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High-resolution images reveal rate and pattern of shrub encroachment over six decades in New Mexico, U.S.A.

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Encroachment of the shrub *Prosopis glandulosa* Torr. (honey mesquite) into semi-arid grasslands is a serious concern in the south-western United States, yet little is known about the long-term dynamics of the invasion process. We used ten high-resolution aerial and satellite images taken from 1936 to 1996 to track the population dynamics and spatial pattern of all *P. glandulosa* greater than 2 m in diameter on a 75 ha area in southern New Mexico.

Shrub cover and patch numbers increased from 1936 to the 1970s, then stabilized at 43% cover and 83 patches ha^{-1}. Individual patches were extremely persistent: 95% of the area occupied by shrub patches in 1936 was still occupied in 1996. Recruitment into the 2 m size class was more variable: 0·6–5·2% year^{-1} (mean 0·8% year^{-1}). Patch-shape complexity increased from 1936 to 1983 as adjacent shrubs merged, and then declined as those clusters filled in and became rounder. Spatial pattern of shrubs showed a distinct trend over time: strongly clustered in 1936 at lag distances up to 250 m, then random arrangement at all scales, and by 1983 pattern was regular at lag distances greater than 100 m. There was no clear relationship with precipitation.

The use of remote sensing imagery allowed us to examine one site over time, and revealed patterns in population dynamics and spatial pattern that would not have been visible otherwise. Comparison of field estimates collected in 2001 with 1996 image data suggest that the canopy cover estimates were accurate, but shrub densities were seriously underestimated in the satellite photographs, which do not show shrubs smaller than 2 m diameter. As long as limitations of the imagery are understood, these methods can be applied over a larger and more heterogeneous area to examine environmental correlates of invasion success.

Keywords: Chihuahuan desert grassland; *Prosopis glandulosa*; remote sensing; shrub encroachment

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Introduction

Woody encroachment is a serious problem in semi-arid grasslands worldwide (Archer, 1994). In the northern Chihuahuan Desert, one of the primary encroaching shrubs is the native *Prosopis glandulosa* Torr. (honey mesquite), which has increased considerably in numbers and area during the past 50–100 years (Buffington & Herbel, 1965; Hennessy *et al.*, 1983; Gibbens *et al.*, 1992; Brown & Archer, 1999; Van Auken, 2000). The *P. glandulosa* root system spreads laterally and can penetrate deeply into the soil, enabling this species to take advantage of both shallow and deep soil water and allowing it to become successful under a variety of conditions (Gibbens & Lenz, 2001). The deep root systems are particularly advantageous during drought conditions, since *P. glandulosa* can reach soil water that is not available to shallow-rooted grasses.

The conversion of desert grassland to shrub-dominated vegetation can have many long-term ecosystem consequences. Under *P. glandulosa* shrubs, there is less water availability, less plant cover, and less soil organic matter than under grasses (Paulsen, 1953). Shrub encroachment may change energy (Archer & Smeins, 1991), hydrologic (Thurow, 1991), and nutrient cycling (Schlesinger *et al.*, 1990; Schlesinger *et al.*, 2000). The shift from grass to shrub dominance reduces species diversity (Gibbens *et al.*, 1992), and alters the temporal dynamics of primary production (Huenneke *et al.*, 2001). These ecosystem changes make it very difficult to restore grasslands to shrub-dominated sites (Van Auken, 2000).

Despite the importance of shrub encroachment to the structure and function of desert ecosystems, little is currently known about the long-term dynamics of the expansion process. The first step in understanding potential drivers of encroachment is to develop a reliable method for quantifying shrub dynamics over large areas and long time periods so that encroachment patterns can be related to physical factors and management regimes. Remotely sensed images provide an important tool for analysing shrub expansion into desert grasslands. The open vegetation and sparse cover makes it possible to obtain data on the rate and pattern of invasion over large areas (Whiteman & Brown, 1998). Aerial and satellite images have been used for this purpose by a number of researchers, including Schlesinger and Gramenopoulos (1996), Brown & Carter (1998), Fransen *et al.* (1998), Hudak & Wessman (1998), Whiteman & Brown (1998), and Ansley *et al.* (2001). Analysis of images can allow causal inferences and provide a way to prioritize areas for management (Whiteman & Brown, 1998).

Plant spatial pattern can be used as a basis for inferences about underlying processes. Ansley *et al.* (2001) identified three major processes determining spatial pattern in desert shrubs: recruitment, coalescence and mortality. Recruitment and mortality both affected the spatial distribution of shrubs, while coalescing of shrubs led to increased shape complexity. Spatial distribution may be related to competition between individuals, especially in strongly resource-limited semi-arid areas. Regular spacing has been found repeatedly in shrub populations of arid and semi-arid regions, although this pattern has been the focus of some controversy (Elbert & McMaster, 1981; King & Woodell, 1973, 1984, 1987). Differences in type of pattern with plant age have also been observed. Stands composed of young shrubs tend to have an aggregated pattern, medium-aged a random pattern, and old shrubs a regular pattern, suggesting the increasing importance of competition as shrubs mature (Anderson, 1971; Phillips & MacMahon, 1981; Fowler, 1986). Remote sensing imagery can be used to examine the dynamics of spatial pattern over long time periods (Rango *et al.*, 2002).

Our main objective was to use commercial aerial photography and satellite images from the U.S. Department of Defense to investigate the population dynamics and spatial pattern of *P. glandulosa* invading a 75 ha area of desert grassland over a 60-year period. Little is known about the long-term population dynamics or changes in spatial pattern over time for this important shrub species. Our secondary objective was to evaluate the potential contribution of U.S. Department of Defense satellite reconnaissance images to ecological research.

Methods

We used ten images collected from various sources, spanning a range of 60 years (Table 1). Seven were satellite images (Mervis, 1999). Those from the 1960s were from the Corona platform and can be obtained through the EROS Data Center, Sioux Falls, SD. More recent images were made available by the U.S. Department of Defense (DOD) as part of its ongoing cooperation with MEDEA, a committee of scientists who work with DOD as advisors on environmental issues. U.S. Department of Defense images were chosen from the available pool based on resolution, lack of cloud cover, lack of distortion, and date, to obtain the clearest possible time sequence. The remaining three images were commercially available aerial photographs. All images were gray-scale, and were rescaled to 2 m resolution using Imagine (Erdas, Inc.). Each image was registered to be internally consistent with the 1996 USGS digital orthophotoquadrangle, so that we could track individual shrubs through time.

Study area

This research was conducted on a 75 ha portion of the Chihuahuan Desert Rangeland Research Center (32·53°N, 106·84°W; 1260 m ASL), owned by New Mexico State University. This area was chosen for analysis because of the marked increase in *P. glandulosa* during the time period for which images were available. *P. glandulosa* was the only important shrub on this site, so that species identification issues were avoided. The research area lies in the northern portion of the Chihuahuan Desert. Long-term average annual precipitation is 230 mm, 52% of which falls in July, August and September. Mean maximum monthly temperature ranges from 13°C in January to 36°C in June (Gibbens & Beck, 1988).

Image analysis

Most studies that have used aerial photography to examine shrub patterns used thresholding to pick out the darkest areas of the image as woody vegetation

Table 1. *Date and source of images used in analyses of* P. glandulosa *encroachment. All satellite images were obtained from the U.S. Department of Defense*

Date	Source
Dec. 1936	Soil conservation service aerial photograph
Dec. 1947	Soil conservation service aerial photograph
Nov. 1964	Satellite
Aug. 1966	Satellite
Jan. 1967	Satellite
Apr. 1967	Satellite
Jul. 1972	Satellite
Aug. 1976	Satellite
Nov. 1983	Satellite
Oct. 1996	USGS digital orthophoto quadrangle

(Hutchinson *et al.*, 2000; Hansen & Ostler, 2001; Lahav-Ginott *et al.*, 2001). Most historical images are panchromatic, and provide limited information for classification of vegetation types, so thresholding is an obvious choice of analysis methods. While this method is simple to execute, and accurate in uncomplicated environments, choice of a threshold is highly subjective. The portion of the northern Chihuahuan Desert chosen for our analysis shows a large variability in background (non-woody vegetation or bare soil) colors on the available images. Thresholding these images includes large areas of background while simultaneously missing much of the shrub area and entire shrubs. We present an alternative semi-manual method for determining shrub numbers and area from high-resolution panchromatic photographs.

We developed a two-step method for identifying mesquite patches in each image using ERDAS Imagine. First, all shrub patches were marked. This was done manually because of the difficulty of developing an automatic method to distinguish between shrub and background pixels of similar values. The second step used an iterative algorithm to expand outward from the marked point until an edge difference value was reached. This parameter was different for each image, and was calculated based on the contrast between dark shrub canopies and lighter background areas for that image. The final product was a black and white image showing shrub canopy sizes and locations. This method is semi-manual, requiring much less human input than outlining shrubs, so it imposes less of a limit on the area and number of images which can be practically analysed (Carmel & Kadmon, 1998). The algorithm was implemented as an Imagine macro, and can be obtained from the authors. We also analysed these images using thresholding so that the two methods could be compared.

Field measurements were used to corroborate the values produced by image analysis. On 1 September 2001, all shrubs were measured in a 50 m × 20 m (0·1 ha) region randomly selected within the northern portion of the study area. Diameters of each patch of shrubs were measured along the longest axis and the axis perpendicular to it. Shrub clumps closer than 1 m were measured as one unit.

Statistical analyses

After each shrub was identified, the binary image was imported into FRAGSTATS (McGarigal & Marks, 1994). This program was used to calculate simple totals, including patch number and area. The shape complexity of all shrub patches was also calculated using the mean shape index (MSI). MSI is based on the perimeter and area of each patch, and averaged across the site. The value is one if all patches are square in a raster-based image, and rises for increasingly irregular patches.

The Ripley's K statistic was calculated from the frequency distribution of all shrub-to-shrub distances (Ripley, 1976; Diggle, 1983). For ease of interpretation, this value was rescaled to $L(d)—d$ for each distance class d, so that values greater than zero represent clumped distributions, and values less than zero represent regular distributions for that distance class. The 95% confidence limits around zero were determined by 99 randomizations of the point data. This analysis was only conducted on the northern one-third of the study area (500 m × 500 m) because of technical limitations, and because that area had the greatest amount of change over time. Distance classes up to 250 m were included in the analysis to reduce the impact of edge effects on the results, and to ensure that a sufficient number of points was present in each class. A modification of the *ripley* function from the S-Plus Spatial Module was used for point pattern analysis (Insightful, Inc.).

Individual patches were tracked over time to create a life table showing transitions between each sequential pair of images. For each image, every shrub patch was compared with the same region in both the previous and the following image. This comparison allowed us to identify areas that remained occupied and those that were newly colonized by *P. glandulosa* patches large enough to be resolved by 2 m pixels. Patches that overlapped in successive images were assumed to be the same shrub. All life table analyses were carried out using S-Plus functions written for the purpose. Because the images have irregular temporal spacing, recruitment, mortality and patch dynamics results were rescaled by year rather than image interval.

Results

There were distinct differences in canopy cover, patch number and spatial pattern among the ten images (Fig. 1). There was a marked increase in both canopy cover (Fig. 2) and number of shrub patches (Fig. 3) over the period for which images were available. Examination of the images suggested that the apparent decline in population size during the 1960s was due to variation in image quality, not to actual changes in number and cover. The 1960s satellite images, all from the Corona platform, had poorer contrast and initial resolution than either the aerial photos or the later satellite images. We did not use these images in further analyses.

Prosopis glandulosa reached its maximum abundance of 43% cover and 83 patches ha^{-1} by the mid-1970s, and changed little after that date. The largest change in cover was between 1947 and 1972, while the largest change in density was between 1936

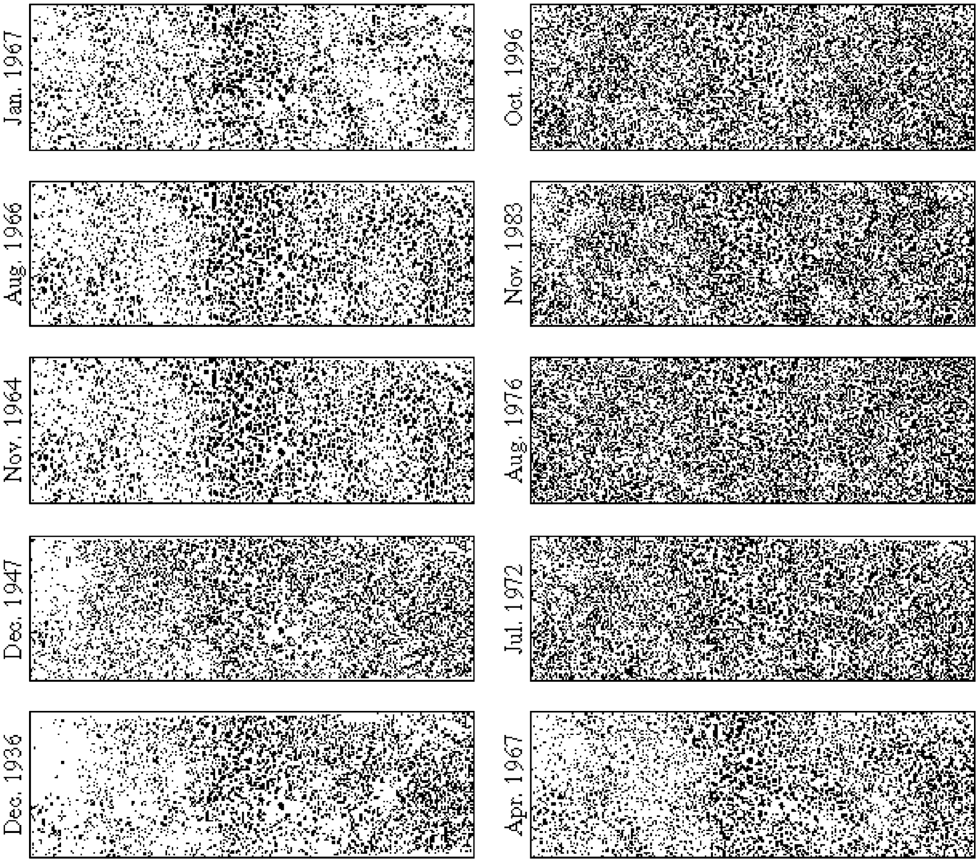

Figure 1. Processed satellite and aerial images (see Table 1) showing shrub patches within the 75 ha study area.

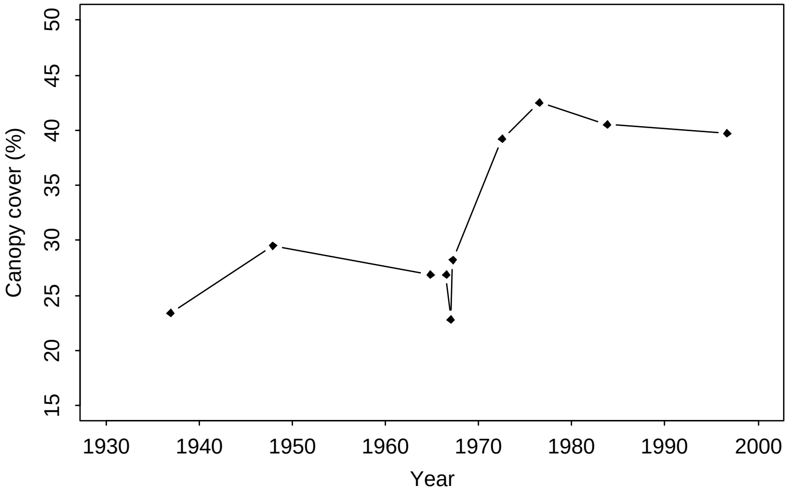

Figure 2. Percentage canopy cover for shrub patches greater than 2 m.

Figure 3. Number of shrub patches greater than 2 m.

and 1947. The ground truth estimate of canopy cover collected in 2001 was 38·9%, as compared to 39·7% estimated from the 1996 image. Density was 390 ha^{-1} in the field measurements for all shrub patches, and 290 ha^{-1} for patches greater than 2 m in diameter, while the 1996 image was interpreted as showing 82 patches ha^{-1}. Thresholding produced results with similar canopy covers, but the patch numbers were less than identified by agglomeration in 1936 and greater in 1996 (Table 2). The patch maps produced by the two methods were extremely different, especially in 1936 (Fig. 4).

Once shrub patches became large enough to appear in a 2 m resolution image, they were highly persistent (Table 3). Only 138 patches disappeared between 1936 and 1996: 95% of the patches that were present in 1936 were still there 60 years later. In any time period, between 85% and 96% of the shrub patches persisted. Losses per year were very small, less than 1·3% year^{-1}. Recruitment into the 2 m size class was

Table 2. *Comparison of thresholding and agglomerative shrub identification results for 1936 and 1996 images*

Year	Agglomeration		Thresholding	
	Patches (*n*)	Cover (%)	Patches (*n*)	Cover (%)
1936	2659	23·4	2364	25·3
1996	3284	39·7	4058	37·9

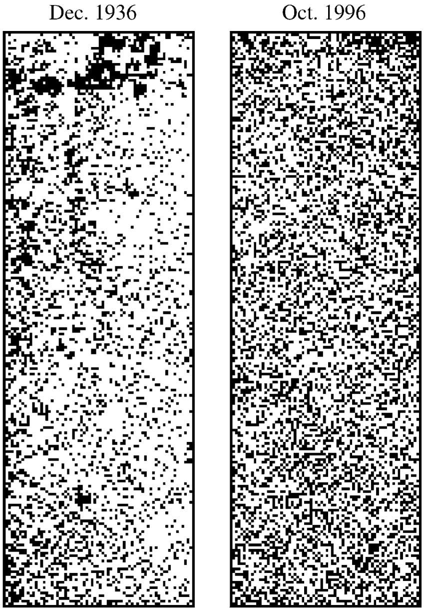

Figure 4. 1936 and 1996 images processed by thresholding for comparison with images processed by semi-manual agglomeration shown in Fig. 1.

Table 3. *Appearance, disappearance and merging of shrub patches greater than 2 m*

Year 1	Year 2	Number of patches		Percent of first year number		
		First year	Second year	Stable	Loss year^{-1}	Gain year^{-1}
Dec. 1936	Dec. 1947	2659	3737	91·3	0·8	5·2
Dec. 1947	Jul. 1972	3737	2957	85·5	0·6	0·6
Jul. 1972	Aug. 1976	2957	2816	94·8	1·3	2·5
Aug. 1976	Nov. 1983	2816	2740	90·7	1·3	0·7
Nov. 1983	Oct. 1996	2740	3284	96·2	0·3	1·1
Dec. 1936	Oct. 1996	2659	3284	94·8	0·1	0·8

Losses describe shrub patches present in the first year and not in the second, while gains describe patches present in the second year and not in the first. (Note that these are numbers of distinct patches, not numbers of individuals.)

highly variable, from 0·6% year^{-1} to 5·2% year^{-1}. The overall gain was 0·8% year^{-1} and the loss was 0·1% year^{-1} for the total 60 years span.

Annual precipitation has been highly variable over the past 75 years (Fig. 5). The greatest changes in both cover (1947–1972) and density (1936–1947) occurred during

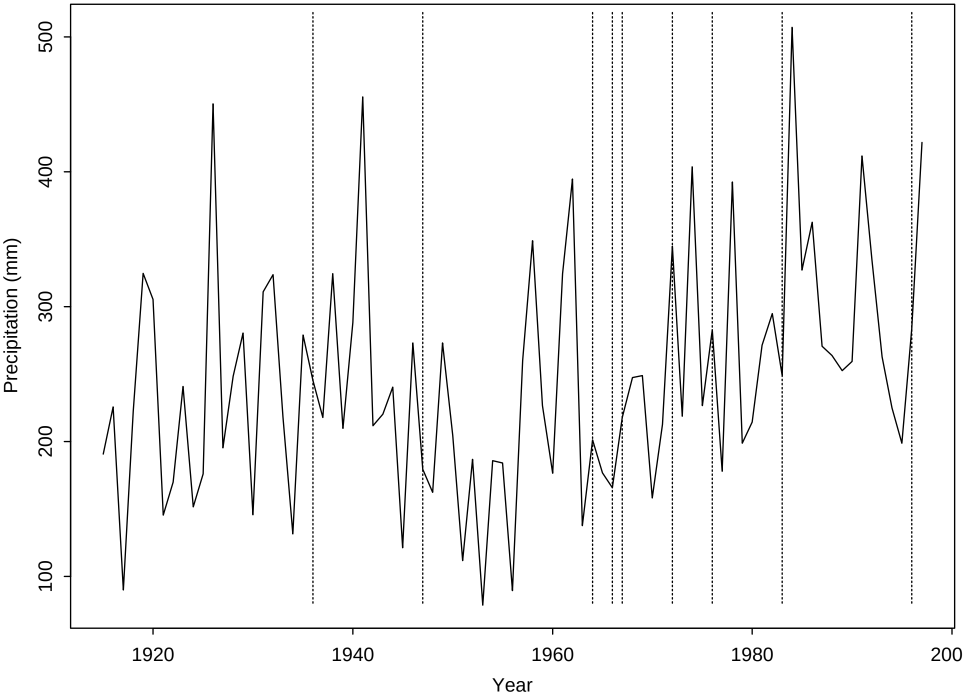

Figure 5. Annual precipitation from the main Jornada Experimental Range weather station. Vertical dashed lines indicate the dates of the satellite and aerial images.

intervals with normal precipitation. During the interval with highest mean precipitation (1984–1996) there was little change in either measure of abundance. The drought during the 1950s occurred during a period for which no high-quality images have been located. The lack of data made it difficult to determine the effects of the drought on shrub dynamics. The very small number of shrub patches that disappeared during this time suggests that drought has little effect on already-established individuals.

Shape complexity was low in 1936, but increased steadily to 1983, and declined again to 1996 (Fig. 6). Point pattern analysis of the same six images showed a distinct change in spatial pattern over time (Fig. 7). In 1936, the shrub patches in the northern third of the analysis area showed a strongly clumped pattern at lag distances up to 250 m. In 1947, the clumping was much weaker, and in the 1970s no spatial pattern was apparent—shrub patches were randomly distributed at all scales. In 1983, regular spacing at large scales was apparent, and this patterning was more pronounced in 1996.

Discussion

This site showed a steady increase in *P. glandulosa* cover and number until an apparent stable state was reached. Density increased earlier than canopy cover as shrubs first became large enough to resolve on these images, and then continued to expand over time. Although other studies have shown a correlation between precipitation and success of *P. glandulosa* (e.g., Gibbens *et al.*, 1992; Ansley *et al.*, 2001), we were unable to demonstrate such a relationship for this study. Large individuals appear to be

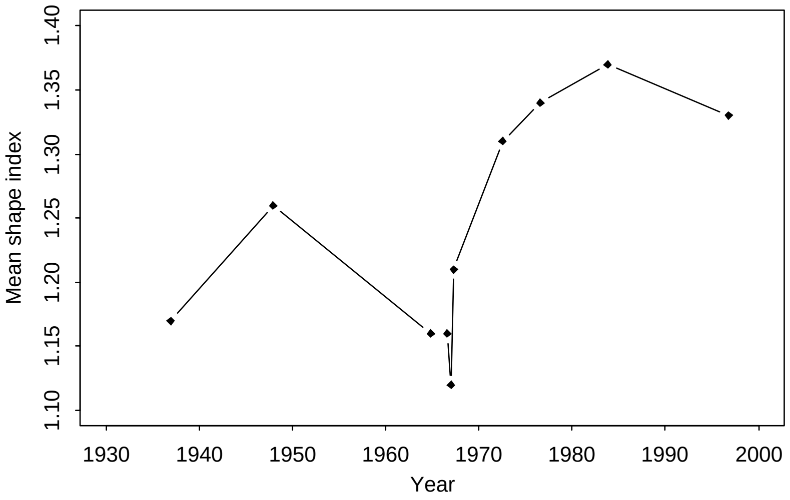

Figure 6. Mean shape index (MSI), a measure of shape complexity, for shrub patches. MSI is 1 for perfect squares on a raster grid, and progressively higher for more complex shapes.

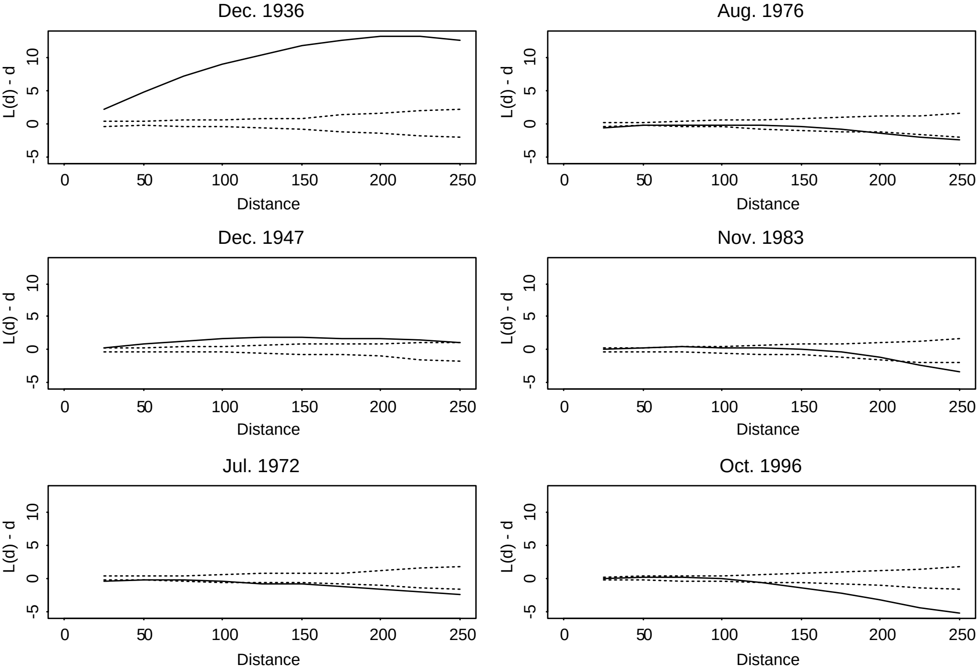

Figure 7. Ripley's *K* point pattern analysis, scaled so that values within the 95% confidence limits around 0 (dashed lines) are randomly distributed, values above the confidence limits are clumped at that lag distance, and values below are regularly distributed.

unaffected by severe drought, although it may have an effect on smaller shrubs and seedlings. This lack of relationship suggests that even earlier data would be needed to provide insight into the conditions that allowed *P. glandulosa* to become established, since that threshold had already been crossed by 1936 (Westoby *et al.*, 1989).

Remote sensing imagery tends to underestimate the number of shrub patches for two reasons. The images do not pick up patches less than the grain size (2 m for these images), and patches closer together than the grain size cannot be distinguished. Physically overlapping shrub canopies are also common, and are difficult to identify in the field and impossible to resolve from aerial imagery. Shrub density is an inappropriate metric for evaluating shrub encroachment; patch density should be reported instead (Ansley *et al.*, 2001).

Small shrubs contribute proportionately less to total cover than large shrubs, so image grain size affects canopy cover measures less than it does patch number estimates. Our estimates of canopy cover based on image analysis and on ground measurements were nearly identical for the October 1996 photo and the September 2001 field measurements. There were very few small shrubs in the area measured, so the value for canopy cover was based almost entirely on large shrubs which could be identified in the imagery. In a similar study of shrub cover in Texas, analysis of aerial images gave a lower estimate of canopy cover than a line transect (41·9% *vs.* 38% in a control area) because small shrubs were common (Ansley *et al.*, 2001).

The life table results support our assertion that poor image quality explains the low cover and number of shrubs in the images from the 1960s, since the total 60 years time span showed little mortality in large shrubs. A study of archival photographs suggested that *P. glandulosa* shrubs are able to live at least 100 years (Bowers *et al.*, 1995). Because these estimates are based on image analysis, we can only assert that there was a shrub in the same spot in two images, not that it was the same individual. Examination of the images shows that many shrub patches are distinctively shaped, so although this was not quantified, we believe that most shrubs listed as being stable in the life table (Table 3) were actually the same individuals. Although large individuals of *P. glandulosa* can be quite stable, seedling survival in this species has been observed to be low. In an earlier study of *P. glandulosa* on the Jornada, only 19% of seedlings that germinated in 1989 were still present in 1990 (Gibbens *et al.*, 1992).

The results of our analysis of shape complexity were unexpected based on a previous study (Ansley *et al.*, 2001). Single shrubs tend to be nearly round, the simplest possible shape, so shortly after establishment the MSI was low. When canopies of adjacent shrubs overlap form a single patch, they have a more complex shape. The MSI is expected to increase over time as shrubs grow and coalesce, forming irregular large patches. The surprising feature of this curve was the decline in later years—after aggregate patches form, they continue to grow and fill in, so that the patch as a whole again tends toward a simpler (rounder) shape. Changes in patch shape could affect wind erosion and deposition patterns.

This study illustrates the importance of observing spatial pattern over time rather than as a single snapshot. In early years of shrub establishment, shrub patches were clumped around dispersal foci, and in later years the pattern moved toward regularity at longer distances. A single image would show only one of these patterns, possibly leading to erroneous conclusions about the causes of spatial pattern. This temporal dynamic has been assumed to reflect the increasing importance of competition as shrubs mature (Anderson, 1971; Phillips & McMahon, 1981). An analysis using estimates of individual shrub centers instead of patch centroids produced very similar results, so the observed change in spatial pattern was probably not due to overlapping adjacent shrubs, as has been suggested by Cox (1987).

Conclusions

The use of high-resolution remote sensing imagery allowed us to examine one site over time, and revealed nonlinear changes in population dynamics and spatial pattern that would not otherwise have been identified. The major drawbacks to the use of these remotely sensed images for this project included the inability to track seedlings and small shrubs, and the strong effect of image quality on our estimates of *P. glandulosa* cover and numbers. Estimates of canopy cover are more robust than estimates of number. Most of the non-Corona images were taken after the growing season, so seasonal variation is unlikely to be a major source of error. The semi-manual agglomerative method proposed here gave more sensible results than the thresholding method frequently used for shrub identification. The U.S. Department of Defense satellite imagery that is gradually being made available to scientists can be a useful tool for ecological research when its limitations are understood, although some products are not suitable for detailed vegetation analysis.

Precipitation, grazing intensity and lack of fire have been identified as the most important agents of vegetation change in semi-arid rangelands (Rodriguez Iglesias & Kothmann, 1997). All of these have been implicated in the increase of shrubs in the south-western United States and elsewhere (Archer, 1994; Van Auken, 2000). Now that accurate methods for tracking shrub invasion in grasslands using remotely sensed imagery have been developed, it will be possible to extend these analyses over larger heterogeneous regions to relate the pattern and dynamics of shrub invasion to soils, geomorphology and grazing history. This knowledge is essential to the proper management of these systems, so that we can preserve remaining grasslands and begin to remediate shrub-encroached areas. It will also improve our ability to accurately predict responses to environmental change and to biotic introductions (Diaz *et al.*, 1999; Wilson, 1999).

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