A COMPARISON OF REMOTE SENSING INDICES AND A TEMPORAL STUDY OF CIENEGAS AT CIENEGA CREEK FROM 1984 TO 2011 USING MULTISPECTRAL SATELLITE IMAGERY

By

NATALIE R. WILSON

MASTER OF SCIENCE
GEOGRAPHIC INFORMATION SYSTEMS TECHNOLOGY
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To my mother and grandfather:
it’s about time.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
BLM	Bureau of Land Management
DEM	Digital Elevation Model
ERDAS	Remote sensing software developer
ESRI	Geographic information system software developer
GPS	Global Positioning System
GREEN	Visible Green; Landsat Thematic Mapper band 2
NDII5	Normalized Difference Infrared Index using Landsat Thematic Mapper band 5
NDII7	Normalized Difference Infrared Index using Landsat Thematic Mapper band 7
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near Infrared; Landsat Thematic Mapper band 4
RED	Visible Red; Landsat Thematic Mapper band 3
SAVI	Soil-Adjusted Vegetation Index
SPSS	Statistics software package
SWIR	Shortwave Infrared; Landsat Thematic Mapper bands 5 and 7
TM	Landsat Thematic Mapper
TWI	Topographic Wetness Index
USGS	US Geological Survey

ABSTRACT

Desert wetlands, in particular those slow moving bodies of water known as cienegas, are important sites for biodiversity in arid landscapes and serve as indicators of hydrological functioning on the landscape level. One of the most extensive systems of cienegas, historical or extant, in southeastern Arizona lies along Cienega Creek, located southeast of Tucson, Arizona. Satellite imagery analysis is heavily utilized to determine landscape-level trends, but cienegas present a challenge to traditional analysis methods. The Normalized Difference Vegetation Index (NDVI), the classic measure of vegetation greenness, reacts counterintuitively to open water and is affected by open ground, both common occurrences in cienega habitats. Additional remote sensing indices have been developed that balance sensitivity to these environmental elements. This research explores these remote sensing indices at Cienega Creek, applying one topographic index to current elevation data and five spectral indices to Thematic Mapper imagery from 1984 to 2011. Temporal trends were identified for all spectral indices and all indices were compared for suitability in cienega habitats. Temporal trends were analyzed for spatial clustering and spatial trends identified. The Normalized Difference Infrared Index utilizing Landsat Thematic Mapper band 5 outperformed other indices at differentiating between cienega, riparian, and upland habitats and may be more suitable than NDVI for analyzing cienega habitats in such circumstances.

INTRODUCTION

Cienegas are low to mid-elevation, slow flowing, perennial wetlands that occur in arid habitats of the southwest. Cienegas are important sites for biodiversity, as they regulate flow regimes downstream and are an indication of landscape-level hydrologic condition. As perennial water sources these sites were historically heavily utilized in southeast Arizona. This anthropogenic utilization is implicated in degradation of cienegas and their surrounding grassland habitats, though early 20th century climate change may also have contributed to periods of incision and arroyo-cutting (Hendrickson and Minckley 1984).

Satellite imagery analysis is often used to determine landscape level trends but cienegas present a challenge to traditional analysis methods. The Normalized Difference Vegetation Index (NDVI) (Rouse et al. 1974), the classic measure of vegetation greenness, reacts counterintuitively to open water and is affected by bare ground (Huete, Jackson, and Post 1985), both common occurrences in cienega habitats. Other remote sensing indices balance sensitivity to these environmental elements using a variety of spectral bands. Vegetation indices include the NDVI and Soil Adjusted Vegetation Index (SAVI), water indices include the Normalized Difference Water Index (NDWI), and a moisture index the Normalized Difference Infrared Index (NDII) can be calculated two ways using different shortwave infrared (SWIR) spectral bands. The Topographic Wetness Index quantifies soil moisture based on topographic parameters (Beven and Kirkby 1979). This research explores these remote sensing algorithms and indices, applying them to Thematic Mapper imagery from 1984 to 2011. Temporal trends were identified for all spectral indices and all indices were compared for suitability in application in cienega habitats.

Study Site

Cienega Creek, southeast of Tucson and a tributary of the Santa Cruz, is classified as an "Outstanding Arizona Water" by the Arizona Department of Environmental Quality (Arizona Department of Environmental Quality 2014). The upper portion of Cienega Creek has one of the most extensive systems of cienegas, historical and extant, in the region (Hendrickson and Minckley 1984). The area was made a National Conservation Area in 2000 and is managed by the Bureau of Land Management (Las Cienegas National Conservation Area Establishment Act 2000). These remaining cienegas are prime targets for conservation due to their vulnerability to degradation, highly localized extents, and involvement in a wide range of ecosystem functions (Figure-1).

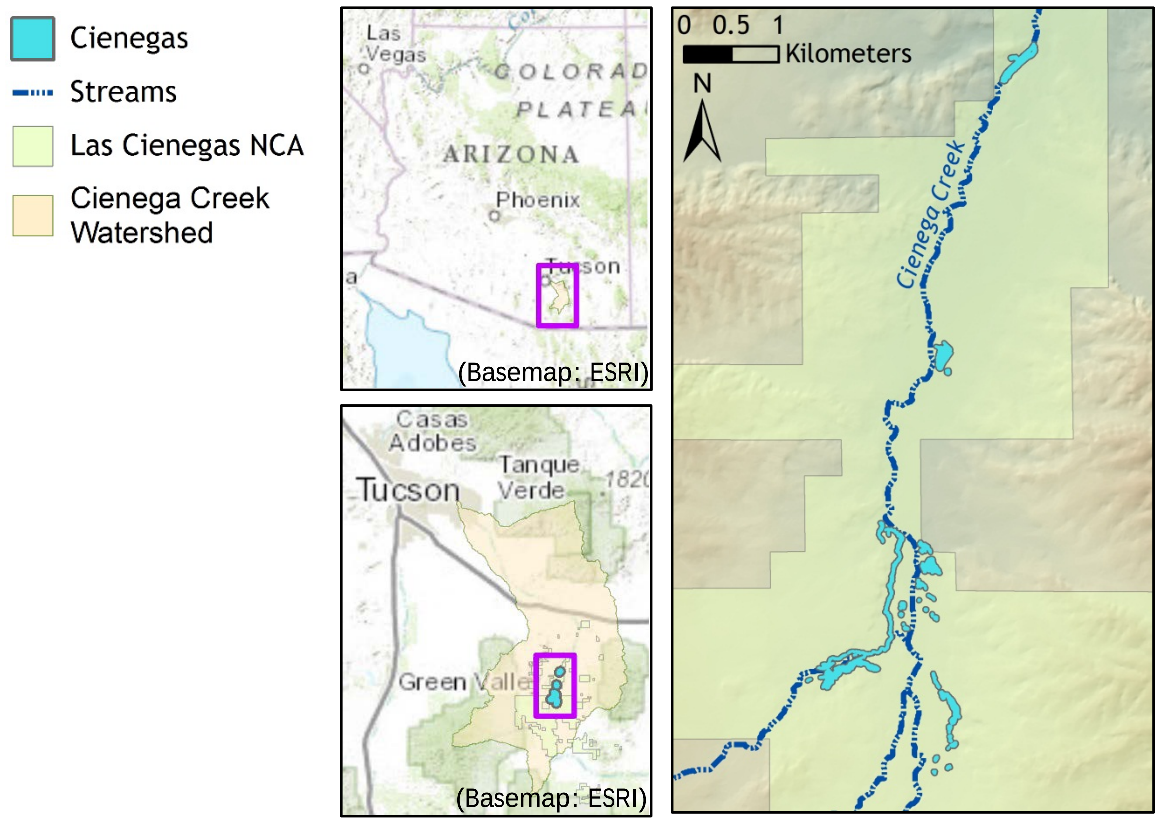

Figure 1. Location of cienegas. Cienega polygons are represented larger than actual size in order for all cienegas to be clearly visualized.

DATA, METHODS & ANALYSIS

Data

Landsat Thematic Mapper satellite imagery was acquired from USGS. May and June are the driest portions of the year and are the months when the presence of water and greenness of vegetation with access to water would be most distinct from the otherwise dry and senescent landscape. One scene was chosen from these months for each year from 1984 – 2011. Scenes were chosen based on low cloud cover. All scenes were atmospherically corrected by Miguel Villarreal of the USGS. Resolution for Thematic Mapper imagery is 30m. Digital Elevation Model (DEM) data was acquired from USGS. Resolution for the DEM was 10m. Cienegas were located in the field and recorded with GPS in 2013.

Methods

Topographic Index

One index is not based on satellite imagery and is derived from a DEM. The TWI combines upslope flow contributing area (a_s) and slope (β) to quantify soil moisture conditions (Equation 1) (Beven and Kirkby 1979). A Python script was developed to automate the process.

Equation 1: $$\mathrm{TWI} = \ln\left(\frac{a_s}{\tan(\beta)}\right)$$

Spectral Indices

The arid lands of the southwest present a challenge to satellite imagery vegetation analysis due to the effects of bare ground on traditional analysis methods. NDVI was one of the first vegetation indices developed for satellite imagery analysis and is widely utilized because it strongly correlates with photosynthesis and primary production of vegetation. It is a ratio combination of near infrared (NIR) and visible red spectral bands which correspond to Landsat Thematic Mapper bands 4 and 3 (Equation 2) (Rouse et al. 1974). SAVI was developed for arid land regions with moderate vegetation cover (Huete 1988). SAVI expands on the combination of red and NIR bands of NDVI by including a factor (L) that controls for soil reflectance (Equation 3). L = 0.5 is suitable for a wide range of vegetation cover and was used for this study.

Cienegas have areas of open water, which confound indices that rely on NIR due to the high absorption of NIR by open water. An NDVI value near 1 indicates green vegetation, 0 indicates brown vegetation and -1 indicates open water. When an area with an even proportion of small non-clustered areas of open water and green vegetation is generalized to a pixel size of 900m^2 the resultant pixel value would be near 0. NDWI was developed to measure water and delineate open water features; it is a ratio combination of green (Landsat TM band 2) and NIR (Equation 4) (Mcfeeters 1996).

Two infrared indices combine NIR and SWIR bands. NDII5 was developed to determine biomass in salt marsh habitats (Hardisky, Klemas, and Smart 1983) and is less attenuated by brown biomass or soil moisture (Hardisky et al. 1984). NDII7 is predominately used in analysis of wildfire extent and severity but is also a measure of vegetation moisture content (Chuvieco et al. 2002). NDII5 utilizes Landsat TM band 5 while NDII7 utilizes TM band 7 (Equations 5 and 6).

Equation 2: $$\mathrm{NDVI} = \frac{(\mathrm{TM4} - \mathrm{TM3})}{(\mathrm{TM4} + \mathrm{TM3})}$$

Equation 3: $$\mathrm{SAVI} = \frac{(\mathrm{TM4} - \mathrm{TM3})}{(\mathrm{TM4} + \mathrm{TM3} + \mathrm{L})}(1 + \mathrm{L})$$

Equation 4: $$\mathrm{NDWI} = \frac{(\mathrm{TM2} - \mathrm{TM4})}{(\mathrm{TM2} + \mathrm{TM4})}$$

Equation 5: $$\mathrm{NDII5} = \frac{(\mathrm{TM4} - \mathrm{TM5})}{(\mathrm{TM4} + \mathrm{TM5})}$$

Equation 6: $$\mathrm{NDII7} = \frac{(\mathrm{TM4} - \mathrm{TM7})}{(\mathrm{TM4} + \mathrm{TM7})}$$

All satellite imagery indices, except NDVI, were processed using ERDAS Imagine automation process codified by Roy Petrakis for the USGS. Models were developed for each index in ERDAS Spatial Modeler, converted to a model library and a batch command file was developed. NDVI imagery was developed by Michelle Coe for the USGS.

Resampling and Zonal Statistics

Many of the cienegas are far smaller in area than the Landsat TM pixel size of $900m^2$. Combining data of such differing resolutions was a challenge for analysis. Liberal methods of converting polygons to rasters would vastly expand the area considered cienega and pixels along the margins of cienegas would be considered equal to those fully contained within cienega boundaries but conservative methods of rasterization would completely ignore many known cienegas. To address this issue, all index results were resampled to a pixel size of $1m^2$ using a Python script. This effectively weights each TM pixel by the area intersecting a cienega (Figure 2).

Descriptive statistics of index values were calculated for all cienega areas as well as all cienegas combined. The ESRI ArcToolbox Zonal Statistics to Table tool was applied to all index imagery using a Python script.

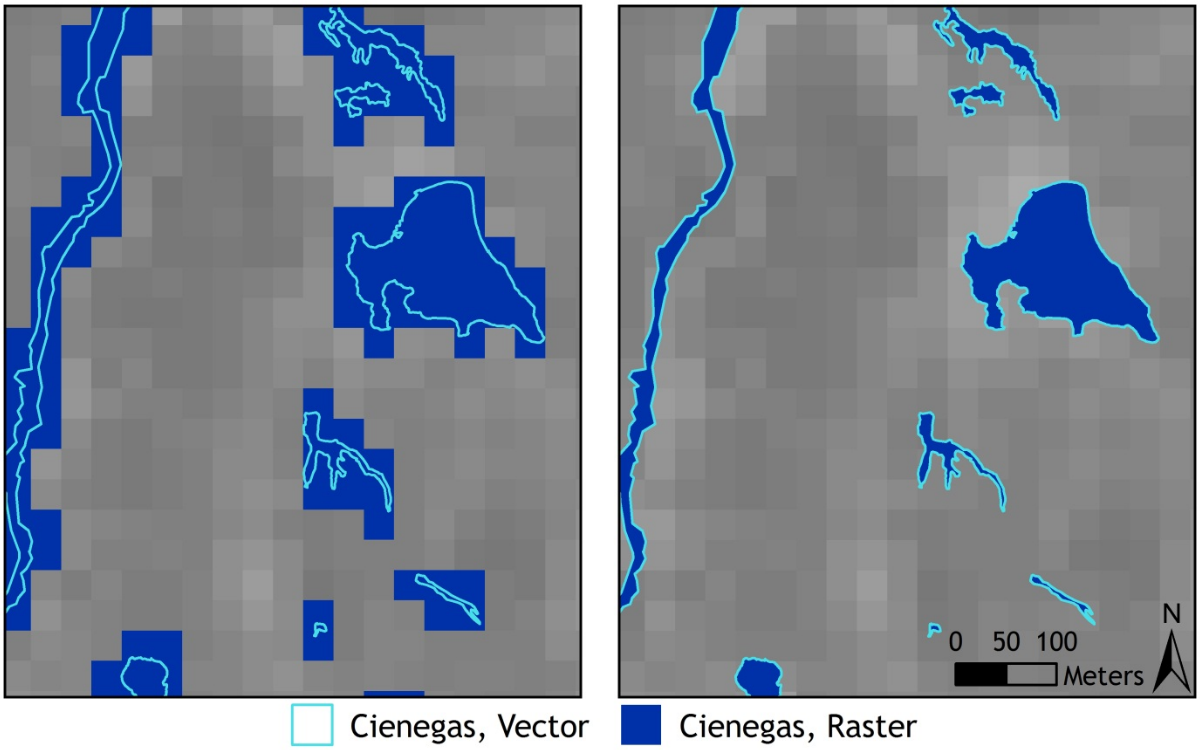

Figure 2. Rasterized cienegas before (left) and after (right) the resampling process. Background is NDVI values derived from Landsat TM.

Random Sample Design

In order to compare the performance of indices in distinguishing cienegas from non-cienegas habitat, a stratified random sample was created (Figure 3). The extent of the study area was confined to the extent of the cienegas for the development of the random sample. Cienega samples were the areas defined by GPS; there were forty-four cienega samples covering an area of 154,133 m^2.

The uplands sample was created by buffering the cienegas and streams by 30m and excluding this area; all other area within the extent was assumed to be upland habitat. Forty-four random points were distributed within this upland zone and each point was buffered 33.4m which would have resulted in a total area similar to the total area of cienegas. When the points were buffered, some of the resulting area overlapped the excluded buffered cienegas and riparian zones, or extended beyond the sample extent. These rogue areas were excluded from the sample, resulting in a final upland habitat sample of forty-four samples with a total area of 151,391 m^2.

A riparian zone was developed by buffering streams and cienegas 30m then excluding buffered cienegas from the buffered stream zone. Random points were created within the resultant riparian zone. Only thirty-three points could be created due to the relatively small extent of the riparian zone. These points were buffered 33.4m; any of the resulting area that extended beyond the riparian zone, beyond the study extent, or overlapped the cienega zone was excluded from the sample. This resulted in a final riparian habitat sample of thirty-three samples with a total area of 84,542 m^2.

The development of the random sample was completed in ESRI ArcMap.

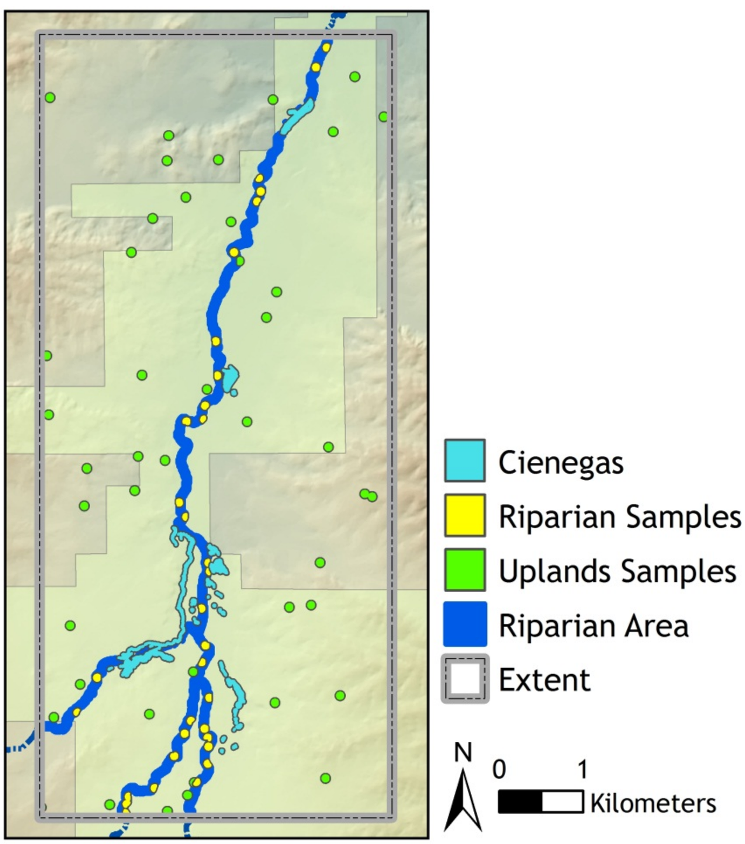

Figure 3. Random sample design. Cienegas and sample polygons are represented larger than actual size in order for all areas to be clearly visualized.

Analysis

Linear Regression

To analyze temporal trends in cienegas, spectral index values were plotted for each cienega from 1984 to 2011. Linear regression was applied over time for each index for each cienega. The slope coefficient was used to quantify the trend for individual cienegas. Linear regression was applied in SPSS. Global Moran's I (spatial autocorrelation) using Dalaunay triangulation was applied to the trends for each spectral index to analyze spatial patterns in spectral index trends for cienegas. Global Moran's I was applied in ESRI ArcMap.

Analysis Of Variance

To examine the suitability of spectral indices for application to cienegas, Analysis of Variance (ANOVA) was applied to the index values derived from the random sample design for cienega, riparian, and upland habitats. The three sample groups are known to be different; it is a question whether remote indices can distinguish them. An ANOVA analysis of the habitat groups for each index, and each year in the case of spectral indices, will determine whether the index values for the different habitats are statistically significant. Untransformed index values were used for the analysis; while little of the data approximated a Gaussian curve, none of the transformation techniques explored normalized the distribution for a large enough subset of the data to warrant a separate analytical process. Levene's statistic was used to assess homogeneity of variances and between group comparisons were made using Tamhane's post-hoc analysis. This analysis was applied in SPSS.

RESULTS

Linear Regression

Trends were determined for spectral index values for each cienega through time using the slope coefficient from linear regression (Table A-1). The trends for individual cienegas were visualized as five choropleth maps, one for each spectral index (Figure 4).

All spectral index trends show a significantly clustered spatial pattern as determined by Moran's I (Table 1). NDVI and SAVI trends are both strongly clustered (P = 0.000) and visually display a directional trend with positive trends in the north and negative trends in the south. NDII5 and NDII7 trends are also strongly clustered (P = 0.000) but no clear north-south spatial trend is apparent; several cienegas on the east side of Cienega Creek show positive trends. NDWI is strongly clustered (P = 0.000) and displays an oppositional directional trend compared with NDVI and SAVI; NDWI trends are strongly negative in the north and moderate to positive in the south.

Table 1. Moran's I analysis of the spatial correlation of trends in spectral index values for cienegas through time.

	NDII5	NDII7	NDVI	SAVI	NDWI
Moran's Index:	0.290296	0.392297	0.452497	0.426714	0.428432
Expected Index:	-0.023256	-0.023256	-0.023256	-0.023256	-0.023256
Variance:	0.007301	0.007391	0.007382	0.007363	0.007353
z-score:	3.669704	4.833490	5.537160	5.243864	5.267515
p-value:	0.000243	0.000001	0.000000	0.000000	0.000000

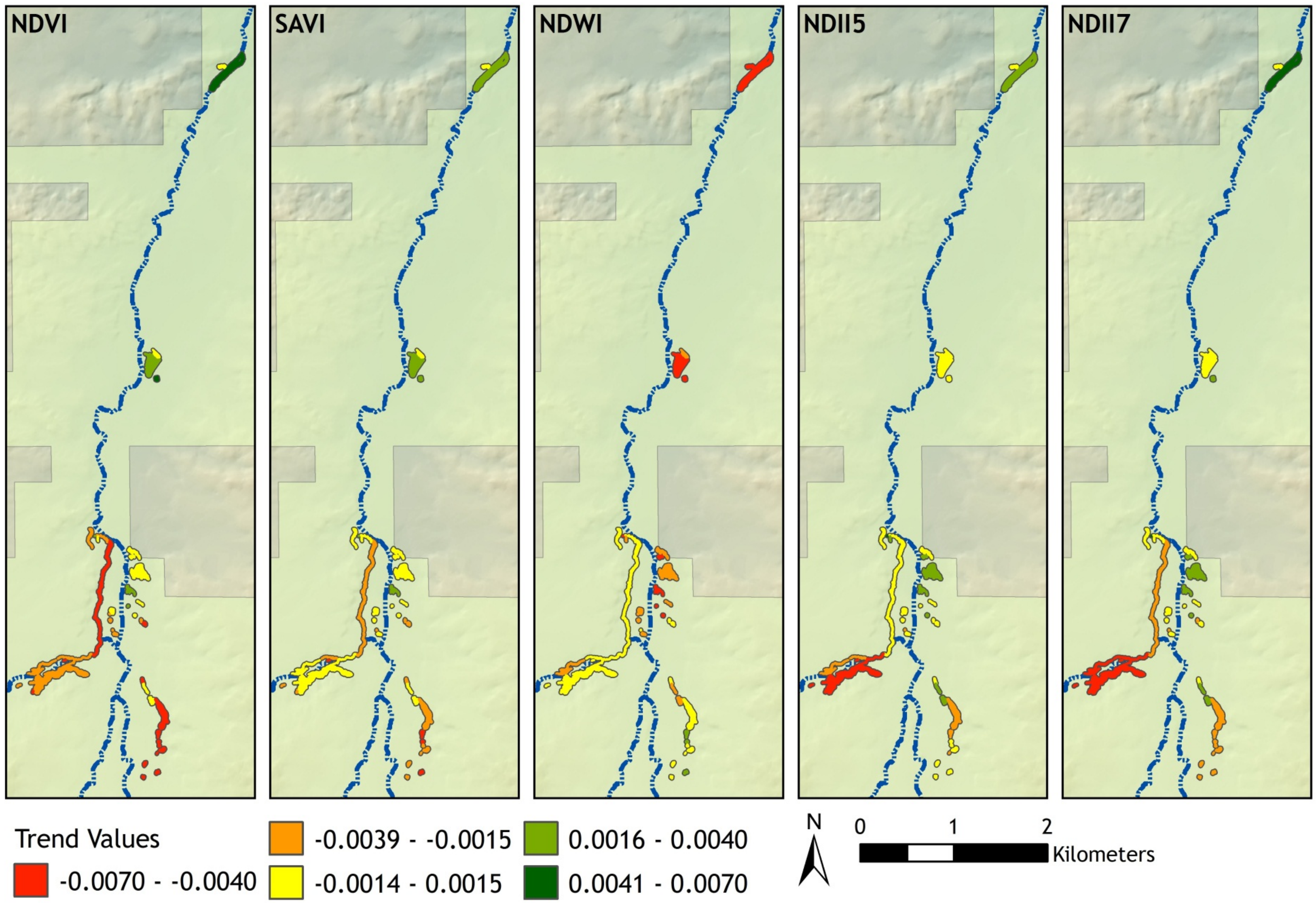

Figure 4. Spectral index trends from 1984 to 2011. Cienega polygons are represented larger than actual size in order for all cienegas to be clearly visualized.

Analysis of Variance

Topographic Index

TWI means are different between habitats as determined by ANOVA ($F(2,118) = 10.955$, $P = 0.000$). The variances of means is heterogeneous as determined by Levene's test ($P = 0.000$) and Tamhane's post hoc test revealed that TWI means are different for cienegas (mean = 625.19, SD = 535.26, $P = 0.000$) and riparian (mean = 1014.71, SD = 1238.14, $P = 0.003$) compared to uplands (mean = 226.80, SD = 227.77) but there is no difference between cienega and riparian groups ($P = 0.266$) (Figure 5).

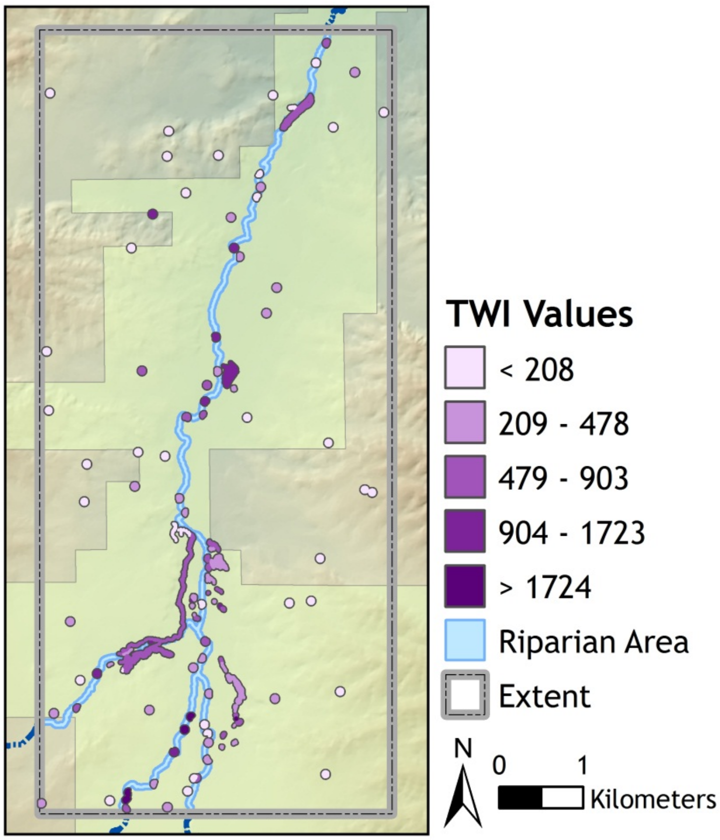

Figure 5. Topographic Wetness Index values. Cienegas and sample polygons are represented larger than actual size in order for all areas to be clearly visualized.

Spectral Indices

Five spectral indices were applied to 28 years of Landsat TM data, providing 140 Index-Year combinations for ANOVA analysis (full statistics available from author). Years were not analyzed together due to the variability in precipitation between years. Index means are different between habitats for all years except 1986 as determined by ANOVA ($P = 0.000$). Index means are not different between habitats groups for any spectral index in 1986 ($P = [0.083, 0.214]$). Since there is no significant difference between means for any index in 1986, that year has been excluded from additional between group analyses.

The variance of means is heterogeneous between groups for most Index-Year combinations as determined by Levene's test. To allow comparisons between statistical analyses of different Index-Year combinations, Tamhane's post-hoc test was used to determine differences between groups for all Index-Year combinations including those with homogenous variances in means. Index means are different for cienegas ($P = [0.000, 0.008]$) and riparian ($P = [0.000, 0.003]$) when compared to uplands for all years. NDII5 means are different between cienega and riparian habitat samples for 16 of 27 years ($P = [0.000, 0.045]$). NDII7 means are different between cienega and riparian habitat samples for 6 of 27 years ($P = [0.017, 0.040]$). NDVI means are different between cienega and riparian habitat samples for 9 of 27 years ($P = [0.000, 0.035]$). NDWI means are different between cienega and riparian habitat samples for 10 of 27 years ($P = [0.000, 0.049]$). Due to the difference in placement of the NIR band in the formulation of NDWI, NDWI means are in inverse relationship between groups compared to the other indices. For NDWI, the upland habitat values are higher than the cienega values which is in turn higher than riparian values. SAVI means are different between cienega and riparian habitat samples for 8 of 27 years (*P* = [0.000, 0.037]). Overall, NDII5 shows a difference between habitat groups for a higher proportion of years than any other index (Table 2).

Table 2. Summation of years in which spectral index means are significantly different between cienega and riparian habitat groups.

	Number of Years		
Index	Significant	Not Significant	% Significant
NDII5	16	11	59.3%
NDII7	6	21	22.2%
NDVI	9	18	33.3%
NDWI	10	17	37.0%
SAVI	8	19	29.6%

DISCUSSION

Temporal Analysis

Spectral index trends for cienegas through time display considerable clustering. For some indices that clustering also shows a directional trend, generally north to south. However, a north-south general spatial trend also corresponds to an elevation and hydrologic trend: north is lower and downstream while south is higher and upstream. Additionally, there is more tree canopy surrounding and within the cienegas in the north. Further analyses would determine the strength of the directional trend and may indicate what factors are more influential: elevation, hydrology, latitude, or canopy cover. The infrared indices do not demonstrate the same directional trend. Also taking into consideration its results in the analysis of variance, NDII5 may be less susceptible to the factors that are influencing this directional trend and therefore be a more robust measure of cienega vegetation and soil moisture.

Comparison of Remote Sensing Indices

All spectral indices are able to reliably distinguish cienega and riparian habitats from upland habitats for all years excluding 1986. In 1986, the best Landsat scene available was cloudy over parts of the study area. This atmospheric presence affected the analysis for that year and it would reasonably be expected that, without clouds, 1986 would have exhibited trends similar to all the other years observed. The TWI also easily distinguished cienegas and riparian areas from upland habitats. This research demonstrates that wetland and upland habitats are easily distinguished using spectral or topographic data.

The spectral index that distinguishes cienega from riparian habitat most reliably is NDII5, most likely due to the sensitivity of band 5 to the moisture content of both soil and vegetation instead of only vegetation moisture or greenness. NDII7 is the least reliable at distinguishing cienega from riparian habitat. While NDII7 responds similarly to NDII5 over time, TM band 7 may be too broad to adequately target cienega moisture content. NDWI is the second most reliable in distinguishing cienega from riparian habitats. NDWI's counterintuitive response to vegetation creates the inverse of a known issue with NDVI, that if a pixel that is a mix of water and vegetation, the index value indicates neither. The two vegetation indices were less reliable in distinguishing cienega from riparian habitats than NDII5 or NDWI. There is a range of capability in spectral indices to separate cienega from riparian habitats. NDII5 is the most reliable and should be further explored as a tool in assessing cienegas.

TWI, being based on topographical data, does not offer the range of conditions and sample sets as the spectral indices. It does not reliably distinguish cienega from riparian habitats. Cienega formation can be highly topographic in nature (Hendrickson and Minckley 1984) but the elevation data used was moderate in resolution. An elevation model with better resolution, and the inclusion of hydrological sinks in the analysis, may increase the performance of this topographic index.

APPENDIX A
STATISTICAL RESULTS

Linear Regression

Table A-1. Linear regression coefficients for each spectral index, for all cienegas, over time.*

Cienega	NDII5	NDII7	NDVI	NDWI	SAVI
Stevenson Spring	0.0	0.0	0.1	-0.4	0.1
Coldwater	0.4	0.5	0.5	-0.6	0.4
Ag Field 1	0.0	0.0	0.1	-0.3	0.0
Ag Field 2	0.0	0.0	0.2	-0.5	0.2
Ag Field 3	0.0	0.1	0.2	-0.5	0.2
Ag Field Pothole	0.1	0.3	0.5	-0.7	0.4
Oak Tree 1	0.0	-0.1	-0.2	-0.1	-0.1
Oak Tree 2	0.5	0.5	0.3	-0.4	0.2
Oak Tree 3	0.0	0.0	-0.2	-0.1	-0.1
Oak Tree 4	0.2	0.1	0.0	-0.2	0.0
Springwater 1	0.1	0.0	0.0	-0.3	0.0
Springwater 2	0.2	0.2	0.1	-0.4	0.1
Springwater 3	0.2	0.2	-0.1	-0.2	0.0
Springwater 4	0.2	0.4	0.4	-0.6	0.4
Springwater 5	0.1	0.1	0.0	-0.3	0.1
Springwater 6	0.0	0.1	0.2	-0.4	0.1
Springwater 7	0.2	0.2	0.0	-0.4	0.1
Springwater 8	-0.1	-0.2	-0.3	-0.1	-0.2
Springwater 9	-0.1	-0.1	-0.4	0.0	-0.3
Empire 1	0.1	0.1	-0.1	-0.2	-0.1
Empire 2	0.0	0.0	-0.2	-0.2	-0.1
Empire 3	0.0	0.0	-0.2	-0.2	-0.1
Empire 4	-0.2	-0.2	-0.3	0.0	-0.2
Empire 5	0.0	0.0	-0.2	-0.2	-0.1
Lower Empire Creek	-0.1	-0.2	-0.4	0.0	-0.3
Cieneguita 1	-0.4	-0.5	-0.3	-0.1	-0.1
Cieneguita 2	-0.5	-0.5	-0.4	-0.1	-0.3
Cieneguita 3	-0.4	-0.6	-0.3	-0.1	-0.2
Rattlesnake 1	-0.3	-0.5	-0.3	-0.1	-0.2
Rattlesnake 2	-0.5	-0.7	-0.5	0.1	-0.4
Rattlesnake 3	-0.2	-0.4	-0.2	-0.2	-0.1
Rattlesnake 4	-0.3	-0.4	-0.2	-0.2	-0.1
Cinco Ponds 1	0.1	0.0	-0.4	0.0	-0.2
Cinco Ponds 2	0.3	0.4	0.1	-0.3	0.1
Cinco Ponds 3	-0.3	-0.3	-0.5	0.1	-0.3

Cinco Ponds 4	-0.2	-0.3	-0.7	0.3	-0.5
Cinco Ponds 5	-0.1	-0.2	-0.5	0.2	-0.4
Cinco Ponds 6	-0.1	-0.2	-0.4	0.0	-0.3
Cinco Ponds 7	-0.1	-0.2	-0.4	0.0	-0.2
Cinco Ponds 8	-0.2	-0.3	-0.4	0.0	-0.3
Cinco Ponds 9	-0.1	-0.3	-0.6	0.3	-0.4
Cinco Ponds 10	0.2	0.3	-0.1	-0.2	-0.1
Cinco Pothole 2	0.0	-0.2	-0.4	0.0	-0.3
Cinco Pothole 3	0.0	-0.2	-0.4	0.1	-0.3

* All regression coefficients are represented multiplied by 100. All significant digits represented.

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