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Detecting changes in riparian habitat conditions based on patterns of greenness change: A case study from the Upper San Pedro River Basin, USA

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ABSTRACT

Healthy riparian ecosystems in arid and semi-arid regions exhibit shifting patterns of vegetation in response to periodic flooding. Their conditions also depend upon the amount of grazing and other human uses. Taking advantage of these system properties, we developed and tested an approach that utilizes historical Landsat data to track changes in the patterns of greenness (Normalized Difference Vegetation Index) within riparian zones. We tested the approach in the Upper San Pedro River of southeastern Arizona of the US, an unimpounded river system that flows north into the US from northern Mexico. We evaluated changes in the pattern of greenness in the San Pedro River National Conservation Area (SPRNCA), an area protected from grazing and development since 1988, and in a relatively unprotected area north of the SPRNCA (NA). The SPRNCA exhibited greater positive changes in greenness than did the NA. The SPRNCA also exhibited larger, more continuous patches of positive change than did the NA. These pattern differences may reflect greater pressures from grazing and urban sprawl in the NA than in the SPRNCA, as well as differences in floodplain width, depth to ground water, and base geology. The SPRNCA has greater amounts of ground and surface water available to support a riparian gallery forest than does the NA, and this may have influenced changes during the study period.

Estimates of the direction of greenness change (positive or negative) from satellite imagery were similar to estimates derived from aerial photography, except in areas where changes were from one type of shrub community to another, and in areas with agriculture. Change estimates in these areas may be more difficult because of relatively low greenness values, and because of differences in soil moisture, sun-angle, and crop rotations among the dates of data collection. The potential for applying a satellite-based, greenness change approach to evaluate riparian ecosystem condition over broad geographic areas is also discussed.

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1. Introduction

In many arid and semi-arid regions of the world there is great concern over the condition of riparian ecosystems (Swift, 1984; Stromberg and Patten, 1990; Armour et al., 1991; Gregory et al., 1991; Zube and Sheehan, 1994; Stromberg et al., 1996; Todd and Elmore, 1997; Nilsson and Berggren, 2000). In the western United States, there may be as little as two percent of the original forested riparian habitat left (Todd and Elmore, 1997), and environmental managers and the general public alike are concerned about how the loss of such large amounts of riparian habitat might affect the sustainability of biological diversity in arid regions where human populations are rapidly expanding. Riparian ecosystems have declined substantially since the early 1900s, primarily as a result of construction of dams for flood control and water storage, pumping of surface and ground water from floodplains for agriculture and human consumption, and livestock grazing (Lytle and Merritt, 2004). Dams, such as those along the Colorado and Gila river systems in the US, have substantially decreased the frequency and magnitude of flooding events that are needed to establish and maintain tree stands over long periods of time (Brady et al., 1985).

Riparian ecosystems, especially those with mature tree stands, often possess a disproportionately larger number of plant and animal species than do adjacent desert areas because of moderated climatic conditions, high plant productivity and structure, and abundant food and water (Jones and Glinski, 1985; Jones et al., 1985; Knopf and Samson, 1994). They also serve as important migration corridors for birds and other wildlife, especially across areas dominated by agriculture or vast deserts (Knopf and Samson, 1994). Riparian ecosystems also serve important ecological functions in arid watersheds, including dissipation of energy associated with flooding events, storage of nutrients and sediments, and filtering of other non-point source pollution that would otherwise end up in streams (Swanson et al., 1982; Lowrance et al., 1984; Rhodes et al., 1985). Mature trees in riparian zones intercept flood waters and trap sediment and debris, helping to reduce sediment in the water and to create debris piles which are important in maintaining wildlife species that are normally associated with more mesic habitats (Jones and Glinski, 1985; Jones, 1988). Vegetation cover along the edge of the riparian zone also helps reduce stream bank erosion (Likens and Bormann, 1974; Swanson et al., 1982; Lowrance et al., 1984; Rhodes et al., 1985).

In arid and semi-arid regions of the western United States, healthy riparian ecosystems are characterized by well-developed stands of cottonwood (*Populus*) and willow (*Salix*), as well as stands of seedlings located in beds along stream margins (Brady et al., 1985; Stromberg, 1998). Periodic flooding helps create and maintain stands in different age classes. High intensity floods often result in relocation of the stream bottom and the distribution of gravel and sand beds where tree seedlings germinate and develop into new stands (Brady et al., 1985; Stromberg, 1998; Levine and Stromberg, 2001). As a result of flooding and stream bank relocation, the distribution of tree patches in floodplains is quite dynamic and spatially heterogeneous, and healthy riparian ecosystems appear to maintain mature tree patches over long periods of time (Brady et al., 1985). Therefore, the condition of the riparian zone is intricately linked to hydrological function and condition.

Despite considerable concern over the condition of riparian ecosystems, we lack both monitoring data and methods for evaluating status and trends of these ecosystems over large geographic areas. Evaluating trends over large areas through a systematic monitoring approach is necessary to evaluate the relative conditions of riparian habitats and the effectiveness of riparian management and restoration programs.

In arid regions, the contrast in greenness between deciduous trees in the riparian zone and desert shrubs in adjacent areas permit a relatively accurate mapping and characterization of riparian ecosystems through the analysis and interpretation of remote sensing imagery, including imagery from the Landsat satellite (Hewitt, 1990; Lee and Marsh, 1995). This interpretation often involves classification of imagery into land cover classes (e.g., Vogelmann et al., 2001) which can be fairly time consuming and costly, especially if applied over extensive areas. Several indices of greenness, including the Normalized Difference Vegetation Index (NDVI), have been generated from satellite imagery and used to evaluate changes in vegetation composition and condition (Huete and Jackson, 1987; Kennedy, 1989; Chilar et al., 1991; Paruelo and Lauenroth, 1995; Shoshany et al., 1996; Grist et al., 1997), including riparian vegetation (Nagler et al., 2001). These indices require less processing and interpretation than generation of land cover and, therefore, may be especially valuable in monitoring the condition of riparian ecosystems over broad areas.

We developed and applied a remote sensing method to detect the amount and pattern of greenness change as it relates to riparian habitat condition, and tested the method by comparing changes in greenness inside an area protected from livestock grazing and mining (the San Pedro River Riparian National Conservation Area, hereafter referred to as the SPRNCA) to a relatively unprotected area north of the SPRNCA with multiple land uses (hereafter referred to as the NA). Since the San Pedro River is unimpounded, we anticipated that both areas would exhibit spatial patterns of gains and losses, due to lateral migration of the stream channel in response to large flooding events and subsequent losses and gains in cottonwood and willow trees. However, we hypothesized that the SPRNCA would exhibit a greater amount of positive greenness change between 1973 and 1992 than the NA, primarily because of protection from grazing, mining, and urbanization in the former area, and because the SPRNCA has greater ground and surface water availability.

2. Materials and methods

2.1. Description of the study area

The study location is the Upper San Pedro River Basin that originates in Sonora, Mexico and flows north into southeastern Arizona (Fig. 1). The Upper San Pedro Watershed represents a transition area between the Sonoran and Chihuahuan deserts and is internationally renowned for its biodiversity. It supports the second highest land mammal diversity in the world (Simpson, 1964) and provides habitat for

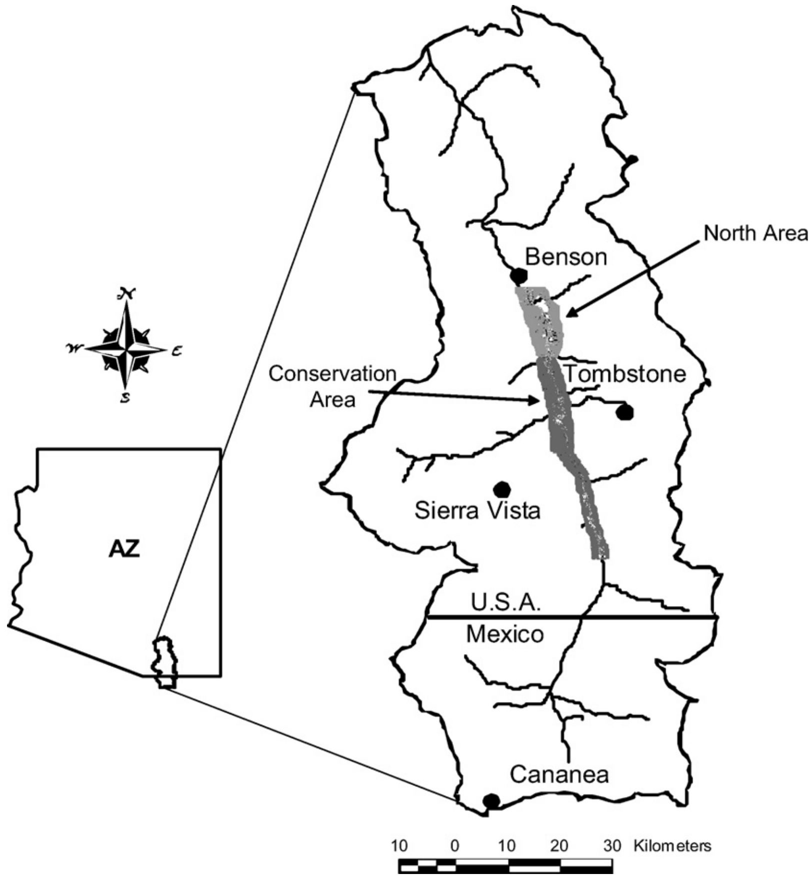

Fig. 1 – The Upper San Pedro River Basin and general location of the SPRNCA and NA.

almost 400 bird species (U.S. BLM, 1998). Topography, climate, and vegetation vary substantially across the watershed. Elevation ranges from 900 to 2900 m and annual rainfall ranges from 300 to 750 mm. Biome types include deserts, grasslands, oak woodland, mesquite woodland, riparian forest, coniferous forest, and agriculture. The upper watershed encompasses an area of approximately 7600 km^2 (5800 km^2 in Arizona and 1800 km^2 in Sonora, Mexico). The River has no water impoundment structures on it and therefore exhibits a cyclical flooding pattern that maintains the riparian corridor (Fig. 2). However, until the late 1970s, the River bottom and its riparian community were heavily grazed by cattle (U.S. BLM, 1998). Beginning in the late 1970s, the amount of livestock grazing in what is now the SPRNCA (Fig. 1) was substantially reduced. A relatively large area of the San Pedro River floodplain (23,000 ha) was acquired by the U.S. Department of the Interior and it was assigned special land status as a National Conservation Area by Congress in 1988. At this time, livestock grazing and mining were largely removed from the SPRNCA. Livestock grazing and mining have continued in riparian communities outside of the SPRNCA, including the NA.

2.2. *Evaluation of greenness change*

To evaluate changes in greenness, we obtained terrain-corrected, spatially co-registered, digital Landsat Multi-spectral Scanner (MSS) data from the North American Landscape Characterization (NALC) program (Lunetta et al., 1998), including images during the growing seasons of 1973, 1986, and 1992 (path 35, row 38). Pixel sizes of the NALC data were 60 m $\times$ 60 m. We used the ENVI image visualizing software to radiometrically correct the raw imagery to ‘‘at-satellite’’ reflectance values and normalized the three images to each other using dark and light targets. Greenness values were then calculated for each pixel element in each of the three images using the normalized difference vegetation index (NDVI, Eq. (1)):

$$\mathrm{NDVI} = \frac{\mathrm{IR(Band\,4)} - \mathrm{Red(Band\,2)}}{\mathrm{Red(Band\,2)} + \mathrm{IR(Band\,4)}} \quad (1)$$

We then subtracted the NDVI values for paired image dates to obtain decadal estimates of change between 1973 and 1986, between 1986 and 1992, and between 1973 and 1992. The analysis was performed within the riparian zone of the SPRNCA and in the NA (Fig. 1). In both areas, we limited the NDVI change analysis to the San Pedro River floodplain. We also masked out large agricultural areas (identified from classified land cover, Kepner et al., 2002) because we were interested in riparian vegetation change, and not changes associated with differences in crop rotation.

We generated means and standard deviations for NDVI change values on 9×9 pixel grid samples (total of 81 pixel each) for the NA (total 353 samples) and within the SPRNCA

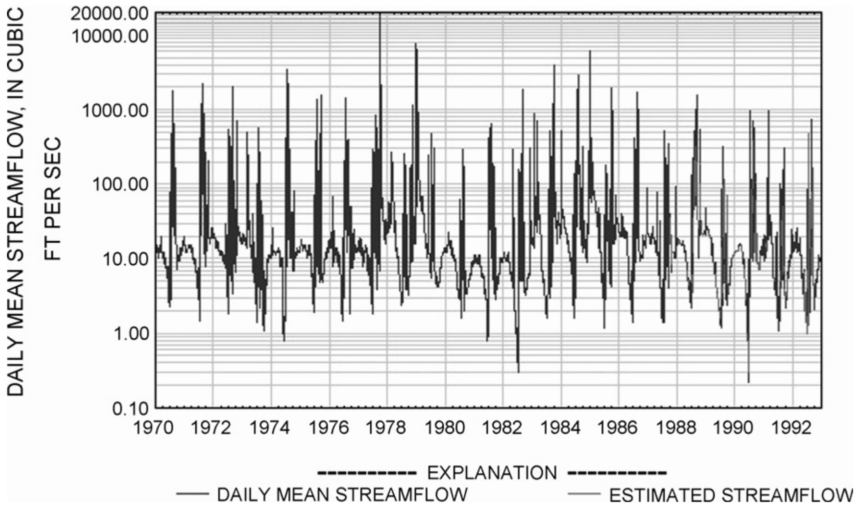

Fig. 2 – Hydrograph of the Charleston gauging station located on the Upper San Pedro River Basin (latitude 31°37′33″, longitude 110°10′26″ NAD27).

(total 663 samples). All of the samples resided within the floodplain of the San Pedro River. A nonparametric two-sided *t*-test, Wilcoxon rank sum (Wilcoxon, 1945) was used to evaluate significant differences between NDVI changes between 1973 and 1986, 1986 and1992, and 1973 and 1992. We also calculated average patch sizes and connectivity of 60 m × 60 m pixels with NDVI values greater than 0.20 for the NA and the SPRNCA using procedures described by Riitters et al. (1995). Based on comparison to aerial photography (see Section 2.4), NDVI values greater than 0.20 tended to indicate riparian vegetation, hence this analysis was an attempt to evaluate changes in the riparian habitat pattern among the years. NDVI values less than 0.20 tended to indicate desert shrub vegetation and/or bare ground. Finally, graphs representing NDVI change values for each 9 × 9 grid sample were created to provide a visual profile of change (from north to south) in both the SPRNCA and NA.

2.3. *Standard deviations of change*

Because NDVI change was normally distributed (Fig. 3), we were able to reclassify NDVI change values into standard deviations of change. We established four classes of NDVI change: (1) 2.0–4.0 standard deviations of positive change, (2) greater than 4.0 standard deviations of positive change, (3) 2.0 to 4.0 standard deviations of negative change, and (4) greater than 4.0 standard deviations of negative change. Pixel elements that had less than 2.0 standard deviations of positive or negative change were classified as no change because we were interested in relatively large magnitudes of change. Average patch size and connectivity were calculated for each of the standard deviation classes. The purpose of this classification was to determine whether there were differences in the spatial pattern of change between the two areas, and to identify and locate large changes in NDVI that could then be compared to changes observed from aerial photography.

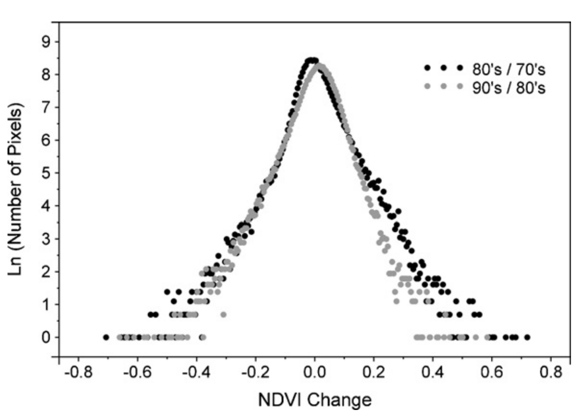

Fig. 3 – Histograms of NDVI change: (a) 1973–1986; (b) 1986–1992; (c) 1973–1992.

2.4. *Cross-sensor comparison of NDVI change*

Aerial photography has been used to map and monitor riparian ecosystem extent in the western US (Cuplin, 1985) and, therefore, provides a way to independently evaluate riparian extent and condition. A search was conducted for historical aerial photographs from commercial and government sources to determine the type and direction of change in NDVI. Candidate photographs were identified based on scale, spatial resolution and temporal correlation with the Landsat MSS imagery used for spectral analysis. Information on photos used in the analysis are found in Table 1.

One hundred and one point locations were randomly selected to compare NDVI and photo change interpretations.

Table 1 – Sources and attributes of aerial photography used to compare vegetation changes derived from photography vs. satellite imagery

Date	Approx scale	Type	Source
29 June 1971	1:70,000	B&W	US Air Force
22 April 1972	1:40,000	B&W	US Geological Survey
6 November 1992	1:40,000	B&W	US Geological Survey

Pixels were randomly selected within each of the four NDVI standard deviation categories, as well as for areas classified as having "no change," based on the Landsat MSS data. Coordinates of each pixel were plotted, in GIS format, and transferred onto 7.5 min USGS quadrangle maps. For each sample pixel the appropriate 1971/1972 and 1992 aerial photographs were retrieved and visually interpreted to determine vegetation change at that location.

3. Results

3.1. Changes in greenness

Overall, the SPRNCA exhibited a significantly greater increase in greenness between 1973 and 1986 and during the entire study period of 1973–1992 (Table 2, Fig. 4a and c). The NA had a slightly greater increase in greenness between 1986 and 1992 than did the SPRNCA, although the difference was not significant (Table 2, Fig. 4b). This difference resulted from a greater amount of negative change in the SPRNCA during this period than between 1973 and 1986, rather than larger gains in the NA as compared to 1973–1986 (Fig. 4b, Table 3). However, between 1986 and 1992, the SPRNCA had a greater net amount of large, positive greenness change (>2 standard deviations of change) than did the NA (Table 3), although these differences were relatively small (Table 3). The differences between greenness change between 1973 and 1986, and between 1986 and 1992, may reflect larger, more frequent peak flow events between the former rather than the later study periods (Fig. 2). The period from 1973 to 1986 had five events where daily stream flow exceeded 3000 cubic feet/s (cfs), and in 1977, one storm produced a flow of 23,700 cfs (USGS, 2006). Moreover, although variable, the period from 1973 to 1986 had a higher annual average stream flow than the period from 1986 to 1992 (53.5 cfs versus 24.5 cfs, respectively, USGS, 2006). The lack of large negative change between 1973 and 1986 in the SPRNCA might reflect the depressed nature of the riparian community up until this point (because of grazing) and increased protection afforded to cottonwood and willow seed islands after grazing started to decline in the late 1970s.

Table 2 – Two-sided Student's *t*-test (Wilcoxon rank sum) of differences in NDVI changes between the SPRNCA and NA for each of the three times periods

Mean difference (SPRNCA − NA)	Lower cl	Upper cl	DF	T	*p*-value
1973–1986					
0.032	0.032	0.036	1014	14.7	<0.0001
1986–1992					
−0.003	−0.007	0.001	1014	11.4	<0.0828
1973–1992					
0.029	0.024	0.033	1014	−1.7	<0.0001

Subsequent flooding events then resulted in losses of part of the riparian community due to stream relocation (Figs. 2 and 4a).

The SPRNCA had greater overall amounts of large net positive changes (>2S.D. of change) during all time periods (Table 3), but especially between 1973 and 1986, and from 1973 to 1992 (Table 3). Most of the positive change was observed for both the SPRNCA and the NA were in the 2–4 standard deviation class (Table 3).

3.2. Changes in greenness pattern

In 1973, the average patch size of pixels with NDVI values exceeding 0.20 was larger in the NA than in the SPRNCA (7.3 versus 21.3, respectively, Table 4). Similarly, the probability of having a same-type edge (pixels with NDVI values >0.20) was greater in the NA than in the SPRNCA (0.58 versus 0.43, Table 4). However, average patch size and same-type edge probability increased more dramatically during each period in the SPRNCA than in the NA (Table 4).

Relatively large positive gains in NDVI values (>2S.D. of change) in the SPRNCA tended to be in larger patches and were more connected than in the NA, except between 1986 and 1992 when the NA had greater connectivity and larger average patch size for the largest levels of change (>+4S.D., Fig. 5). Conversely, the NA had the largest patches and average patch size of negative change (<−4S.D.), and these levels of change also tended to be more connected than in the SPRNCA

Table 3 – NDVI changes in the SPRNCA and NA

Site	2–4S.D. gain	>4S.D. gain	2–4S.D. loss	>4S.D. loss	Total change	
					2–4S.D.	>4S.D.
1973–1986						
NA	5.1% (1363)	2.0% (543)	5.3% (1419)	2.9% (780)	−0.2	−0.9
SPRNCA	8.2% (3878)	2.2% (1055)	0.9% (432)	0.1% (67)	+7.3	+2.1
1986–1992						
NA	8.0% (2141)	1.3% (343)	2.5% (670)	0.6%(172)	+5.5	+0.7
SPRNCA	9.8% (4627)	0.9% (418)	1.2% (587)	0.3% (144)	+8.6	+0.6
1973–1992						
NA	6.6% (3452)	1.8% (965)	3.8% (1992)	2.4% (1247)	+2.8	−0.6
SPRNCA	14.6% (6962)	3.9% (1875)	0.5% (258)	0.1% (35)	+14.1	+3.8

NDVI changes are given in four categories based on standard deviations (S.D.): >4 standard deviations of increasing NDVI; 2–4 standard deviations of increasing NDVI; 2–4 standard deviations of decreasing NDVI; >4 standard deviations of decreasing NDVI. Total number of 60 m × 60 m pixels analyzed for change in the SPRNCA and the NA = 47, 649 and 26,830, respectively.

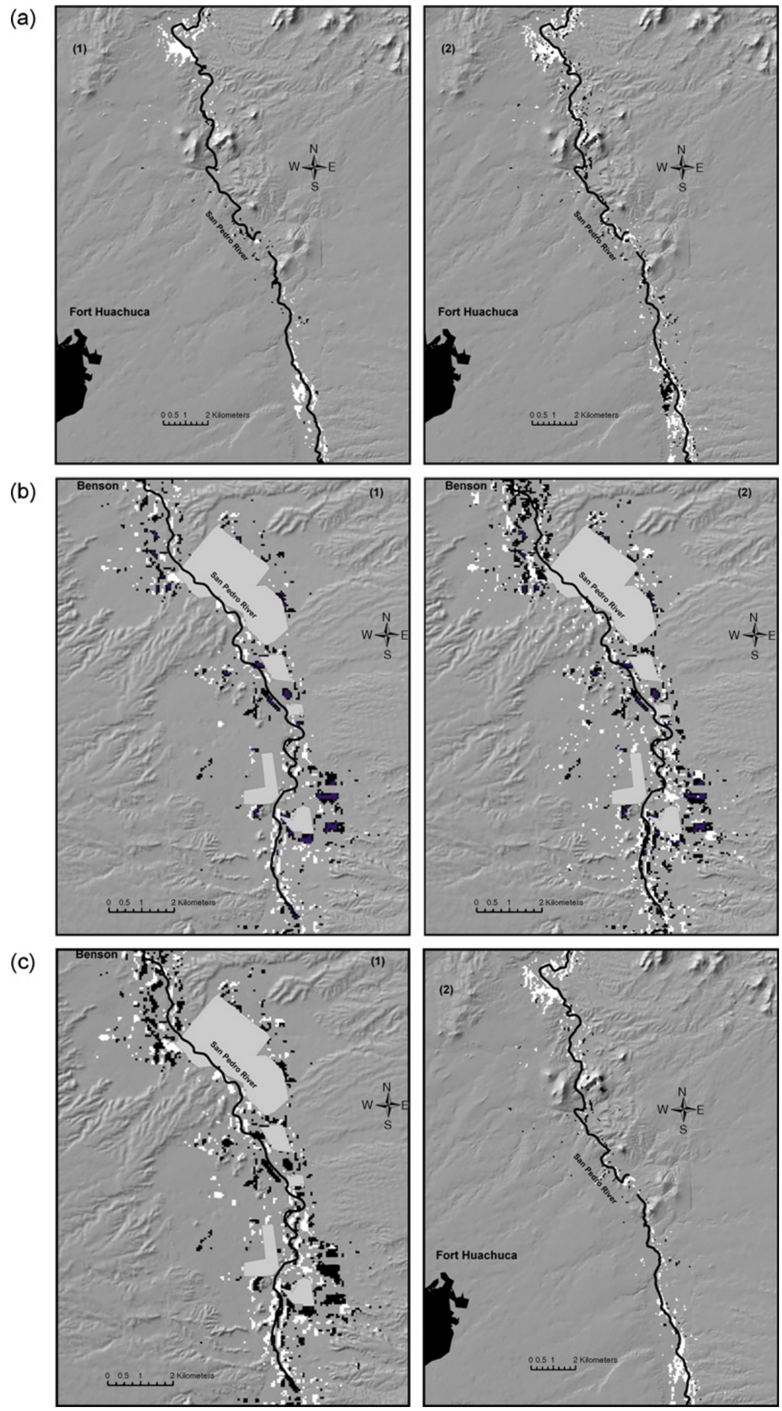

Fig. 4 – Spatial depiction of NDVI change: (a) SPRNCA from 1973 to 1986 (1) and 1986 to 1992 (2); (b) NA from 1973 to 1986 (1) and 1986 to 1992 (2); (c) the NA (1) and the SPRNCA (2) from 1973 to 1992. Areas in white represent ≥+2 standard deviations of change and areas in black represent areas of ≤−2 standard deviations of change. Blocked gray areas indicate cropland removed from the analysis.

(Table 5). However, there was little difference in the pattern of negative change between the two areas between 1986 and 1992 (Table 5).

There was considerable difference in the spatial pattern of change from north to south between the two areas (Fig. 5a–c). Between 1973 and 1986 the SPRNCA exhibited spatially clustered patterns of gain and loss of greenness, with a relatively large, clustered area of gain near its south end and a clustered area of greenness loss in its north end (Fig. 5a). Between 1986 and 1992, the north area of the SPRNCA that exhibited loss between 1973 and 1986, experienced a large gain in greenness (Fig. 5b). Overall, the SPRNCA exhibited large areas of positive greenness change, with the exception of the middle area, which exhibited mostly losses in greenness

Table 4 – Patch statistics for pixels with an NDVI value of greater than 0.20 for the SPRNCA and the NA for 1973, 1986, and 1992

Area	1973	1986	1992
Average patch size			
SPRNCA	7.3	21.7	35.8
NA	21.3	25.0	25.0
Same-type edge			
SPRNCA	0.43	0.56	0.68
NA	0.58	0.61	0.65

Average patch size is the number of 60 m × 60 m pixels and connectivity is the probability of being adjacent to another pixel where the NDVI is greater than 0.20.

(Fig. 5c). The NA exhibited a consistent pattern of greenness loss from north to south between 1973 and 1986 (Fig. 5a) and an opposite pattern of greenness gain between 1986 and 1992 (Fig. 5b), although similar to the previous period, there were a few areas with large amounts of greenness loss (Fig. 5a and b). Unlike the SPRNCA, the overall pattern of change in the NA was very heterogeneous (Fig. 5c).

3.3. *Cross-sensor comparison of NDVI change*

Relative to the direction of NDVI change (positive, negative, no change), there was a 93% agreement between aerial photography and Landsat MSS in identifying positive change, a 69% agreement in identifying negative change, and a 53% agreement in identifying no change (Table 6). Most of the disagreement in no change related to shrub communities (Table 6). In eight cases, the satellite estimates of NDVI change were negative whereas the aerial photography estimates were no change (Table 6). Regarding disagreement in negative change estimates, most of this related to greenness changes associated with transitions from agricultural crops to annual grasslands (Table 6). In these cases, the satellite estimates of greenness change were negative and the aerial photography positive (Table 6). Finally, there were three cases where aerial photography revealed positive greenness changes (scattered shrubs to dense shrubs) and the satellite-based NDVI estimates indicated negative changes (Table 6). However, in 18 out of the 21 cases of this type of transition, there was agreement between the two independent approaches (Table 6).

4. Discussion

4.1. *Evaluating changes in riparian vegetation conditions*

The satellite-based approach of evaluating patterns and extent of greenness change described in this paper appears to capture important aspects of changes in riparian ecosystem condition. Such an approach requires less time and effort than the more traditional land cover change approach. Estimates of the direction of greenness change derived from the reclassification of the Normalized Difference Vegetation Index (NDVI) into standard deviations of change compared favorably to vegetation transitions derived from aerial photography. Some of the disagreement between the estimates of the direction of greenness change may have resulted from soil moisture or sun-angle differences between measurement dates. For example, in eight cases the satellite estimates of NDVI change were negative whereas the aerial photography estimates were no change. The aerial photography classified these sites as desert shrubs in both dates. Soil moisture and sun-angle differences between dates has been shown to be problematic in evaluating NDVI in sparsely vegetated areas where NDVI values tend to be relatively low (Huete et al., 1985; Qi et al., 1993). Although we attempted to mask out cropland, some smaller cropland patches may have persisted in the images, and therefore, differences among years in crop rotation may also have led to disagreement between the two approaches. For example, in a few cases aerial photography showed a negative greenness transition from crops to annual grasslands, whereas satellite-derived NDVI showed an increase in greenness. In these particular cases the satellite may have passed over the crop fields when they were fallow (1973), and when annual grasses had become established (1992), hence a positive change in greenness. Despite these differences, most of the transitions from and to the riparian vegetation type

Table 5 – Same-type edge and average patch size statistics for different classes of NDVI standard deviation (S.D.) changes in the SPRNCA vs. the NA

	1973–1986		1986–1992		1973–1992	
	SPRNCA	NA	SPRNCA	NA	SPRNCA	NA
Same-type edge						
−2S.D.	0.16	0.20	0.17	0.20	0.11	0.18
−4S.D.	0.11	0.35	0.21	0.19	0.27	0.37
+2S.D.	0.27	0.17	0.23	0.21	0.31	0.23
+4S.D.	0.30	0.19	0.17	0.29	0.31	0.27
Average patch size						
−2S.D.	2.0 (11)	2.4 (22)	2.1 (26)	2.5 (35)	2.0 (9)	2.5 (22)
−4S.D.	1.6 (19)	4.1 (116)	2.3 (26)	2.2 (19)	1.6 (22)	4.1 (55)
+2S.D.	3.7 (106)	2.1 (31)	2.8 (84)	2.6 (45)	3.6 (323)	2.1 (60)
+4S.D.	3.7 (122)	2.2 (32)	2.0 (18)	3.1 (86)	3.7 (108)	2.2 (29)

Same-type edge is the probability of finding a same-type S.D. class edge. Average patch size = the mean number of pixels per patch. Number in parentheses = the size of the largest patch (number of 60 m × 60 m pixels).

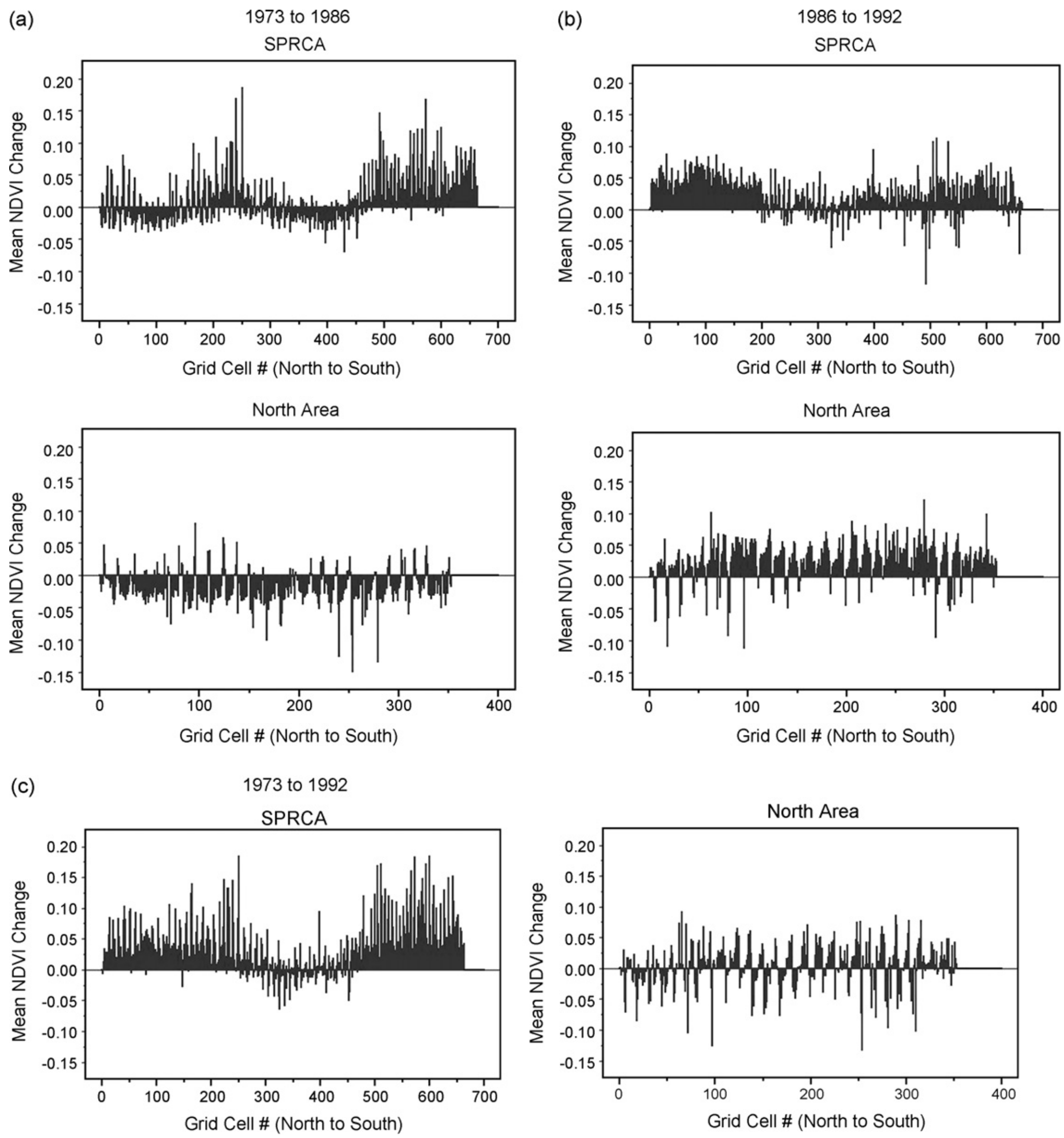

Fig. 5 – Graphic depiction of north-to-south NDVI change profiles between (a) 1973 and 1986, (b) 1986 and 1992, and (c) 1973 and 1992. Values are mean NDVI change for 9 × 9 pixel grid cells.

(identified by the aerial photography) were captured by the NDVI estimates. Moreover, in a few cases (transition from shrubs to riparian vegetation), the satellite-derived, NDVI change estimates were able to identify areas where individual cottonwood trees became established. This suggests that it is possible to identify small areas of change in greenness (e.g., individual trees) where a high degree of contrast in greenness exists (e.g., between desert plants and broad-leaf, deciduous vegetation), even with a nominal pixel resolution of 60 m × 60 m. Similar results have been obtained using multi-temporal Landsat imagery in agricultural communities (Uchida, 2001).

Results from this study are concordant with results of other studies in the Upper San Pedro River Basin. Kepner et al. (2002) reported a 2.2% increase in riparian land cover in the Basin between 1973 and 1986, and a 0.4% increase from 1986 to 1992 based on the same data used in our study. However, estimates from Kepner et al. (2002) are from classified land cover data. Krueper et al. (2003) reported an increase in herbaceous vegetation and overall bird species abundance in the SPRNCA between 1986 and 1990. They found no statistically significant changes within habitats adjacent to the SPRNCA. They attributed increases in bird abundance during this period to increases in herbaceous vegetation in the riparian zone and suggested that the removal of livestock may have been an important factor in the observed changes. Some of the positive gain in NDVI observed in this study may also have resulted from increases in herbaceous cover.

Stromberg (1998) reported on the relationships between flooding frequency, timing, and magnitude, and establishment and survivorship of cottonwoods in the area north of the SPRNCA (middle basin), as well as within the SPRNCA (upper basin). She found annual flooding events to be critical in establishing cottonwood trees, but especially large flooding

Table 6 – Comparison of NDVI change estimated from Landsat MSS data from 1973 and 1992 and descriptions of landscape change estimated from a randomly sampled set of high-resolution aerial photography (total 101 samples)

Transition estimated from aerial photography	Type of greenness change	Estimates of NDVI (by # of S.D.)				
		+2S.D.	+4S.D.	−2S.D.	−4S.D.	No Change
Grassland to grassland	No change	1	0	1	0	3
Shrubs to shrubs	No change	2	1	8	0	11
Sandy wash to sandy wash	No change	0	0	0	0	4
Agriculture to agriculture	No change	0	0	1	0	0
Riparian forest to riparian forest	No change	0	1	1	1	2
River bed to riparian forest	Positive	0	3	0	0	0
Barren to riparian forest	Positive	1	1	0	0	0
Shrubs to riparian forest	Positive	2	4	0	0	0
Scattered riparian forest to dense riparian forest	Positive	2	0	0	0	0
Grass to grass/riparian forest	Positive	1	0	0	0	0
Shrubs to grassland	Positive	4	0	0	0	0
Shrubs to shrubs with grass	Positive	3	2	0	0	0
Scattered shrubs to dense shrubs	Positive	15	3	0	3	0
Sandy wash to shrubs in wash	Positive	1	0	0	0	0
Sandy wash to mesquite shrubs	Positive	2	2	0	0	0
Sandy wash to grassland	Positive	1	0	0	0	0
Planted crops to grassland	Positive	1	0	0	0	0
Agriculture (cleared) to mesquite	Positive	1	0	0	0	0
Grass/ditch to grassland	Positive	0	1	0	0	0
Agriculture to mature crops	Positive	0	1	0	0	0
Shrubs to shrubs and farm pond	Negative	0	0	2	0	0
Small farm to large farm	Negative	0	0	2	0	0
Shrubs to barren agriculture	Negative	0	0	2	0	0
Shrubs to shrubs with ditch	Negative	0	0	1	1	0
Agriculture crops to grassland	Negative	4	1	3	0	0
Shrubs to sandy wash	Negative	0	0	1	0	0

Type of greenness change indicates the direction of change based on the transition derived from the aerial photography. Estimates of NDVI change are the number of pixels in each standard deviation (S.D.) class derived from the satellite imagery that overlaps spatially with the aerial photography samples. The percent collaboration is the number of sites where the estimated direction of change was the same for the two methods. Collaboration of change estimates: positive change estimates (46/49) = 93%; negative change estimates (11/16) = 69%; no change estimates (19/36) = 53%.

events that occurred between October and March. In late 1977, a large flood (23,700 cfs) occurred within the SPRNCA (USGS, 2006) and this may have led to the large number of new riparian patches that showed up by the mid-1980s. Additionally, a relatively large flood in late 1984 (13,000 cfs, USGS, 2006) may have lead to additional cottonwood establishment seen in the NDVI change estimates between 1973 and 1986, and 1986 and 1992.

Stromberg et al. (2006) found a strong relationship between the type of riparian vegetation community and surface and ground water availability within the SPRNCA. Northern areas of the SPRNCA had longer stretches of intermittent flow whereas the middle and southern portions of the river tended to have longer stretches of permanent flow. The floodplain in the northern part of the SPRNCA tended to be broader than middle and southern portions of the river. Ground water at or near the surface in the middle and southern portions of the SPRNCA accounted for greater abundance of water-loving, herbaceous vegetation, and cottonwoods (*Populus*) and willows (*Salix*). Mesquite (*Prosopis*) and salt-cedar (*Tamarix*) tended to be more common in the northern part of the SPRNCA where surface and ground water were more limited (Stromberg et al., 2006). However, our data show that nearly all of the SPRNCA, including northern areas, experienced considerable greenness gain over the course of the study period.

4.2. *Profiles of NDVI change and the influence of land use on the pattern and scale of change*

The NDVI change profiles illustrated in this paper may provide a way to assess the degree of land use impact for an entire riparian zone of a river system. The NA showed a profile of NDVI change representative of a free-flowing river (e.g., positive and negative changes in space and time), but the relatively fine-scale nature of change from north to south may reflect a greater influence of local, unrestricted land uses. Livestock grazing has occurred for many decades throughout the NA whereas livestock grazing diminished substantially in the SPRNCA in the late 1970s and was eliminated by the late 1980s (U.S. BLM, 1998; Krueper et al., 2003). Livestock tend to congregate near water and the result is usually reduced vegetation vigor in and around these areas (Pickup et al., 1993). Stromberg (1998) and Krueper et al. (2003) have suggested that the removal of livestock has played a big role in the improvement of the SPRNCA. The larger patches of negative change observed in the NA may reflect urbanization processes associated with the expansion of Benson, Arizona. Additionally, negative greenness losses in the NA may reflect a reduction in agricultural irrigation associated with establishment of Arizona's Groundwater Management Act of 1980. Negative changes in the NA may also reflect an increasing trend of intermittency of surface flow in the NA (Leenhouts et al., 2006), and the broader, more gradual sloping floodplain which increases the feasibility of development. Conversely, the larger, more continuous patches of change in the SPRNCA may reflect responses to flooding events without the influences of more localized land use pressures seen in the NA. However, increased urbanization in the region (rapid expansion of Sierra Vista and Fort Huachuca, Arizona) has resulted in increased use of ground water and this may dramatically affect the condition of the SPRNCA riparian zone in the near future (Stromberg et al., 1996).

4.3. *Using NDVI patch changes to assess hydrologic condition*

Changes in greenness patch distributions and patterns in the floodplains of rivers may provide a relatively easy way to assess hydrologic condition within arid and semi-arid regions of the world. Free-flowing rivers within arid and semi-arid regions migrate horizontally as a result of large flooding events and the result is a shifting pattern of vegetation in response to shifts in soil, gravel bars (for deciduous tree establishment), nutrients, and water availability (Brady et al., 1985; Stromberg, 1998). The Upper San Pedro River exhibits this pattern of vegetation change as indicated by the NDVI patch analysis highlighted in this paper. Conversely, impounded rivers experience less severe and frequent flooding and, as a result, the stream or river course remains relatively stationary over time. Since horizontal movement of the stream bottom is necessary to create changing substrates for deciduous tree establishment (Levine and Stromberg, 2001), impounded rivers lose their deciduous tree component over time (Brady et al., 1985). Therefore, the magnitude and pattern of NDVI changes in the riparian zone could be used to evaluate the hydrologic condition of arid and semi-arid river systems. Moreover, this method could be used to evaluate how far one would have to travel below a dam before lateral in-flow resulted in nominal hydrologic conditions (horizontal NDVI patch movement). Such an approach would extend estimates of hydrologic condition beyond the sparsely distributed network of gauging stations. In many areas of the US and in other areas of the world, archival Landsat imagery are available to perform these kinds of analyzes. However, there are differences in bandwidths among Landsat sensors that are used to calculate NDVI (http://edc.usgs.gov/products/satellite/band.html). The primary differences exist between the Landsat Multi-spectral Scanner (MSS) and the Landsat Thematic Mapper. Although these differences appear to be relatively small, studies are needed to determine how such differences might affect NDVI comparability across dates.

5. Conclusions

In conclusion, the methods described in this paper provide a way to evaluate changes in vegetation conditions of riparian habitats, and potentially, the influence and scale of land use that structure the responses of the riparian community to periodic flooding. The NDVI change approach is less time consuming than the more traditional land cover change classification method and therefore can be applied over larger areas at a reduced cost. Moreover, the approach offers the potential to evaluate hydrologic conditions in both impounded and free-flowing river systems within arid and semi-arid regions of the world. However, in order to understand potential changes in riparian plant species, it will be important to characterize stream and river channel morphology and width, as well potential linkages between surface and ground water, since these factors are known to affect potential plant community responses (Stromberg et al., 2006). Additionally, it may be advantageous to narrow the buffer zone around the stream channel in order to more accurately capture vegetation response to flooding. Finally, further studies are needed to evaluate the effectiveness of the NDVI change approach on river systems with altered hydrologic flow and different intensities of land use.

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