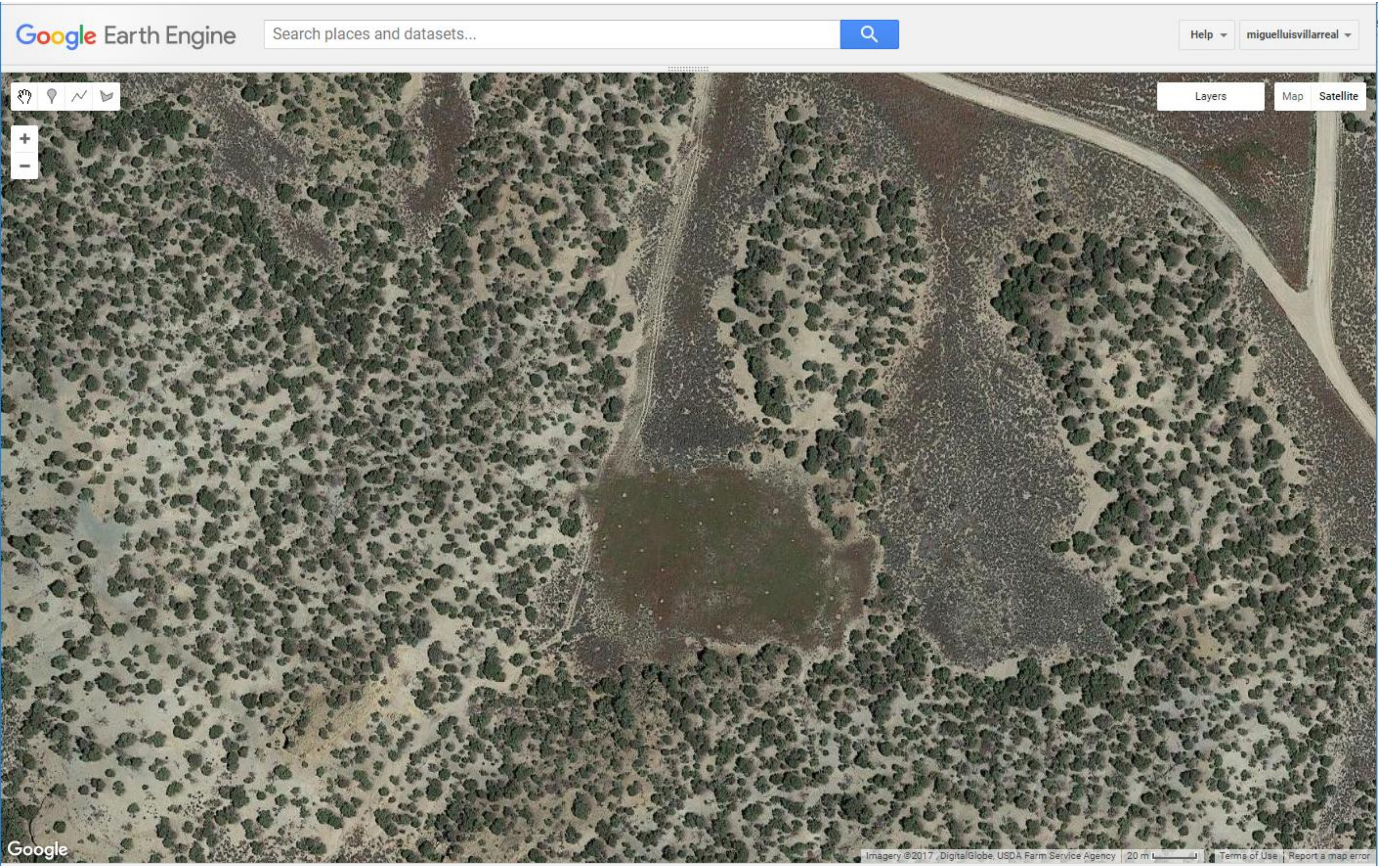


Methods: Cheat index



Results

- The median RFVC for the 365 wells five years after abandonment was 25.8% with a mean of 35.9% and a standard deviation of 32.5% (Table 1).
- 32.9% of the wells had greater than 50% RFVC.
- These values steadily rise over time, in the aggregate, as indicated by additional composite results for year 3, year 4, and year 6.

	Year 3	Year 4	Year 5	Year 6
Median	19.3	24.6	25.8	35.7
Mean	28.2	32.3	35.9	42.2
Std. Dev.	29.1	30.8	32.5	34.2
> 50%	20.8	26.8	32.9	38.1

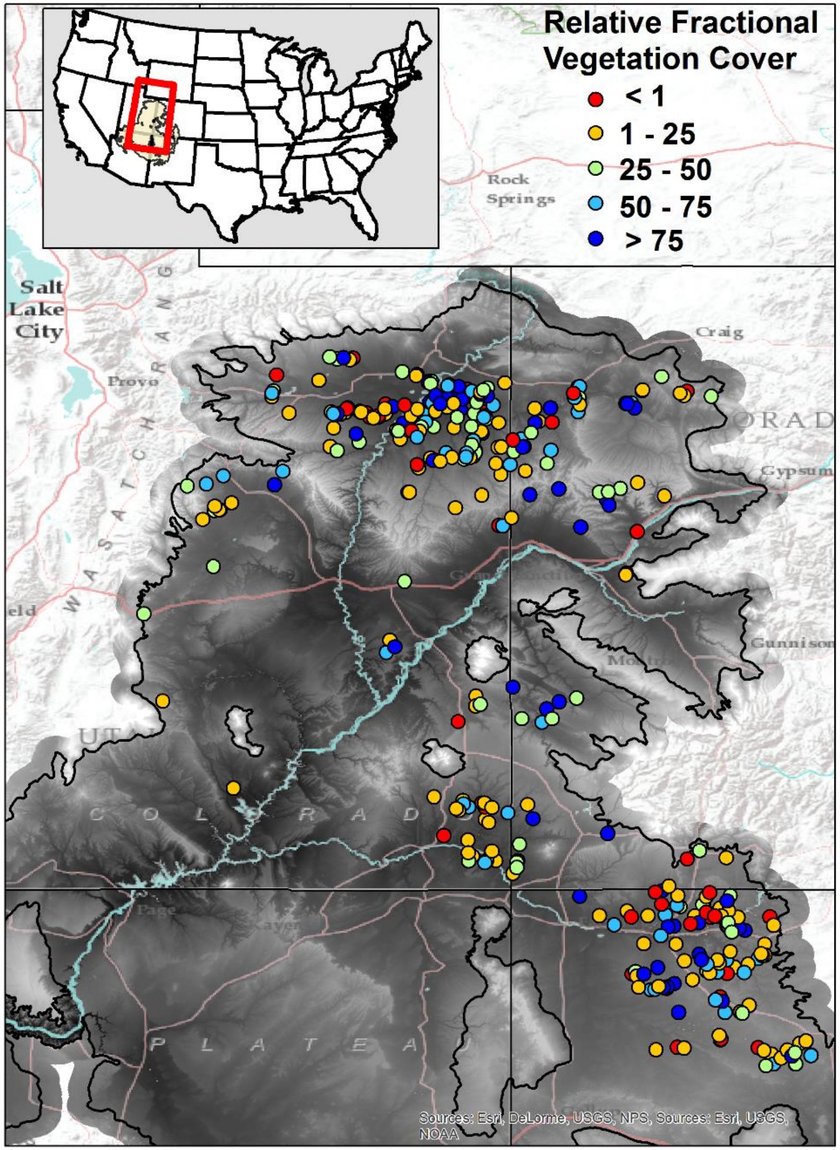


Table 2. Well site relative recovery metric summary statistics by year post-abandonment (Percent)

Results

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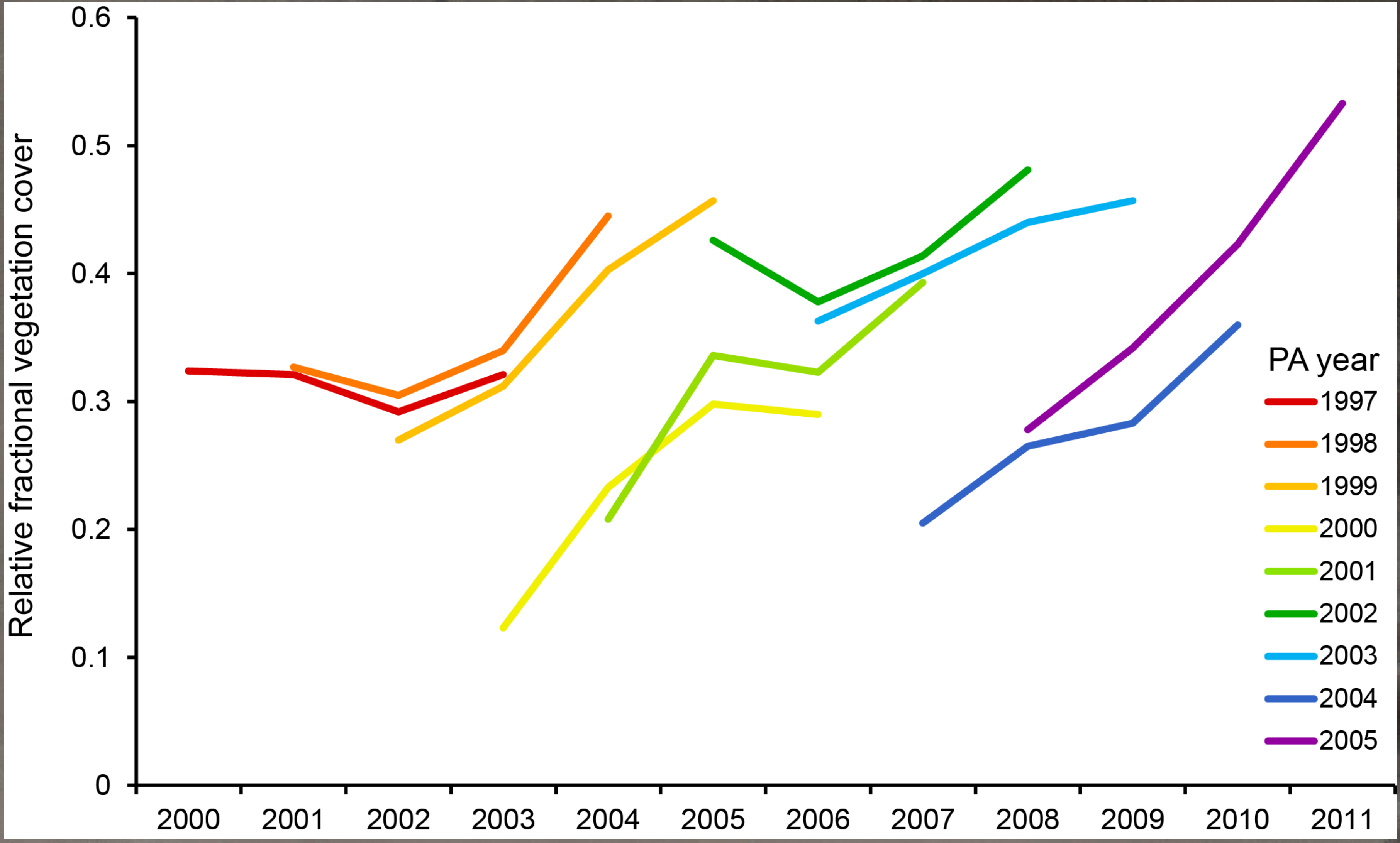
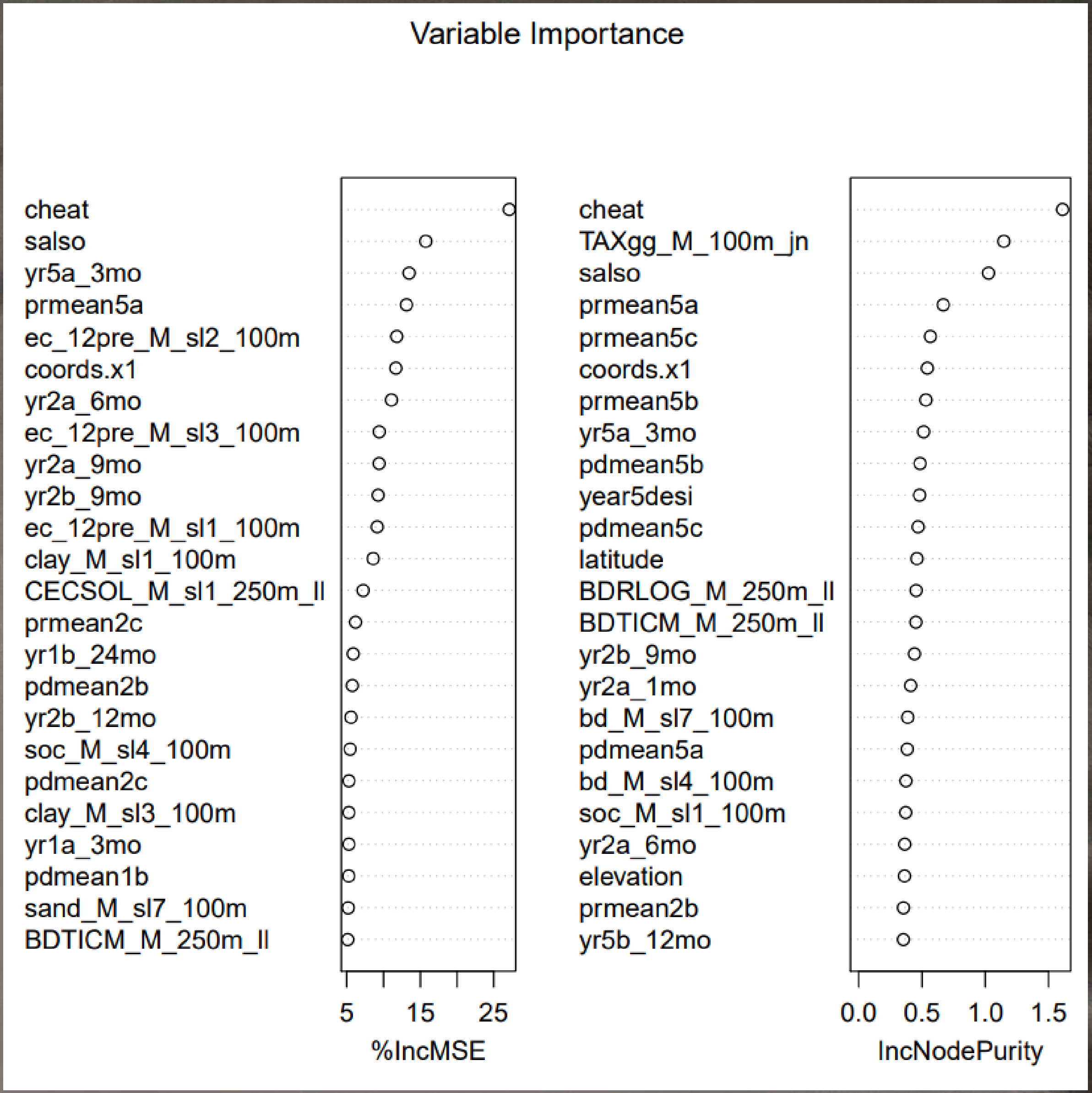
Mean RFVC evaluated 3-6 years after abandonment



Results: Random Forest

RF variables:

- Cheatgrass/Salsola index
- SPEI
- Precipitation
- Soil electrical conductivity
- DESI



Results

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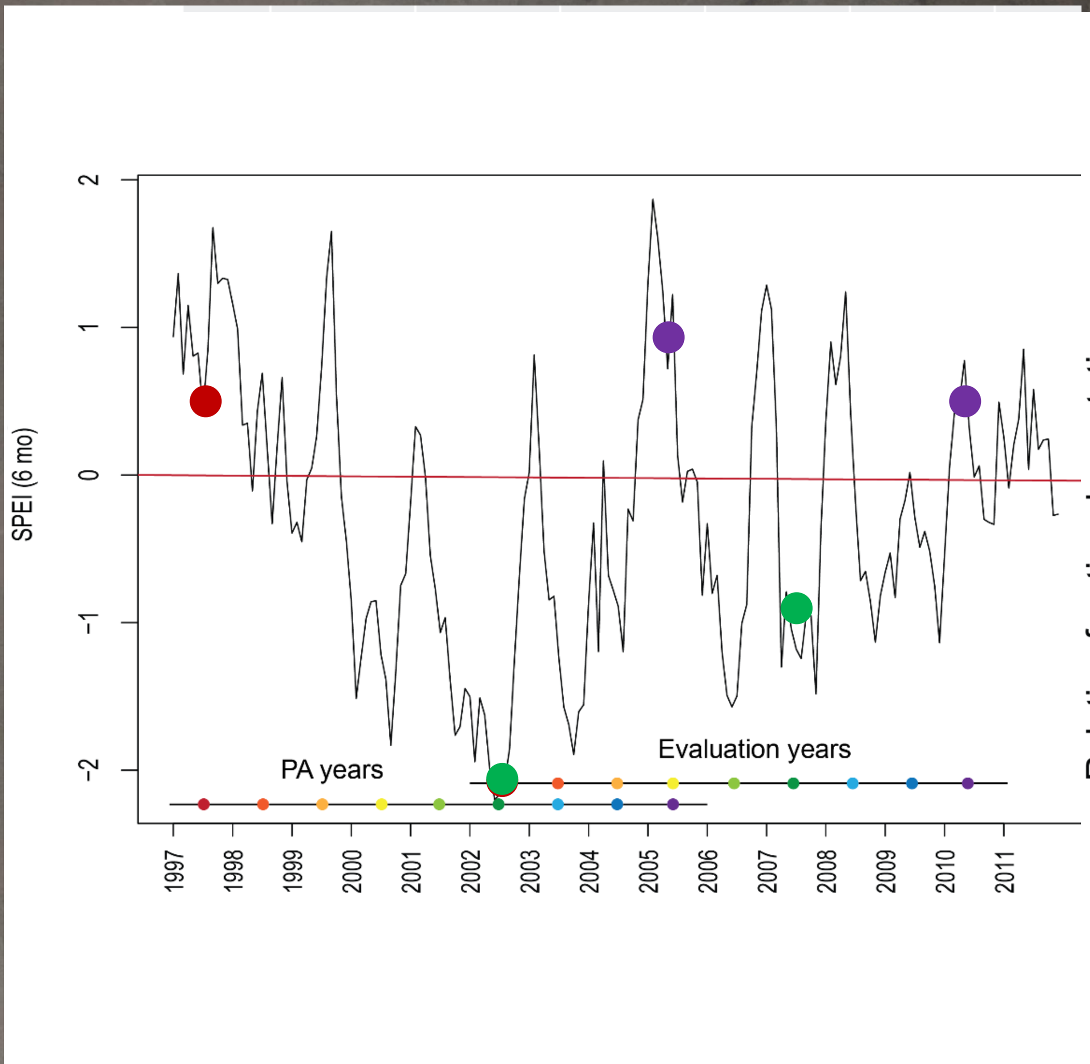
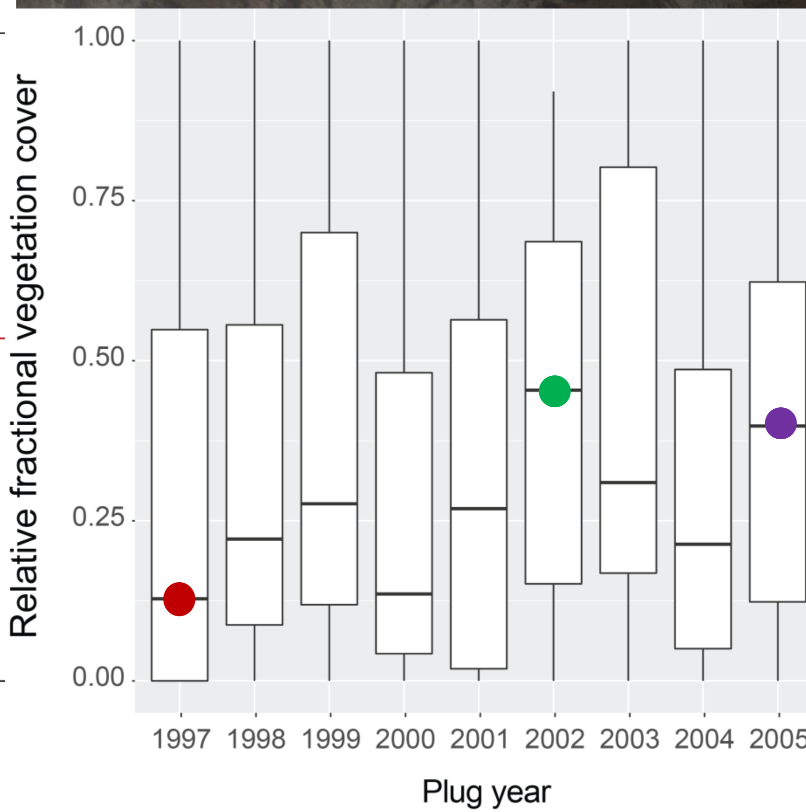
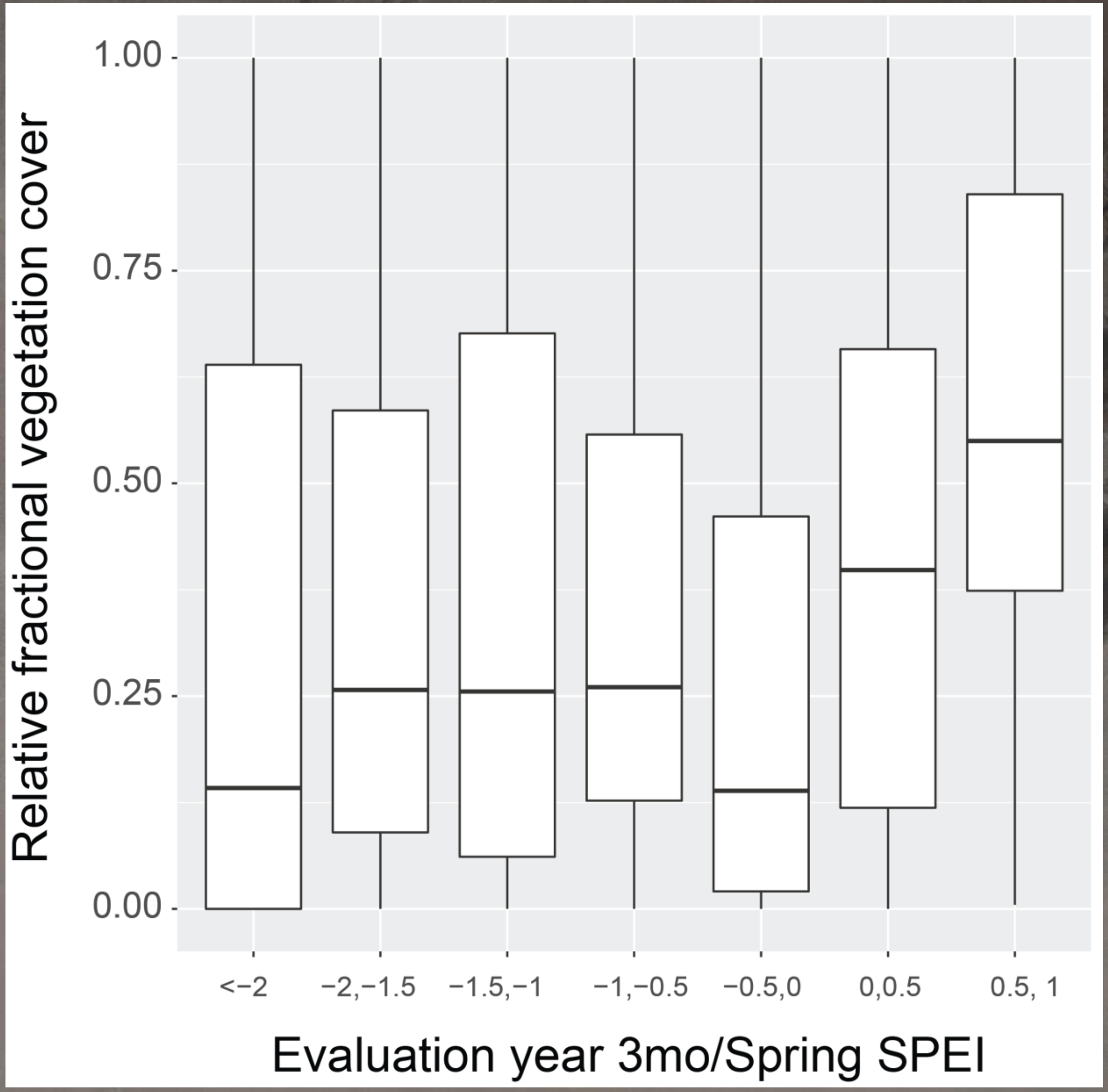


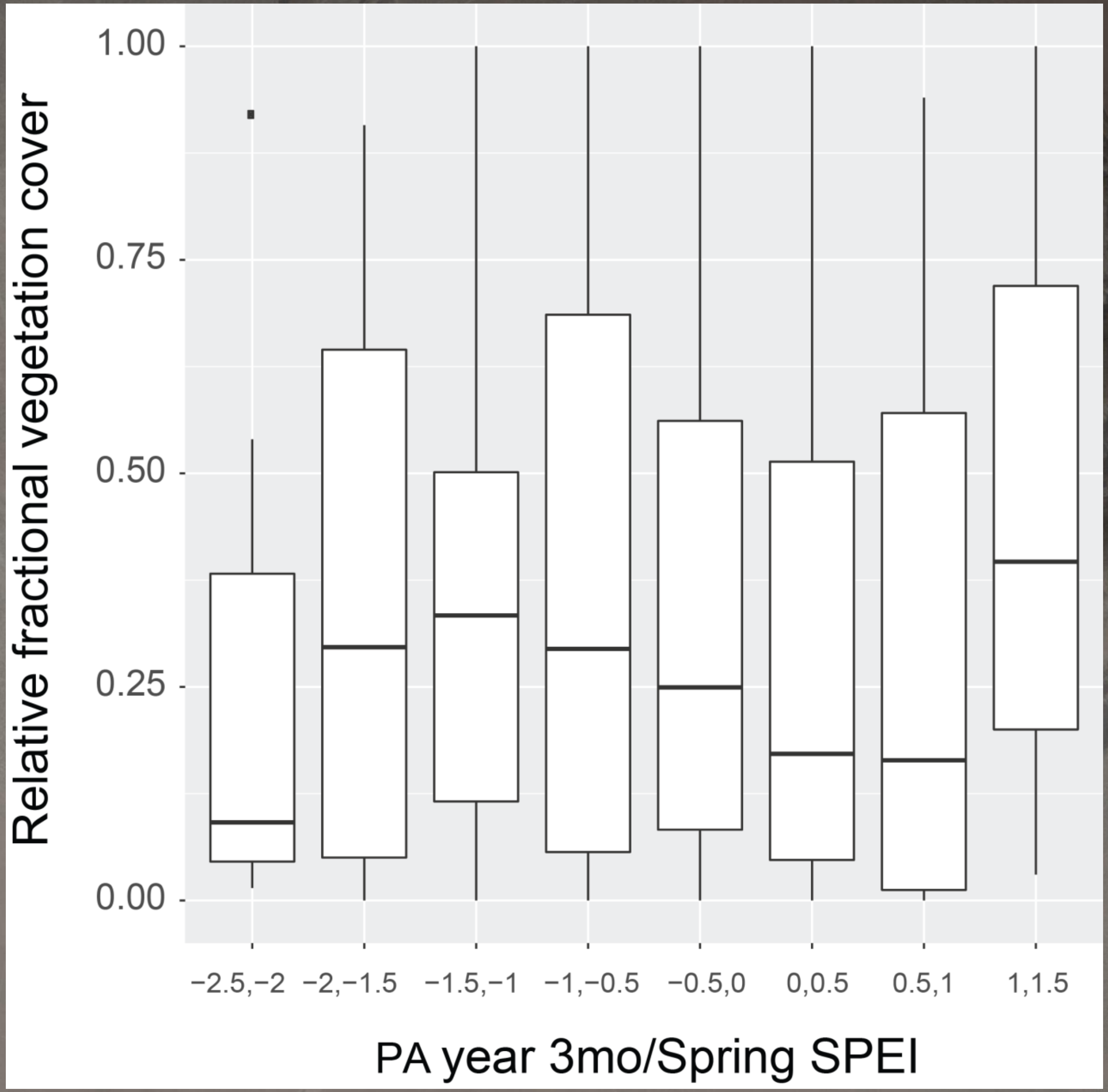


Results



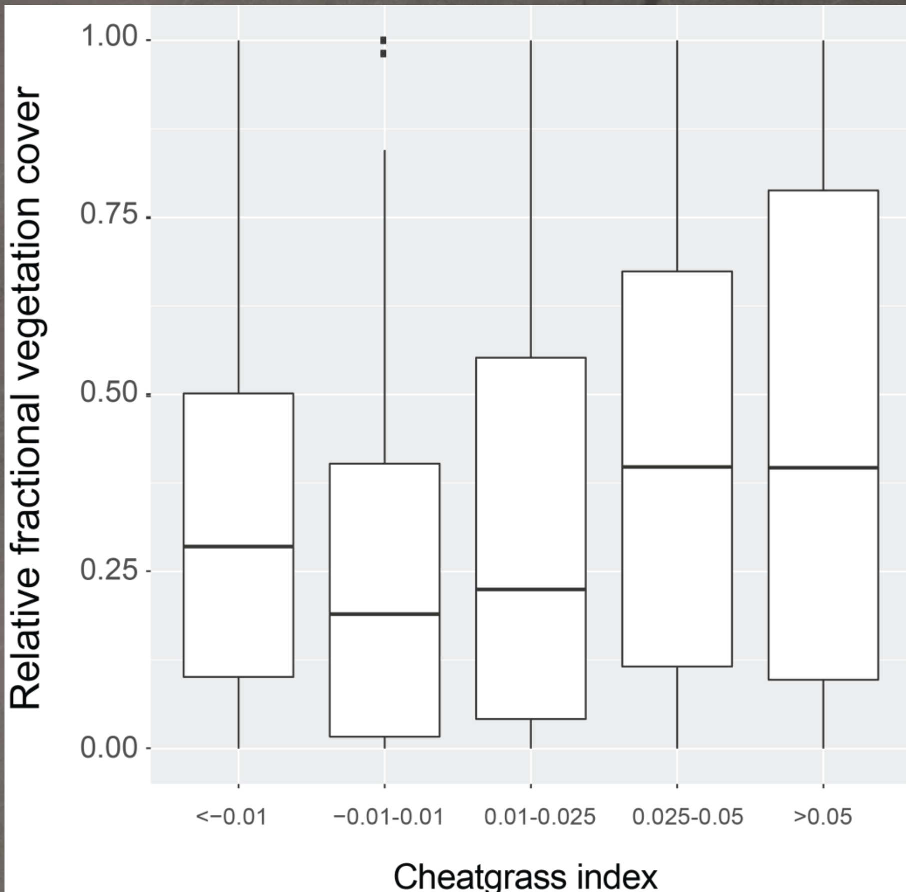
Relative fractional vegetation cover
1.00
0.75
0.50
0.25
0.00
<−2
−2,−1.5
−1.5,−1
−1,−0.5
−0.5,0
0,0.5
0.5, 1
Evaluation year 3mo/Spring SPEI

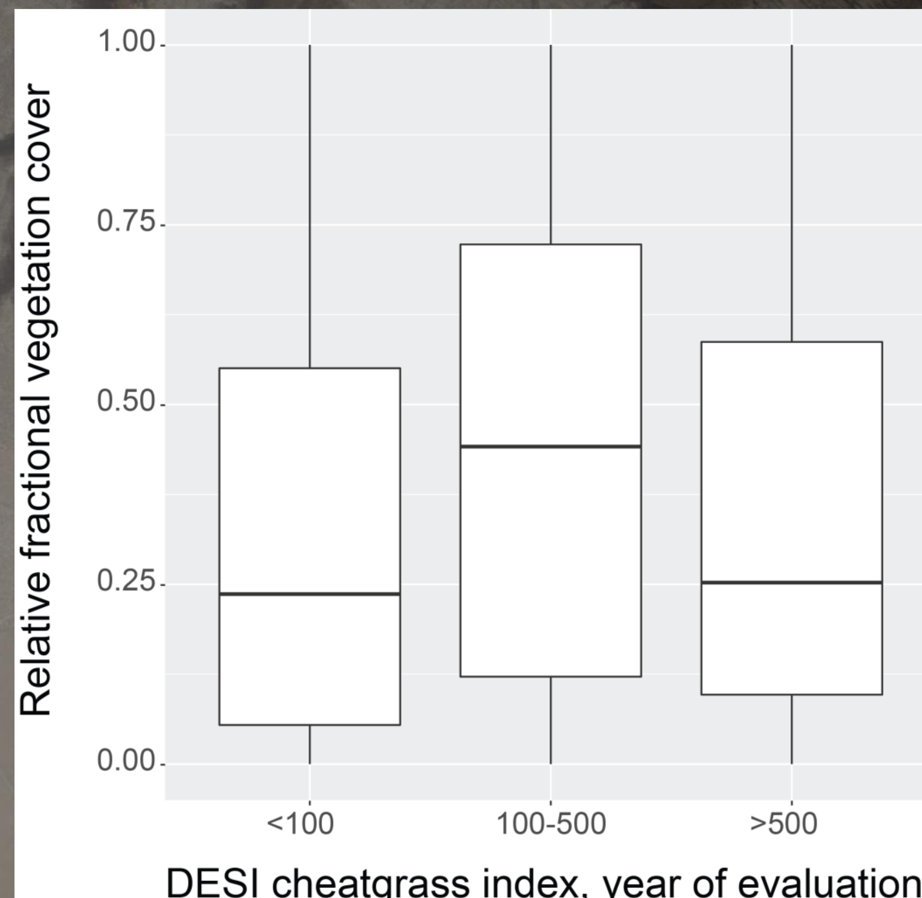
Results



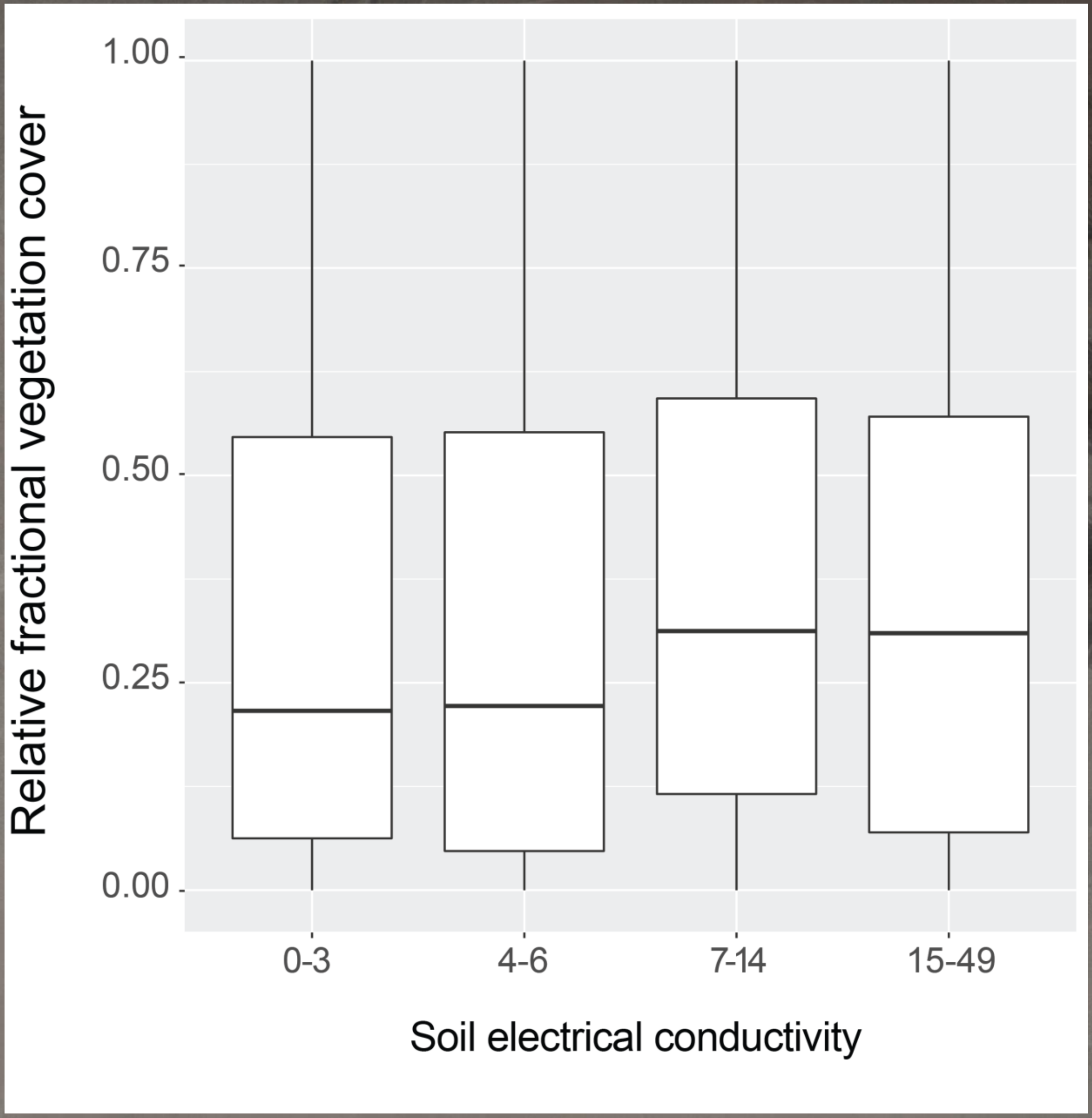
Relative fractional vegetation cover
1.00
0.75
0.50
0.25
0.00
−2.5,−2
−2,−1.5
−1.5,−1
−1,−0.5
−0.5,0
0,0.5
0.5,1
1,1.5
PA year 3mo/Spring SPEI

Results


1.00
0.75
0.50
0.25
0.00
Relative fractional vegetation cover
<−0.01
−0.01-0.01
0.01-0.025
0.025-0.05
>0.05
Cheatgrass index

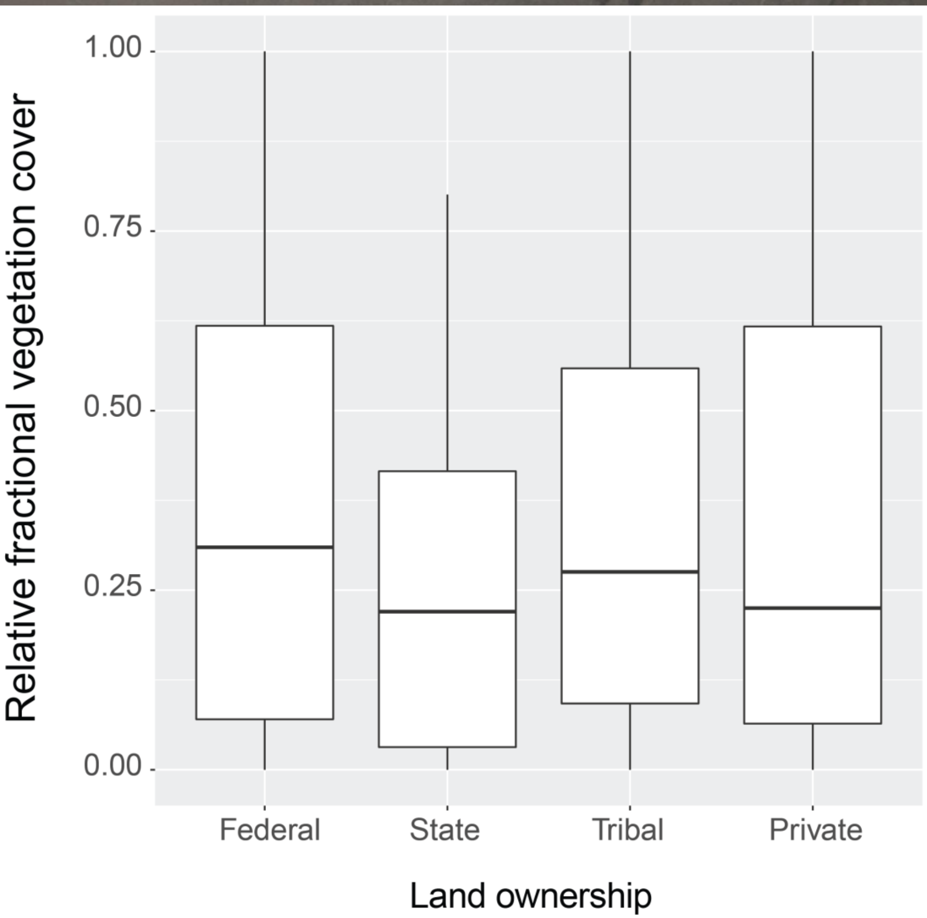

1.00
0.75
0.50
0.25
0.00
Relative fractional vegetation cover
<100
100-500
>500
DESI cheatgrass index, year of evaluation

Results

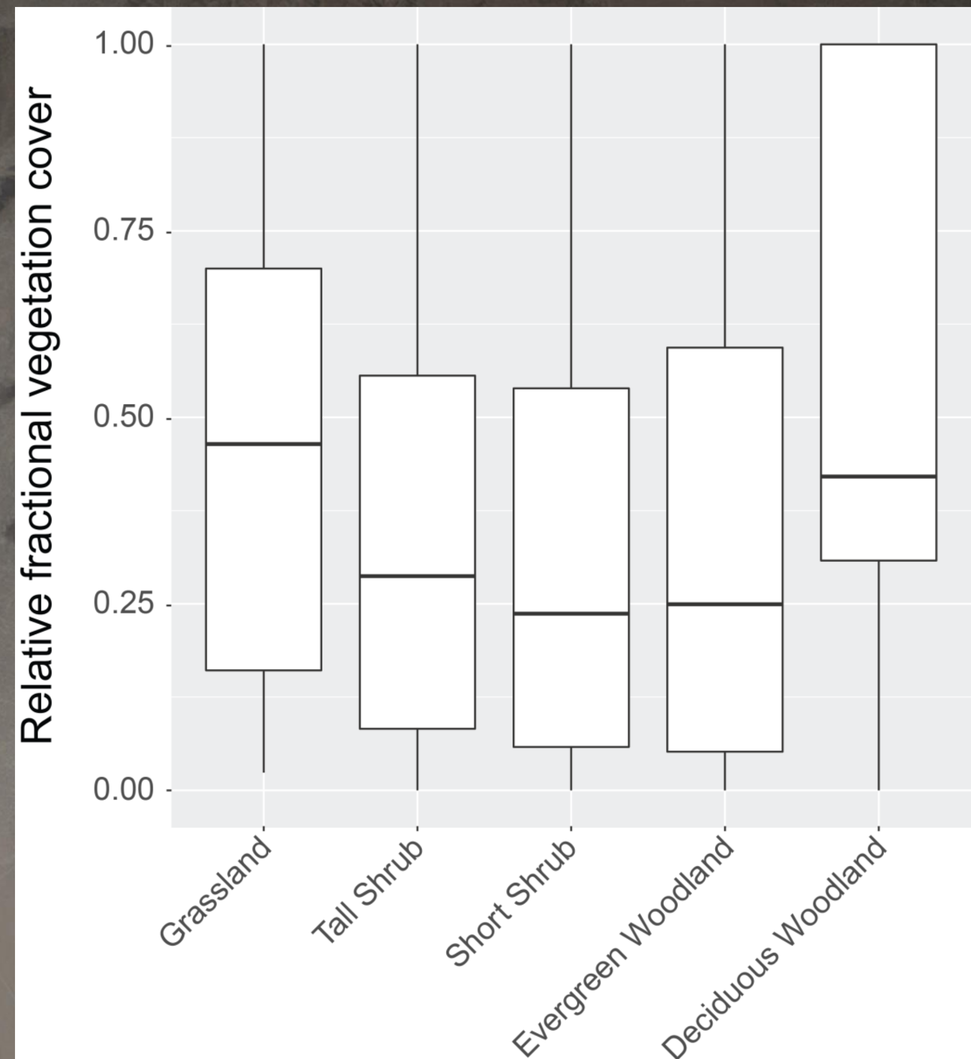


Relative fractional vegetation cover
1.00
0.75
0.50
0.25
0.00
0-3
4-6
7-14
15-49
Soil electrical conductivity

Results



1.00
0.75
0.50
0.25
0.00
Relative fractional vegetation cover
Federal
State
Tribal
Private
Land ownership

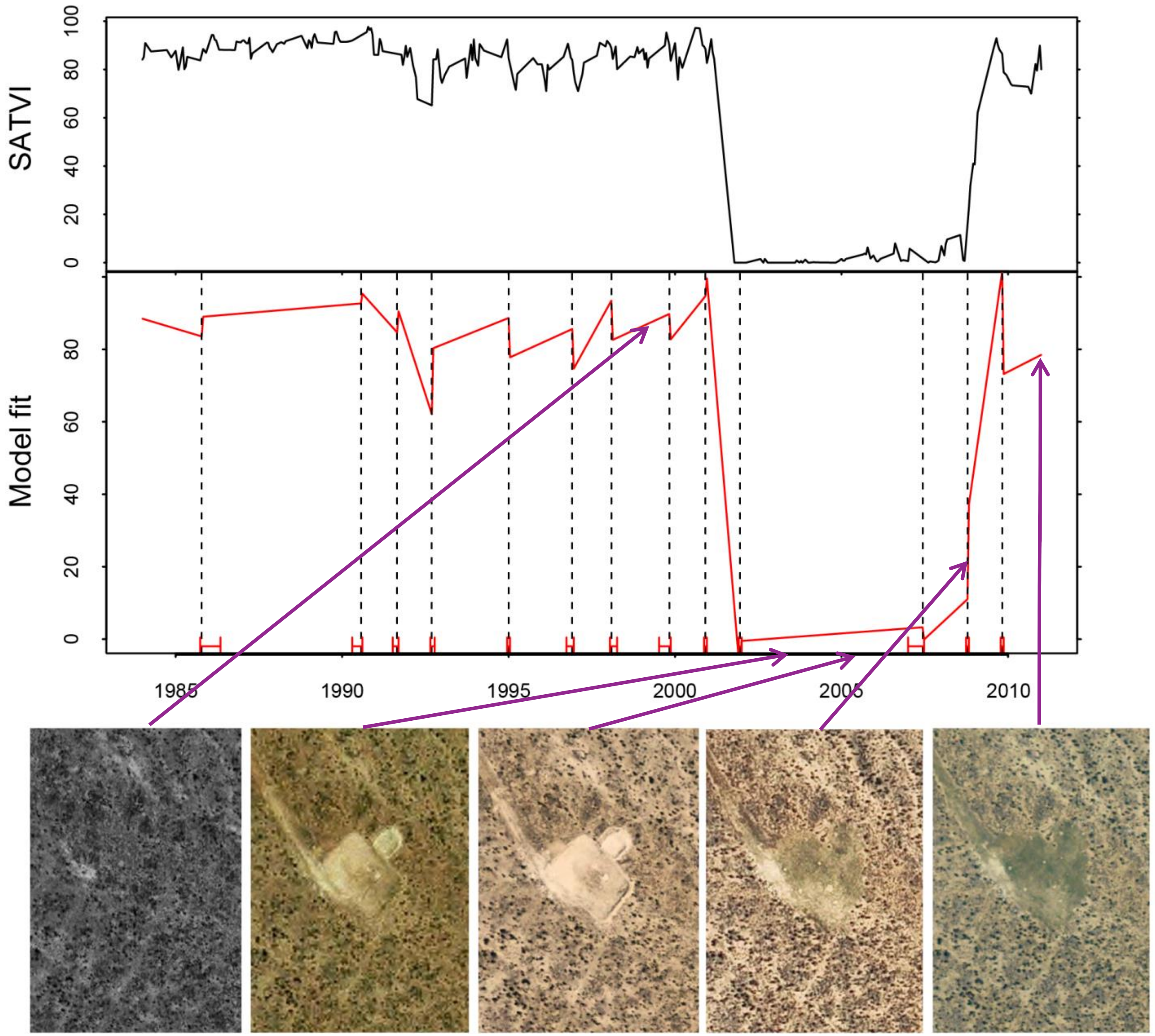


1.00
0.75
0.50
0.25
0.00
Relative fractional vegetation cover
Grassland
Tall Shrub
Short Shrub
Evergreen Woodland
Deciduous Woodland

Results

What is going on?

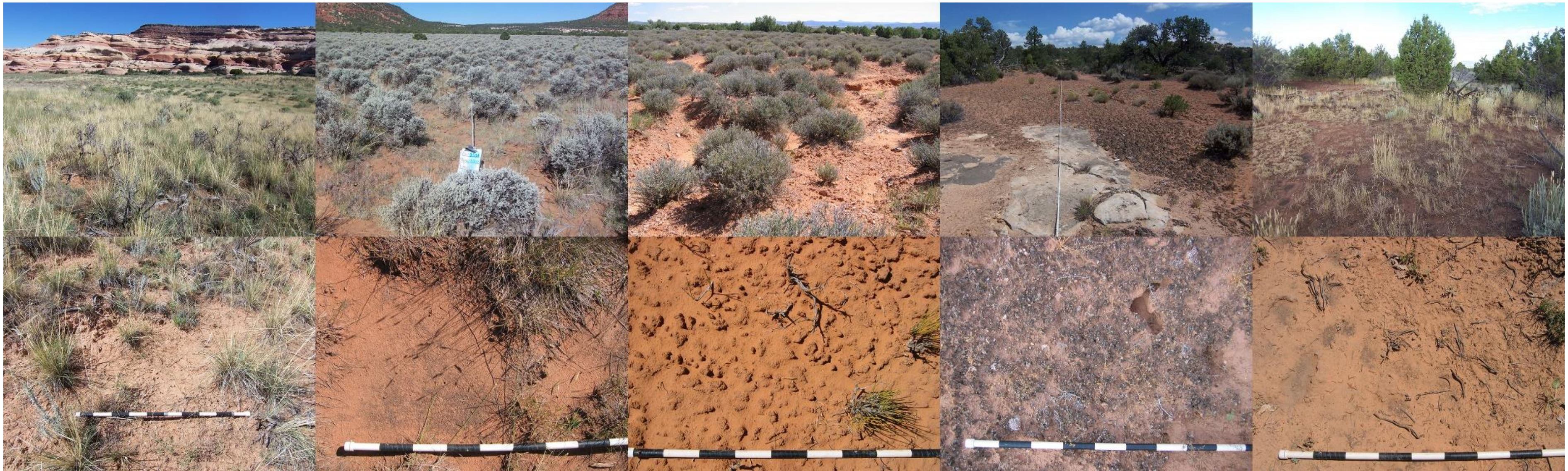
- Higher RFVC = Eval. year SATVI
- Higher RFVC = cheatgrass and Russian thistle dominated
- This may be the case for invaded pads with very high RFVC
- Others with lower/moderate RFVC change may have less invasion/more native vegetation?



Conclusions

Time-series data and analysis approaches are accurate and robust for measuring restoration and recovery

- SATVI models very useful for temporal monitoring of drylands
- Noisy spatial data, compounded across analysis steps
- Weak link in historical records and GIS data (plug date, treatment info), but will likely be more accurate in future



Conclusions

Some year/climate influence

- Confounding factors of later wet period (2005-2010) and possibly improved treatments?

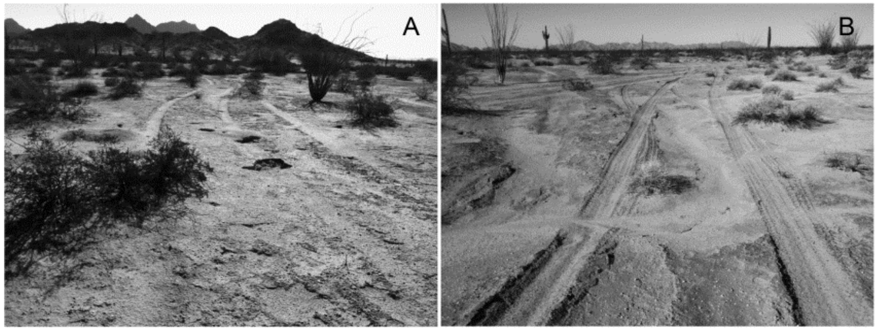
Short-term "recovery" is mostly weeds

- Not ideal but perhaps better than exposed ground, soil loss and dust

Photos: Linda Baker, Upper Green River Valley Coalition

Future applications

- Now possible to establish operational monitoring of vegetation changes on DOI and other lands
- The technology and data quality are rapidly improving
- Time series approaches can be used to assess other dryland management issues
  - OHV and pedestrian trails, military land uses
  - Post-fire vegetation recovery
  - Cheatgrass dynamics
  - Ephemeral waters



Thank you!

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