International Journal of Geographical Information Science
Vol. 25, No. 6, June 2011, 913–930

Taylor & Francis
Taylor & Francis Group

Temporal dynamics of shrub proliferation: linking patches to landscapes

Dawn M. Browning[a]*, Andrea S. Laliberte[b] and Albert Rango[a]

[a]*US Department of Agriculture, Agricultural Research Service, Jornada Experimental Range, Las Cruces, NM, USA;* [b]*Jornada Experimental Range, New Mexico State University, Las Cruces, NM, USA*

(*Received 12 August 2009; final version received 28 May 2010*)

Downloaded by [New Mexico State University] at 11:09 15 August 2011

Shifts in vegetation composition and cover are the result of processes acting at different levels such as landscapes, hill slopes, or plant interspaces. Analytical approaches designed for discrete objects which are based upon the inherently hierarchical nature of complex systems are well suited to research applications conducted across spatial scales. We quantified spatial and temporal vegetation dynamics over 71 years at three spatial scales, landscape, plot, and patch, in a Chihuahuan Desert ecosystem in southern New Mexico, USA, using object-based analysis. We analyzed time series aerial photography from 1937 to 2008 to include automated image analysis at the landscape scale and manual delineation of shrub image objects at the patch scale. We sought to identify patch mechanisms associated with changes in shrub patch density and percent cover by characterizing structural changes in individual shrub patches from one image to the next in the time series. The classification scheme captured colonization by new shrub patches, growth or decline in patch area, and patch stability (i.e., change in size of less than 15%). Patch growth was categorized as growth by coalescence with neighboring patches or canopy expansion. Similarly, patch decline was distinguished as either loss of patch area due to canopy dieback or fragmentation of conglomerate patches. Interpretations of change in patch density based solely on shrub colonization and mortality can be too simplistic. Increases in patch density can result from an influx of new patches or fragmentation of patches into its constituent patches; conversely, decreases in density may be due to mortality of patches or coalescence of existing patches. We demonstrate that patches grew in size at the beginning of the study in conjunction with increases in shrub cover (0.5% in 1937 to 11% in 1960) and patch density increased during the initial encroachment phase of shrub proliferation (4 patches ha^{-1} in 1937 to 80 patches ha^{-1} in 1960). Shrub cover remained stable at 7% from 1967 to 1989 and over this period, patch dynamics were broadly characterized by growth and persistence of patch area with roughly equal proportions of mortality and colonization. Shrub cover increased linearly from 8% in 1989 to 14% in 2008, approaching a projected maximum shrub cover of 18% based on mean annual precipitation (MAP) of 230 mm. Patch fate over this period constituted growth and persistence of shrub patch area whereas appearance of new patches remained relatively stable. Shrub patch dynamics were non-linear and variable over time. We documented the transition from grass- to shrub-dominated states with patch dynamics signifying a shifting mosaic in which shrub patch establishment, growth, and mortality wax and wane. Monitoring patch dynamics will become increasingly important in actively managed ecosystems as an important indicator of impending shifts in ecosystem structure and function.

Keywords: cross-scale analysis; shrub encroachment; object-oriented classification; Jornada Experimental Range; patch dynamics

*Corresponding author. Email: dbrownin@nmsu.edu

ISSN 1365-8816 print/ISSN 1362-3087 online
© 2011 Taylor & Francis
DOI: 10.1080/13658816.2010.498789
http://www.informaworld.com

Downloaded by [New Mexico State University] at 11:09 15 August 2011

1. Introduction

Change in vegetation composition, cover, and pattern can occur abruptly and in a nonlinear fashion (Peters *et al.* 2004). Processes driving such changes, for example, dispersal, disturbance, erosion, act at discrete spatial scales which are hierarchically structured (Allen and Starr 1982, O'Neill *et al.* 1989). Interactions between processes occurring at different spatial or temporal scales constitute a challenge for identifying the underlying causes of dramatic as well as subtle shifts in vegetation and ultimately for formulating strategies for ecosystem recovery and sustainability (Peters and Havstad 2006). To understand the relative importance of prospective drivers of land cover change, it is necessary to observe patterns at multiple scales. To achieve this, object-oriented approaches are superbly relevant from analytical and ecological perspectives due to the inherently hierarchical nature of complex systems and emphasis on discrete features of interest, i.e., objects (Burnett and Blaschke 2003). However, the integration of information from different organizational levels is not particularly straightforward.

Landscape-level changes in cover reflect the net outcome of recruitment, mortality, canopy growth, and decline. Knowledge of the demographic contributions to patterns in shrub cover and density (e.g., establishment of new patches, dieback of existing patches) offers insight into land management efforts such as shrub eradication and native grass establishment. Spatially explicit time series with ecologically meaningful assessments of change is necessary for broad-scale mapping and monitoring efforts and can assist with devising effective and sustainable land management practices when based on an understanding of patch- and population-level responses to prescribed treatments.

Shrub encroachment is a global phenomenon in savanna and grassland ecosystems (hereafter, 'rangelands') with implications for nitrogen cycling, soil stability, and sustainability of land use practices pertaining to 40% of the global land surface (Asner *et al.* 2003, Throop and Archer 2008). While increases in the abundance of woody plants in rangelands have been widely reported (Archer 1994, Van Auken 2000), quantitative insights relating changes in population structure, biomass, and spatial dynamics of shrub proliferation are few (e.g., Goslee *et al.* 2003, Browning *et al.* 2008). Dramatic vegetation transitions render forecasting vegetation dynamics relative to land management a challenging endeavor. As perspectives on the spatial arrangement of shrubs and population structure may foreshadow imminent shifts in vegetation in arid ecosystems (Rietkerk *et al.* 2004, Kefi *et al.* 2007), effort should be placed on bridging landscape depictions of vegetation cover with patch dynamics that manifest at the population level.

Object-oriented approaches to classifying remotely sensed imagery are well suited for cross-scale research efforts targeting population-level processes and their aggregate effects on landscape-level depictions of land cover change. Image objects, homogeneous aggregations of digital values, correspond to ecologically defensible units which, in this case, are shrub canopies. Object-based image analysis combines automated machine processing with expert knowledge to segment digital values into discrete objects and subsequently defines spatial, spectral, and contextual properties to classify objects in a hierarchical framework (Benz *et al.* 2004, Laliberte *et al.* 2004). Selected advantages of object-based image analysis of high-resolution aerial photography over pixel-based classification include a reduction in within-class variability due to the aggregation (i.e., segmentation) of image pixels into homogenous objects and the ability to incorporate expert knowledge into classification schemes (Platt and Rapoza 2008). In addition, object-based analysis reduces discrepancies that arise from differences in photo scale, quality, illumination, and contrast of aerial photos in a time series due to the ability to incorporate shape and contextual properties to define

Downloaded by [New Mexico State University] at 11:09 15 August 2011

image classes (e.g., shadow). Manual approaches to image object delineation (e.g., hand-digitizing or image interpretation) encompass a number of the same advantages over pixel-based image analysis but are not generally amenable to mapping across broad spatial extents due to logistical constraints on time and technical expertise.

Object-based analysis of time series aerial photography in a geospatial framework provides opportunities to monitor land cover change over expansive landscape areas, enhance our understanding of the relative importance of the drivers, and improve predictive capabilities under alternative land use and climate change scenarios. The objectives of this study were to (1) quantify changes in shrub cover and patch density derived from object-based classifications of time series aerial photography; (2) construct a spatially explicit database to denote the fate of individual shrub patches with 11 digitized aerial photographs from 1937 to 2008; (3) explore the utility of fate-based metrics for shrub objects to augment interpretation of landscape perspectives of change in shrub cover; and (4) evaluate patterns in shrub patch growth and mortality in the context of seasonal precipitation.

2. Methods

2.1. Study site

The study was conducted on the Chihuahuan Desert Rangeland Research Center (CDRRC), a component of the Jornada Basin Long-Term Ecological Research site (JRN) near Las Cruces, New Mexico, at the northern extent of the Chihuahuan Desert (Figure 1). The JRN spans an area representing a mosaic of sandy (ref. # R042XB012NM), shallow sandy (ref. # R042XB015NM), and deep sandy (ref. # R042XB011NM) NRCS ecological sites within the southern desertic basins, plains, and mountains major land resource area. The 150 ha landscape examined in this study occurred exclusively on the sandy NRCS ecological site.

We built upon a study conducted by Laliberte *et al.* (2004) across a 150-ha landscape at 1324 m elevation (NAD83 13 N, 0323482E, 3601557N). The area was historically dominated by grasses but has transitioned to a shrub-dominated ecosystem (Buffington and Herbel 1965, Gibbens *et al.* 2005). A 2004 field survey of all shrubs within 20 – 20 × 20 m plots across the 150-ha study site revealed that honey mesquite (*Prosopis glandulosa* Torr.) constituted 89.3% of all shrubs with Mormon tea (*Ephedra torreyana*) and soap-tree yucca (*Yucca elata*) representing 7.0 and 2.6%, respectively. Grass cover, constituting black grama (*Bouteloua eriopoda*), tobosa (*Pleuraphis mutica*), dropseed species (*Sporobolus* spp.), and bush muhly (*Muhlenbergia porteri*), declined precipitously from approximately 18% in 1937 to 4% by 1960 (Laliberte *et al.* 2004). In this study, research emphasis was placed on shrub cover, dominated by honey mesquite. Long-term local average annual rainfall (coefficient of variation) was 231 (2.48) mm with 120 (1.94) mm occurring from July to September and 111 (1.84) mm occurring in the remaining months. Monthly records were compiled from 1930 to 2009 for Selden rain gauge that is 2.3 km from the study site. Mean maximum monthly temperatures range from 13.5°C in January to 35.0°C in July (Wainwright 2006).

2.2. Cross-scale approach

We employed object-based methods to generate both landscape and patch perspectives on shrub cover dynamics. Landscape analyses were conducted with an automated approach through object-based image analysis of co-registered time series aerial photography. Binary images of shrub cover were the basis for landscape metrics describing cover and shrub patch

Downloaded by [New Mexico State University] at 11:09 15 August 2011

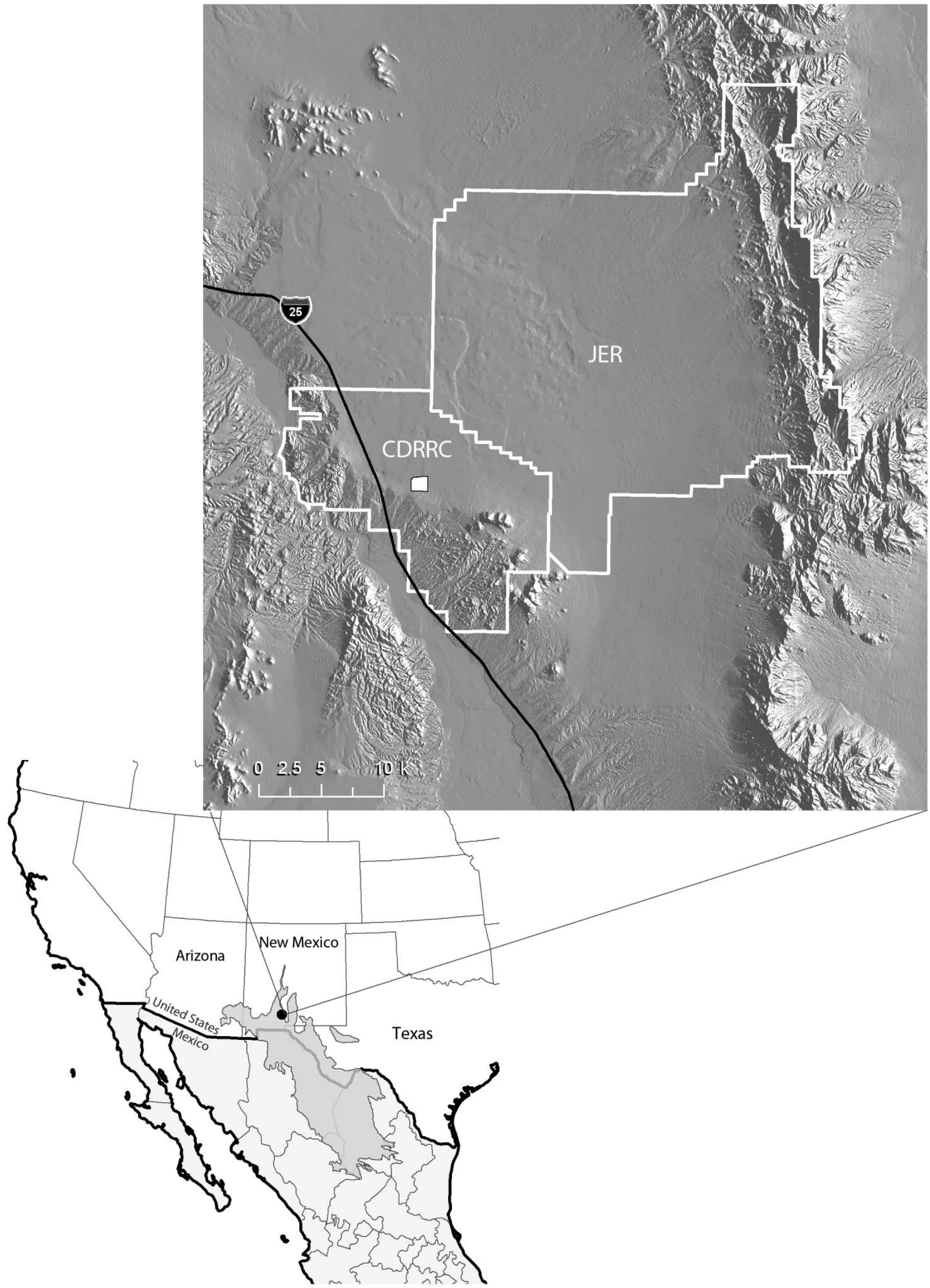

Figure 1. Location of the Jornada Basin LTER (JRN) in southern New Mexico at the northern extent of the Chihuahuan Desert (depicted in gray). The 1.5 km^2 study site (white on inset map) occurs on the Chihuahuan Desert Rangeland Research Center (CDRRC), which together with the Jornada Experimental Range (JER) constitutes the JRN. Topographic complexity of the JRN is illustrated with a shaded relief map from a 10 m digital elevation model.

density. Patch scale analyses were conducted by manually digitizing shrub patches on the 11 co-registered images to build an object-specific database representing dynamics across the study site from 1937 to 2008 (Table 1).

2.2.1. Landscape analysis

We expanded the long-term study of shrub cover dynamics over the 1.5 km^2 landscape on the CDRRC by mapping shrub cover in two recent images using color-infrared aerial photographs acquired on 4 November 2004 and 22 October 2008 by the Agriculture Research Service and National Aeronautics and Space Administration, respectively (scale parameters for photographic time series found in Table 1). Digital images were geometrically corrected to a 2005 digital ortho-quarter quadrangle to achieve RMS errors <0.2 m. Geocoded images were resampled to 0.86 m spatial resolution and subjected to object-based image analysis that entailed multiscale image segmentation and hierarchical object-based classification. Shrub cover classifications of the 2004 and 2008 images were classified in the same manner as the earlier scenes in the time series (Laliberte *et al.* 2004), described as follows. The images were segmented at a fine and coarse scale (scale parameters 3 and 250), and the shrub classification was performed at the fine scale using a rule-based approach with three features: mean brightness, mean difference to neighbor, and mean

Downloaded by [New Mexico State University] at 11:09 15 August 2011

Table 1. Attributes of aerial photography series used in this analysis of shrub cover change and shrub patch dynamics. Film type corresponds to panchromatic (B/W), natural color (Color), or color-infrared (CIR) film. Metadata denoting photo scale was not readily available for all images; we calculated photo scale for each series by relating photo features to published geocoded maps. Classification accuracy for binary images includes the overall percentage and kappa statistic for the shrub class. *K*hat ranges from −1 to 1 with 1 signifying complete agreement for classified and reference values.

Acquisition date	Photo scale	Film type	Source	Classification accuracy (% overall)	*K*hat (shrub class)
18 March 1937	1:31,200	B/W	Soil Conservation Service (SCS)	93.5	0.792
4 October 1947	1:9000	B/W	Agriculture and Stabilization and Conservation Service (ASCS)	91.6	0.713
8 June 1955	1:11,700	B/W	ASCS	84.4	0.517
13 November 1960	1:22,000	B/W	ASCS	94.9	0.876
28 March 1967	1:20,800	B/W	ASCS	93.2	0.771
14 September 1977	1:15,000	CIR	Agricultural Research Service (ARS)	91.9	0.840
10 September 1980	1:40,000	Color	Bureau of Land Management (BLM)	92.9	0.873
15 September 1989	1:23,700	Color	BLM	90.3	0.760
8 October 1996	1:38,800	CIR	National Aerial Photography Program	92.6	0.900
4 November 2004	1:10,500	CIR	ARS	98.0	0.940
22 October 2008	1:17,600	CIR	National Aeronautics and Space Administration	89.9	0.965

difference to super-object. Relating the two segmentation levels in this fashion allowed for simultaneous extraction of shrubs in both light and dark backgrounds.

To evaluate performance of the shrub cover classifications and inform interpretation of landscape depictions of changes in shrub density and cover, we conducted an image-based accuracy assessment for the 11 binary maps. One hundred and fifty points stratified by image class (i.e., shrub, nonshrub) were randomly generated and examined on the digitized imagery and then assigned to the appropriate reference class. Cohen's kappa coefficient (*K* hat; Cohen 1960) was calculated to represent agreement between the reference data and the classified result; *K* hat ranges from −1 to 1 with 0 indicating no better agreement of reference data with the classified result than expected with a random classified map. For each classified image, we report accuracy as the overall classification accuracy and the *K* hat value for the shrub image class.

To represent a measure of heterogeneity in shrub cover across the 150 ha study area and ascertain how the variability of shrub cover estimates changed over time, cover from binary classified images was summarized within 20 × 20 m quadrats. This was achieved by intersecting a 20 × 20 m polygon feature class encompassing the study site with co-registered binary images to derive percent shrub cover by quadrat over time. This window size was selected by calculating the variance of estimated shrub cover (%) across window sizes from 2 to 70 m and identifying the window size at which variance stabilized (Greig-Smith 1983). Variance associated with mean cover did not decrease appreciably beyond window size 20 m. Patch density was calculated from entire binary classified images as the number of patches divided by the study area size.

2.2.2. *Plot-based analysis of shrub patch dynamics*

To enhance interpretation of commonly used metrics to characterize changes in shrub abundance and patch density, we devised a two-phase protocol using manual interpretation to monitor the fate of individual shrub patches through time. First, all shrub patches were uniquely identified and manually delineated on co-registered aerial imagery using a plot-based sampling scheme; and second, patches were assigned to predefined categories representing different fates based on changes in patch shape, size, and configuration. For this analysis, we define a patch as a discrete shrub canopy image object comprising one or more individual mesquite shrubs with overlapping canopies. Within 63 randomly selected 20 × 20 m plots, all shrub patches intersecting plot boundaries were hand-digitized and monitored through time (hereafter, 'focal patches'). Manual digitizing of shrub patches circumvented misidentification of individuals due to co-registration errors and discrepancies that could arise from differences in classification accuracy. The plot-based sampling scheme enabled us to capture the appearance of new patches in the time series as well as note the spatial rearrangement of patches such as those which occur when focal patches (within the plot) coalesce with neighboring shrubs outside the plot.

A number of factors can influence the detectability of plant canopies (e.g., image quality, photo scale, time of day, and season of image acquisition) (see Figure 2). For consistency in denoting new patches, we digitized small patches (<4 m^2 in area) as points and larger patches as polygons (Figure 3a; Archer *et al.* 1988). To standardize the detectability and delineation of shrub patches, the 11 geocoded images were aggregated to a common spatial resolution of 1 m using a nearest-neighbor resampling method. Digitizing methods were designed to minimize observer error following Browning *et al.* (2009). Identification of shrub patches to be digitized was conducted at a fixed magnification level (1 : 800) and on-screen digitizing of shrub polygons was conducted in stream mode which placed vertices at

Downloaded by [New Mexico State University] at 11:09 15 August 2011

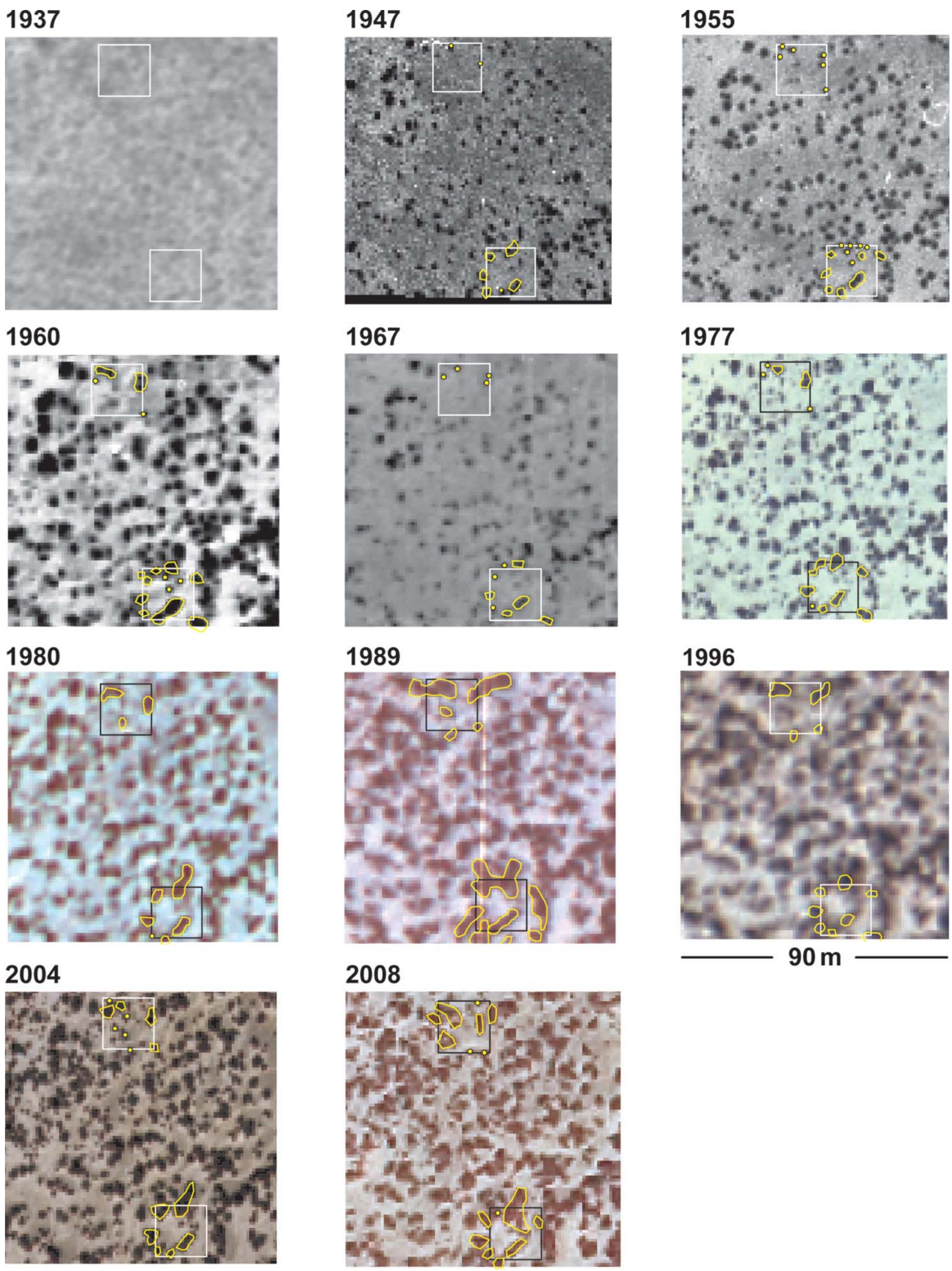

Figure 2. Sample images representing a 90 × 90 m area from each of 11 digitized aerial photographs used in this analysis. Two sample plots (20 × 20 m) are depicted in white (or black) outlines. Shrub patches identified for analysis by manually digitizing imagery exist as either points or polygons (in yellow).

2 m intervals along the object perimeter. Once all shrub patches were depicted (as either points or polygons), a unique identifier was assigned to represent individuals and permit categorization of fate between one image and the next.

Downloaded by [New Mexico State University] at 11:09 15 August 2011

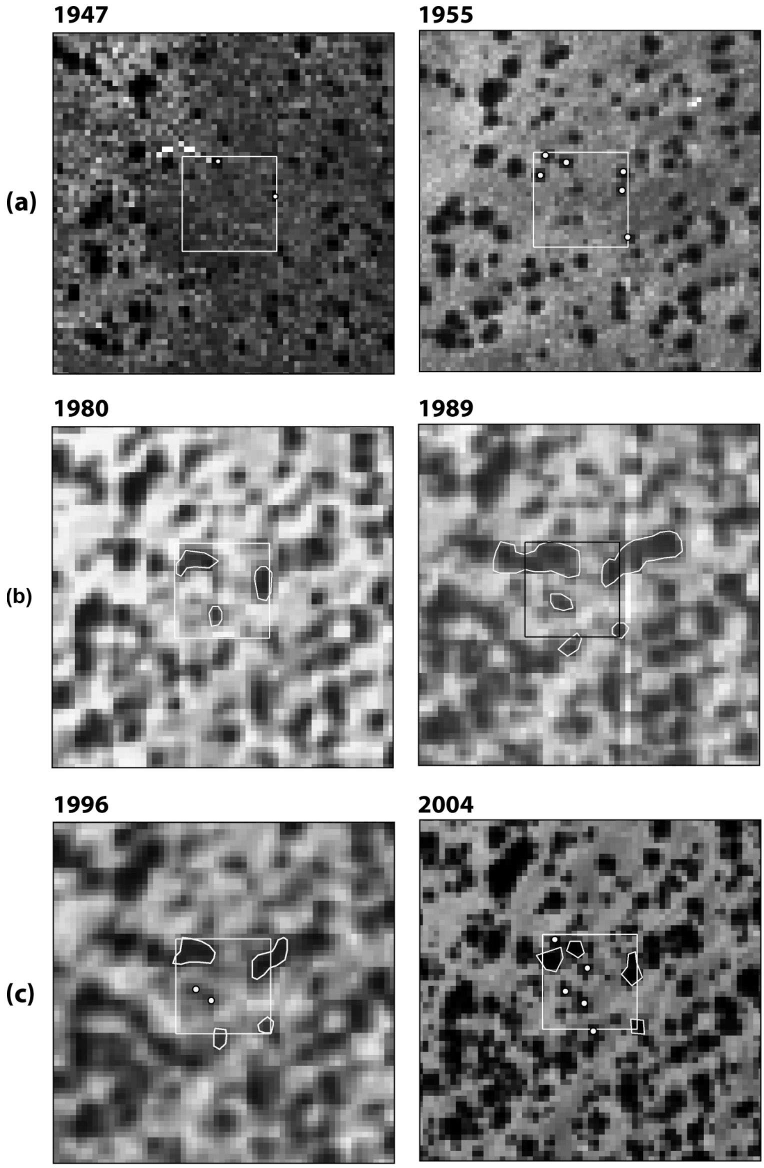

Figure 3. Six sample images covering a 62 × 62 m area for 6 of 11 images (see Figure 2) used in the analysis of patch dynamics. Panels denote the appearance of new shrub patches (a) and illustrate changes in patch structure that include coalescence (b) and fragmentation (c) from one image to the next. Color images in panels (b) and (c) were converted to gray scale. See Table 1 for detailed descriptions of patch fate classes.

Downloaded by [New Mexico State University] at 11:09 15 August 2011

Fate assignments were designed to quantify patch dynamics encapsulating shrub recruitment, growth, and mortality for detailed monitoring of individuals (Browning *et al.* 2008). Increases and decreases in canopy size for relatively small circular patches were categorized as canopy expansion and canopy dieback, respectively. In addition, intermediate categories were specified to include canopy growth by coalescence with neighboring patches and dieback by fragmentation into constituent patches (Figure 3c). When focal patches coalesced

Table 2. Descriptions of fate attributes assigned to shrub objects manually delineated on co-registered digital photography. Categorical designations characterize fate between two aerial photographs. 'Fate' values were assigned to objects in building the database; 'Group' corresponds to the generalized grouping created to summarize shrub patch dynamics over the 71-year period (Figure 5).

Group	Fate	Description
Appearance	New	First appearance of a shrub patch on a digital image
Growth	Expan	Increase in patch size due to canopy expansion; this category corresponds to circular patches possibly corresponding to a single shrub canopy
	ExpanP	Canopy expansion resulting in the transition of a patch depicted as a point to that of a polygon
	Coal	Increase in patch size due to coalescence of the focal shrub with neighboring shrub patches, thereby increasing shape complexity
Decline	Dieback	Decrease in size of shrub polygon due to canopy dieback; this designation applies to circular rather than larger complex patches
	DiebackP	Decrease in patch area resulting in transition from a polygon to a point
	Fragment	Loss of patch area resulting from the fragmentation of conglomerate patches into constituent shrubs
	Disapp	Previously existing patch that is no longer discernable, representing patch mortality. Patch mortality does not imply plant mortality
Reappearance	Reapp	Reappearance of shrub patch that was not discernable on one or more previous images; we assume the patch represents the same individual. In many cases, focal patches were not detected on multiple images
Stability	Maintain	Shrub polygons do not change appreciably in size (15% of patch area) or shape from one image to the next
	Persist	Shrub objects persist as points with no recognizable canopy growth

Downloaded by [New Mexico State University] at 11:09 15 August 2011

with shrub patches outside the study plot (Figure 3b), the entire patch was delineated. If conglomerate patches subsequently fragmented into their patch components, only the focal patch was delineated and subsequently monitored (Figure 3b). Persistence and stability denote maintenance of shrub canopy size as polygons or points from one image to the next; a threshold of $<15\%$ change in shrub patch area was set to represent persistence in size. Transition in spatial configuration was specified by denoting canopy expansion from a point to a polygon and canopy dieback from a polygon to a point.

Bestelmeyer *et al.* (2006) devised a multiphase framework to encompass six mechanisms associated with vegetation change in Chihuahuan Desert grasslands using repeat ground photographs as an interpretable matrix to classify vegetation transitions. The shrub fate classification scheme in this study was designed to accommodate an array of research objectives and was patterned after that of Bestelmeyer *et al.* (2006). For this effort to evaluate the utility of the patch-oriented database to enhance landscape analysis of shrub cover change, we collapsed 11 fates into five broader categories to denote appearance of new shrub patches, growth or decline of existing patches, stability in patch area, and patch mortality (Table 2).

3. Results

3.1. Landscape analysis

Shrub cover increased steadily from 1937 to 1967 at which point it was relatively stable until 1989. Shrub cover from 1989 to 2008 consistently increased from 8 to 14%. Laliberte *et al.* (2004) noted an increase in cover in that time series concluding with a 2003 Quickbird image

Downloaded by [New Mexico State University] at 11:09 15 August 2011

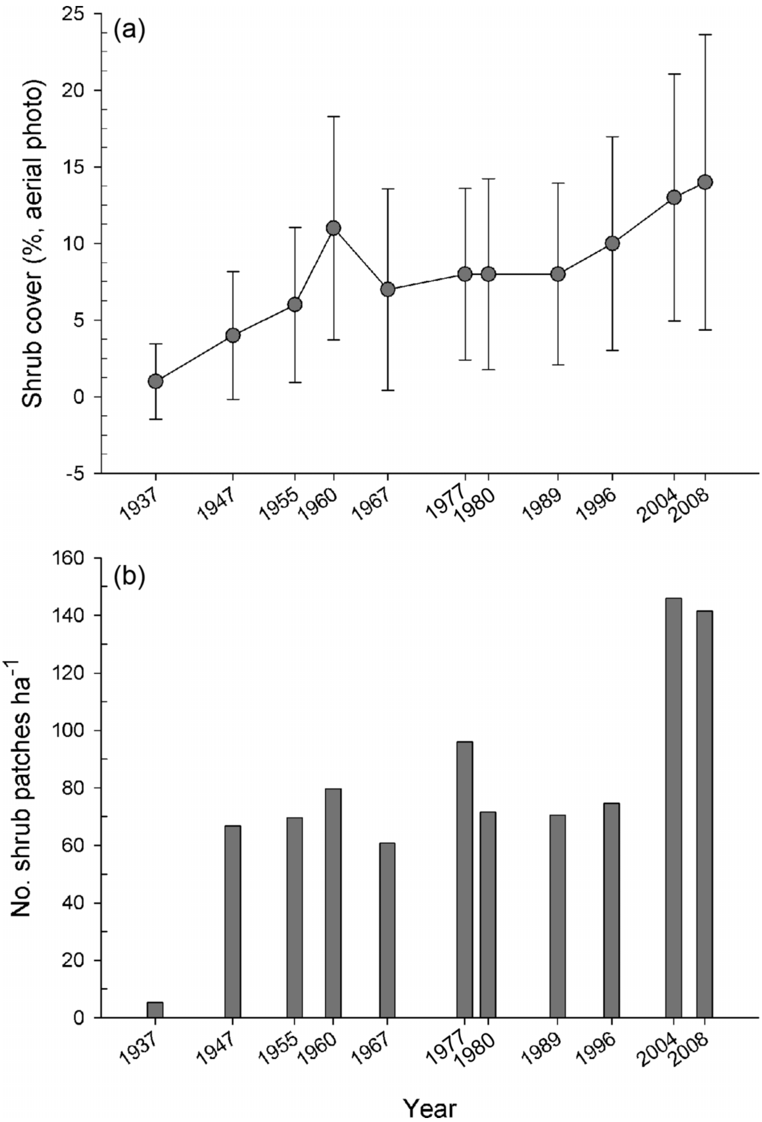

Figure 4. Percent shrub cover and shrub patch density on the CDRRC study site as derived from an automated object-based classification of 11 digitized co-registered aerial photographs from 1937 to 2008. Shrub cover (a) is represented as the mean of 3879 – 20 × 20 m quadrats with one standard deviation. Patch density (b) was calculated by dividing the total number of shrub patches by study site area (150 ha).

(13% cover); the increase in cover was sustained through 2008 (Figure 4a). Variability in shrub cover estimated from classified aerial photography was high and yet steadily increased over the 71-year period. Changes in patch density mirror those in shrub cover with biggest increases between 1937 and 1947 and 1996 and 2004 (Figure 4b, Table 3). Patch density fluctuated between 65 and 75 patches ha^{-1} between 1947 and 1996. Patch density increases sharply between 1996 and 2004 (to 146 patches ha^{-1}) and remained high in 2008 (at 142 patches ha^{-1}).

Downloaded by [New Mexico State University] at 11:09 15 August 2011

Table 3. Shrub colonization (appearance of patches), disappearance, fragmentation, and coalescence rates as determined from manually digitized shrub patches on time series aerial photography. Shrub appearance, disappearance, fragmentation, and coalescence are defined in Table 1. The plot-based metrics that reflect processes which translate to landscape-level decreases in patch density (i.e., disappearance and coalescence) are shown in gray whereas those which translate to increase in patch density (i.e., colonization and fragmentation) are unshaded. Absolute changes in shrub cover, patch density, and mean patch size (from classified images at the landscape scale) were calculated by subtracting the value in year 1 from the value in year 2.

	Plot				Landscape		
Period	Colonization rate (patches per year)	Fragmentation rate (patches per year)	Disappearance rate (patches per year)	Coalescence rate (patches per year)	Change mean patch area (m^2 per year)	Change shrub cover (% per year)	Change patch density (patches ha^{-1} per year)
1937–1947	9.7	0.0	0.0	0.1	−1.0	0.3	6.1
1947–1955	10.0	3.6	0.1	0.1	0.2	0.3	0.4
1955–1960	6.2	0.0	1.4	4.4	1.1	1.0	2.0
1960–1967	2.9	3.3	3.7	0.4	−0.2	−0.6	−2.7
1967–1977	2.0	1.8	2.8	0.3	−0.4	0.1	3.5
1977–1980	4.0	0.7	6.0	1.0	0.8	0.0	−8.1
1980–1989	3.3	2.2	4.6	0.9	0.1	0.0	−0.1
1989–1996	1.7	3.1	5.1	0.4	0.3	0.3	0.6
1996–2004	6.0	3.0	0.3	0.3	−0.6	0.4	8.9
2004–2008	1.0	1.0	2.0	2.8	0.4	0.3	−1.1

3.2. Plot-based analysis of shrub patch dynamics

Manual assessments reveal dynamic processes at the level of individual patches amidst broad-scale stability in shrub cover and density (Figure 5). Appearance of new shrub patches (i.e., colonization) was high at the beginning of the study when shrub cover was low, but decreased by 1960. Patch persistence was high as indicated by the large percentage of patches that maintained canopy size from 1947 through 2008 (Figure 5). Patch loss (i.e., 'decline') encompasses both canopy dieback and patch mortality. Losses in patch area peaked between 1960 and 1977, thereafter accounting for change in an average of 22.5% of shrub patches from 1977 to 2008.

3.3. Cross-scale perspective

Early increases in patch density (Figure 4b) were due to high colonization rates (9.7 new patches per year from 1937 to 1947, Table 3). High colonization was sustained from 1947 to 1955 with increasing persistence of patches (Figure 5). While colonization decreased from 1955 to 1960, the increase in shrub cover was due to the coalescence and growth of existing patches (Table 3). Shrub cover and mean patch size (from the landscape perspective) were stable from 1967 to 1989 amidst dynamic changes in patch configuration (e.g., fragmentation and coalescence) with roughly equal percentages of mortality and appearance of individual patches (Table 3, Figure 4). Subsequent increases in shrub patch density from 1996 to 2004 encapsulated the appearance of new patches (*n* = 47) and fragmentation of existing patches

Downloaded by [New Mexico State University] at 11:09 15 August 2011

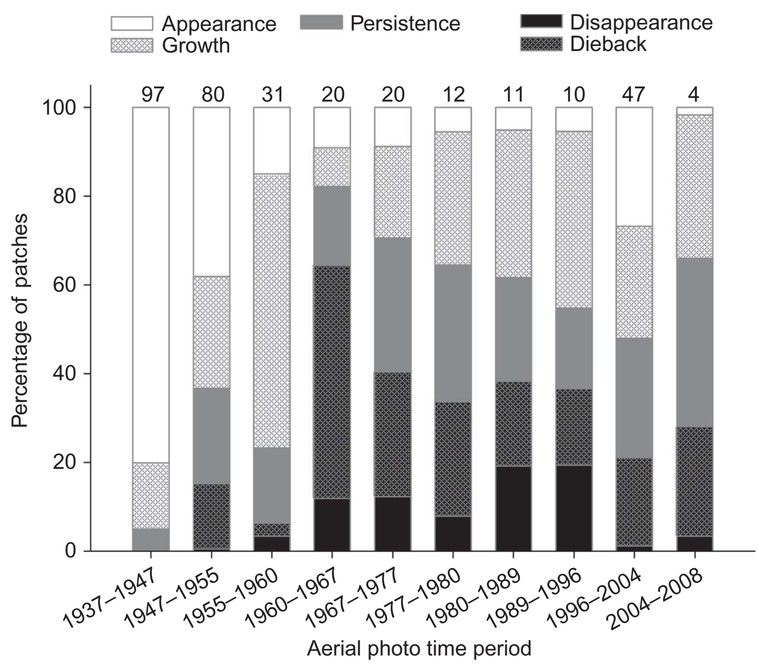

Figure 5. Fate of individual shrub patches manually digitized on 11 aerial photograph images spanning 71 years. Shading represents the percentage of patches monitored by category of change for each time period. Fate designations are defined in Table 1. The number of patches to appear during each time period appears at the top of each bar.

(*n* = 24 patches) reflecting the array of demographic processes contributing to increases in cover and density. Patch persistence and growth dominated dynamics from 2004 and 2008.

4. Discussion

By integrating landscape- and patch-level information, we gained a novel perspective on how patch structure influenced cover dynamics. Shrub patches exhibited a high degree of dynamism as shrub cover remained relatively stable. Periods of increase in cover at the beginning and end of the study were the net result of different demographic processes.We capitalized on a rich aerial photographic record that affords landscape and patch perspectives over seven decades that would not be available otherwise (Rango and Havstad 2003, Rango *et al.* 2005). We monitored the fate of individuals by manually delineating shrub patches on co-registered digital images. Populating the database by hand-digitizing patches took 27 person hours and assigning fate and unique identifier attributes took 45 person hours. Quality assurance constituted approximately 28 person hours to review point and polygon features and their associated fate assignments. This time-consuming process involving 2237 patches was deemed necessary to circumvent issues associated with the analysis of archival time series aerial photography. For instance, even the most fastidious approach to geometric correction of historic imagery is unlikely to yield data sets in which individual patches are coincident between images. Human interpretation is required to confidently monitor changes in patch structure, especially where individual patches might not overlay perfectly. Under such conditions, plot locations (for a given image date) were shifted to ensure the same sample area was analyzed across all images.

4.1. Effects of photo quality

Differences in image quality are inherent to long-term studies using time series photography; photo scale is known to influence vegetation cover estimates (Fensham and Fairfax 2007). Potential biases imposed upon our results include misclassification of change in patch size and appearance of new patches due to differences in image clarity. Efforts to account for differences in photo scale included aggregating images to a common spatial resolution (i.e., 1 m) and manually digitizing and assigning shrub fate classes; however, detection limitations of time series photography (especially the oldest imagery) are difficult to retrospectively validate (Browning *et al.* 2009). Our criteria for designating growth and canopy dieback were conservative (change in area $>$15% patch area) to alleviate classification errors due to image quality.

Object-based classifications of shrub cover performed consistently well (*K* hat values ranged from 0.517 to 0.965, see Table 1) with overall accuracies between 89.9 and 98.0%. Therefore, our interpretations of change in shrub cover and patch density (Figure 4) are sound. Increases in patch density (landscape level) and appearance of new patches (manual interpretation) from 1996 to 2004 are consistent with patterns depicted using 2003 Quickbird imagery (Laliberte *et al.* 2004). While efforts to account for differences in detectability across image series may not have been impenetrable, the influx of new shrub patches from 1996 to the early 2000s is real. Furthermore, we maintain that such inconsistencies are inevitable for archival photography at decadal time scales.

Downloaded by [New Mexico State University] at 11:09 15 August 2011

Downloaded by [New Mexico State University] at 11:09 15 August 2011

4.2. Seasonal precipitation

Precipitation is highly variable in space and time in the arid and semiarid regions of the southwestern US where convective summer storms constitute the majority of rainfall. We present data from the closest rain gauge, 2.3 km from our study site, with records dating back to 1930. Winter precipitation occurs in the form of frontal systems originating largely from the Pacific Coast that are less localized than monsoonal summer storms that originate in the Gulf of Mexico (Wainwright 2006). Recognizing that summer rainfall is highly spatially variable, we present seasonal precipitation as the best index of rainfall over the course of this study. Laliberte *et al.* (2004) related annual precipitation patterns to changes in shrub cover at this site from 1937 to 2003. Mesquite is capable of using winter rainfall that accumulates in the soil profile for spring leaf emergence (Scott *et al.* 2008), whereas perennial herbaceous species are generally most responsive to summer rainfall (Cable 1975).

In addition to phenological differences between plant functional groups, soil properties influence the proportion of rainfall that penetrates the soil profile as well as the spatial distribution (e.g., depth) of water that becomes available to plants. Duniway *et al.* (2010) demonstrated that the presence of calcic-cemented restrictive layers in the soil profile greatly increases the quantity and duration of plant available water in the soil profile during extreme dry and wet periods in this Chihuahuan Desert ecosystem. Soil mapping efforts for our study site were part of a third-order soil survey (Bulloch and Neher 1980) which is coarse relative to the patch-level analysis. Quantifying the effects of soil properties such as soil texture and depth to restrictive layer on observed patch dynamics was beyond the scope of this study and will be conducted in future work.

We examine the seasonal distribution in rainfall in the context of shrub dynamics, both in terms of absolute values (Figure 6a) and values standardized relative to long-term means by season (Figure 6b). Seasonal precipitation was highly variable from 1930 to 1947. Precipitation was consistently below-average through the 1950s; increases in mesquite cover, density, and patch size were consistent from the beginning of the study through the drought of the 1950s. Seasonal patterns in rainfall from 1977 to 2008 were marked by increased winter rainfall with above-average winter and summer rainfall during the 1980s. Patch dynamics during this period (1977–2008) were characterized by increases and stability in patch size in conjunction with mortality of existing patches and low establishment. We recognize the potential for self-regulating mechanisms (i.e., intra-specific competition) in shrub stand structure to interact with precipitation or dampen the climate signal with regard to shrub patch dynamics.

4.3. Cross-scale approach to quantifying vegetation dynamics

Mesquite patch persistence was high and patterns in shrub patch development varied widely over the 71-year period. In an analysis of shrub cover change over 60 years in the CDRRC using aerial photography and CORONA satellite imagery, Goslee *et al.* (2003) noted high shrub patch persistence and that shrub cover stabilized following initial increases. Ansley *et al.* (2001) quantified shrub cover change over 20 years by hand-digitizing mesquite canopies on high-resolution aerial photography. High-resolution photography acquired at this scale (e.g., 1 : 5000) permits designation of mechanisms influencing changes in shrub patch density such as coalescence, mortality, and growth. Dynamics observed at CDRRC were more complex than these three processes proposed by Ansley *et al.* (2001). We signified patch fragmentation, establishment, and transition as additional processes to assist our interpretation of changes in patch density. Increases in patch density can result from the influx of new patches as well as fragmentation of conglomerate patches; both processes

Downloaded by [New Mexico State University] at 11:09 15 August 2011

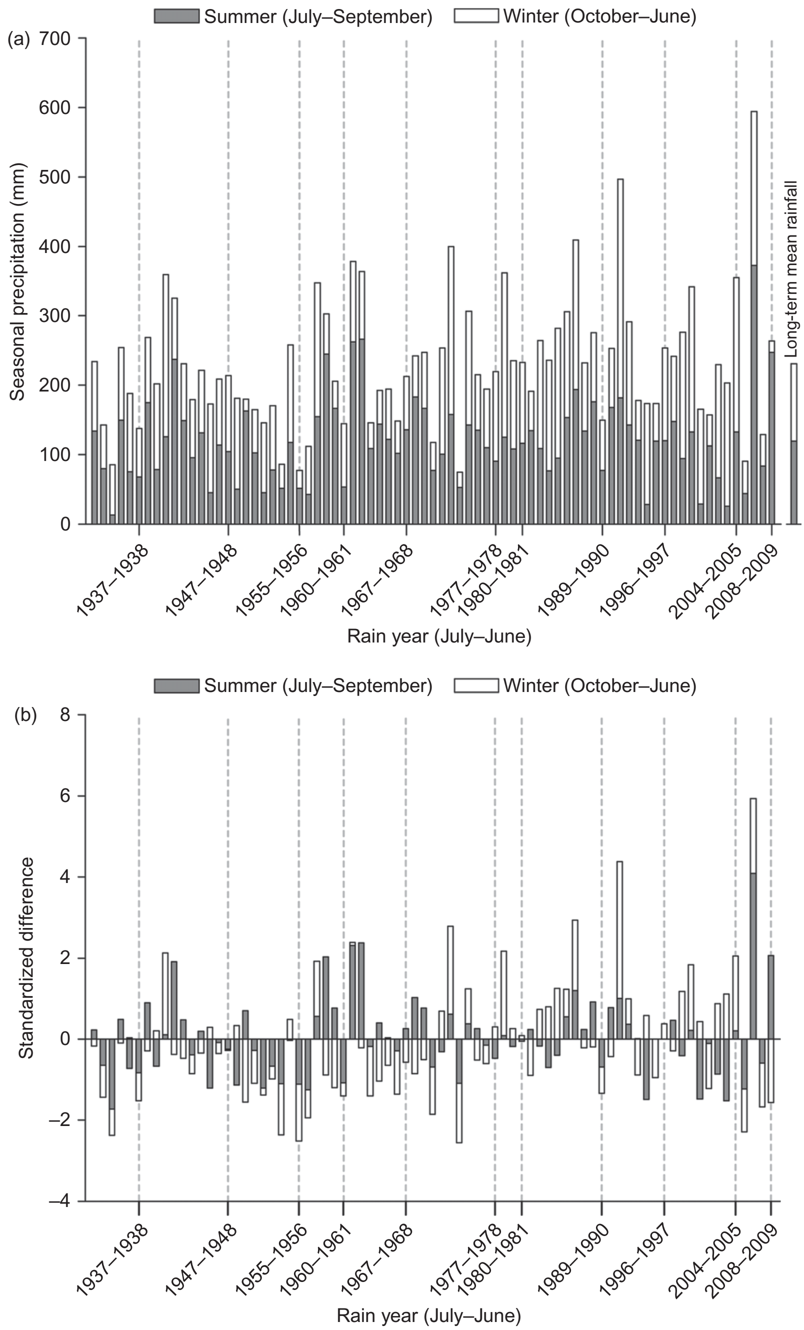

Figure 6. Seasonal precipitation (1930–1931 to 2008–2009) for the Selden rain gauge on CDRRC which occurs 2.3 km from the study site. Summer includes the monsoon season from July to September and winter includes October to the following June (a). Precipitation is also expressed as the standardized difference, which is the seasonal value minus the seasonal long-term average divided by the standard deviation (b). Aerial photo dates are designated by vertical dotted gray lines.

represent entirely different demographic processes. Conversely, decreases in patch density can reflect both patch mortality or coalescence of existing patches, or a combination of both. Such realizations reflect the importance of identifying patterns in patch structure in long-term studies of vegetation dynamics.

This study was conducted to evaluate landscape-level changes in shrub cover at multiple scales of observation. We used aerial photography for its temporal depth of record and because it allowed us to examine changes across a heterogeneous landscape typical of those in the southwestern US rangelands. Transitions in vegetation composition may change abruptly or slowly, but capturing dynamic transitions is best approached from multiple scales of observation and is enhanced by knowledge of site history and landscape spatial context.

Downloaded by [New Mexico State University] at 11:09 15 August 2011

4.4. Phases of encroachment in a shifting mosaic

The general pattern of initial increases in cover driven by patch establishment that transitioned to patch-level fluctuation amidst stasis in cover corresponds to dynamics associated with shrub encroachment in Sonoran Desert grasslands. From landscape- and patch-level analyses of aerial photography from 1936 to 1996, Browning *et al.* (2008) proposed a two-phase model of shrub encroachment based, in principle, on the shifting mosaic proposed for forested ecosystems (Bormann and Likens 1979) and subsequently for savanna ecosystems (Scholes and Archer 1997). In the encroachment phase of woody plant proliferation, shrub cover increases are associated with the influx of new shrub patches and growth of existing patches whereas in the subsequent stabilization phase, patch-level mechanisms (e.g., canopy growth, dieback, and mortality) oscillate while shrub cover fluctuates little around a dynamic equilibrium.

Identifying factors or the combination of factors determining maximum potential woody cover in mixed tree–grass systems that define savannas has been a matter of debate (House *et al.* 2003, Sankaran *et al.* 2005, 2008), yet one model proposed by Sankaran *et al.* (2005) signifies that maximum woody cover in savanna systems receiving less than ~650 mm mean annual precipitation (MAP) is limited by and increases linearly with MAP. Estimates of shrub cover on the Santa Rita Experimental Range in southeastern Arizona (receiving 370 mm MAP) fell directly in line with the predicted maximum of 37% cover based on the Sankaran *et al.* (2005) algorithm. Our study site on the CDRRC with a MAP of 230 mm is predicted to support a maximum potential shrub cover of 18%. From our landscape-based shrub cover estimates, we are approaching this proposed maximum (18%) whereas plot-based patch dynamics signify a shifting mosaic among patches marked by simultaneous growth and decline. Future and consistent monitoring efforts are required to ascertain whether we are reaching maximum potential woody cover at this site.

5. Conclusions

Our approach to manually delineate individual shrub objects was essential to characterize change in patch configuration with time series aerial photography. Object-based analysis revealed patch-level processes that were otherwise unattainable. Landscape-level interpretations alone were not capable of capturing patch dynamics representing the full range of demographic processes (e.g., colonization, persistence, mortality) that contradict most simplistic assumptions regarding progressive increases in shrub cover in arid and semiarid rangelands. We present a tool, albeit time- and labor-intensive, to validate depictions of vegetation cover and distribution to enhance interpretative capabilities at the level of individual patches. Our approach, which bridges geospatial data collected at different spatial scales using both manual and automated methods to delineate discrete image objects, is suitable for environmental problem solving that often requires multiscale perspectives.

The schema devised for this study (Table 2) can be easily adapted to address other research objectives associated with vegetation transitions in an array of ecosystems with historic aerial photography from as early as the mid-1930s which is also available from a variety of databases (Rango *et al.* 2008). Such analyses serve as the first step in characterizing demographic contributions to landscape change in a range of ecosystems. Future efforts will focus on reliably distinguishing patch fate in a semiautomated fashion for broader implementation. In this arid rangeland ecosystem, we discerned variability in shrub patch dynamics amidst broad-scale stability in shrub cover and patch density in agreement with a shifting mosaic framework for stand dynamics. The encroachment process leveled off following initial high rates of increase to transition to a phase in which patch-level stability dominated. Monitoring shrub patch dynamics will become increasingly important as indicators of impending shifts in ecosystem structure and function in actively managed ecosystems.

Downloaded by [New Mexico State University] at 11:09 15 August 2011

Acknowledgments

A. Moreno's dedication and hard work in digitizing and categorizing shrub patches is appreciated and recognized. C. Steele, B. Nolen, and S. Schrader shared insights and suggestions regarding geoprocessing challenges that arose during the course of this project. P. Gronemeyer assisted with assessing image classification accuracy. K. Havstad and three anonymous reviewers provided constructive criticisms that improved the quality of this work. This research was funded by the US Department of Agriculture, Agricultural Research Service, and the National Science Foundation Long-Term Ecological Research Program, Jornada Basin LTER V: Landscape Linkages in Arid and Semiarid Ecosystems.

References

Allen, T.F.H. and Starr, T.B., 1982. *Hierarchy: perspectives for ecological complexity.* Chicago, IL: University of Chicago.

Ansley, R.J., Wu, X.B., and Kramp, B.A., 2001. Observation: long-term increases in mesquite canopy cover in a north Texas savanna. *Journal of Range Management*, 54, 171–176.

Archer, S., 1994. Woody plant encroachment into southwestern grasslands and savannas: rates, patterns, and proximate causes. *In*: M. Vavra, W. Laycock, and R. Pieper, eds. *Ecological implications of livestock herbivory in the West*. Denver, CO: Society for Range Management, 13–68.

Archer, S., *et al.*, 1988. Autogenic succession in a subtropical savanna: conversion of grassland to thorn woodland. *Ecological Monographs*, 58, 111–127.

Asner, G.P., *et al.*, 2003. Net changes in regional woody vegetation cover and carbon storage in Texas drylands, 1937–1999. *Global Change Biology*, 9, 1–20.

Benz, U.C., *et al.*, 2004. Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. *ISPRS Journal of Photogrammetry and Remote Sensing*, 58, 239–258.

Bestelmeyer, B.T., *et al.*, 2006. A multi-scale classification of vegetation dynamics in arid lands: what is the right scale for models, monitoring, and restoration? *Journal of Arid Environments*, 65, 296–318.

Bormann, F.H. and Likens, G.E., 1979. *Pattern and process in a forested ecosystem*. New York: Springer-Verlag.

Browning, D.M., *et al.*, 2008. Woody plants in grasslands: post-encroachment dynamics. *Ecological Applications*, 18, 928–944.

Browning, D.M., Archer, S.R., and Byrne, A.T., 2009. Field validation of 1930s aerial photography: how much are we missing? *Journal of Arid Environments*, 73, 844–853.

Buffington, L.C. and Herbel, C.H., 1965. Vegetational changes on a semidesert grassland range from 1858 to 1963. *Ecological Monographs*, 35, 139–164.

Bulloch, H.E.J. and Neher, R.E., 1980. *Soil survey of Dona Ana County Area, New Mexico*. Washington, DC: USDA-SCS.

Burnett, C. and Blaschke, T., 2003. A multi-scale segmentation/object relationship modelling methodology for landscape analysis. *Ecological Modelling*, 168, 233–249.
Cable, D.R., 1975. Influence of precipitation on perennial grass production in semidesert southwest. *Ecology*, 56, 981–986.
Cohen, J., 1960. A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, 20, 37–46.
Duniway, M.C., Herrick, J.E., and Monger, H.C., 2010. Spatial and temporal variability of plant-available water in calcium carbonate-cemented soils and consequences for arid ecosystem resilience. *Oecologia*, 163, 215–226.
Fensham, R.J. and Fairfax, R.J., 2007. Effect of photoscale, interpreter bias and land type on woody crown-cover estimates from aerial photography. *Australian Journal of Botany*, 55, 457–463.
Gibbens, R.P., *et al.*, 2005. Vegetation changes in the Jornada Basin from 1858 to 1998. *Journal of Arid Environments*, 61, 651–668.
Goslee, S., *et al.*, 2003. High-resolution images reveal rate and pattern of shrub encroachment over six decades in New Mexico, USA. *Journal of Arid Environments*, 54, 755–767.
Greig-Smith, P., 1983. *Quantitative plant ecology*. 3rd ed. Oxford, UK: Blackwell Scientific Publications.
House, J.I., *et al.*, 2003. Conundrums in mixed woody-herbaceous plant systems. *Journal of Biogeography*, 30, 1763–1777.
Kefi, S., *et al.*, 2007. Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature*, 449, 213–215.
Laliberte, A.S., *et al.*, 2004. Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico. *Remote Sensing of Environment*, 93, 198–210.
O'Neill, R.V., Johnson, A.R., and King, A.W., 1989. A hierarchical framework for the analysis of scale. *Landscape Ecology*, 3, 193–205.
Peters, D.P.C. and Havstad, K.M., 2006. Nonlinear dynamics in arid and semi-arid systems: interactions among drivers and processes across scales. *Journal of Arid Environments*, 65, 196–206.
Peters, D.P.C., *et al.*, 2004. Cross-scale interactions, nonlinearities, and forecasting catastrophic events. *Proceedings of the National Academy of Sciences of the United States of America*, 101, 15130–15135.
Platt, R.V. and Rapoza, L., 2008. An evaluation of an object-oriented paradigm for land use/land cover classification. *Professional Geographer*, 60, 87–100.
Rango, A. and Havstad, K., 2003. The utility of historic aerial photographs for detecting and judging the effectiveness of rangeland remediation treatments. *Environmental Practice*, 5, 107–118.
Rango, A., *et al.*, 2005. Using historic data to assess effectiveness of shrub removal in southern New Mexico. *Journal of Arid Environments*, 62, 75–91.
Rango, A., Laliberte, A., and Winters, C., 2008. Role of aerial photos in compiling a long-term remote sensing data set. *Journal of Applied Remote Sensing*, 2, 023541.
Rietkerk, M., *et al.*, 2004. Self-organized patchiness and catastrophic shifts in ecosystems. *Science*, 305, 1926–1929.
Sankaran, M., *et al.*, 2005. Determinants of woody cover in African savannas. *Nature*, 438, 846–849.
Sankaran, M., Ratnam, J., and Hanan, N., 2008. Woody cover in African savannas: the role of resources, fire and herbivory. *Global Ecology and Biogeography*, 17, 236–245.
Scholes, R.J. and Archer, S.R., 1997. Tree-grass interactions in savannas. *Annual Review Ecology and Systematics*, 28, 517–544.
Scott, R.L., Cable, W.L., and Hutline, K.R., 2008. The ecohydrologic significance of hydraulic redistribution is a semiard savanna. Water Resources Research, 44, W02440, doi: 10.1029/2007WR006149.
Throop, H.L. and Archer, S.R., 2008. Shrub (Prosopis velutina) encroachment in a semidesert grassland: spatial-temporal changes in soil organic carbon and nitrogen pools. *Global Change Biology*, 14, 2420–2431.
Van Auken, O.W., 2000. Shrub invasions of North American semiarid grasslands. *Annual Review Ecology and Systematics*, 31, 197–215.
Wainwright, J., 2006. Climate and climatological variations in the Jornada Basin. *In*: K.M. Havstad, L.F. Huennecke, and W.H. Schlesinger, eds. *Structure and function of a Chihuahuan Desert ecosystem. The Jornada Basin Long-Term Ecological Research site*. Oxford, UK: Oxford University Press, 44–80.

Downloaded by [New Mexico State University] at 11:09 15 August 2011