MULTI-TEMPORAL SPATIAL MODELLING OF NOXIOUS WEED DISTRIBUTION USING HISTORICAL REMOTE SENSING IMAGERY

T.P. Robinson[a] and G. Metternicht[b]

Department of Spatial Sciences
Curtin University of Technology
GPO Box U 1987
Perth WA 6845
[a]Email: T.Robinson@curtin.edu.au
[b]Email: G.Metternicht@curtin.edu.au
Tel: 9266 3935; Fax: 9266 2703*[*]

ABSTRACT

In order to develop coherent management programs aimed at halting and restoring the conversion of grassland to woodland it is necessary to identify, among other data prerequisites, the rate of change. We used a technique based on segmentation and unsupervised classification to extract vegetation in a mesquite dominated area from a temporal dataset of aerial photography. To quantify the rate of recruitment, mortality or coalescence in a temporal study of mesquite, the following metrics were used: patch density (PD); mean patch size (MPS); mean nearest neighbour distance (MNND); mean patch shape index (MPS). We determined that encroachment is continuous, with the fastest rate occurring in the period from 1970 to 1993 (54 ha per year). The rate of encroachment was less (25 ha per year) in the period from 1993 to 1998, however, this implies that if this rate continues then control methods would need to remove 25 ha per year just to nullify encroachment. An attempt to relate precipitation to the increase in plant cover proved difficult because of the irregularity of the rainfall and the large temporal spacing between the imagery.

INTRODUCTION

Originally introduced to Mardie Station in the 1930's as a shade and fodder plant, mesquite (*Prosopis* spp.) has since become an aggressive invader, infesting thousands of hectares of potential grazing land. Whilst the plants showed little tendency to spread at first, the first major outbreak is said to have followed the wet season of 1945 and then proceeded to spread further in favourable seasons (Meadly, 1962). Today, mesquite is a weed of national significance to Australia for several reasons: It is still persistently increasing both by new recruitment into existing grasslands and from the coalescing of older stands into thickets; its surface roots compete strongly with grasses which soon disappear from around the trees which in turn causes a deterioration of the grazing value of the pastoral country; thicket formation, combined with its large thorns (some three inches long) prevent stock from accessing watering holes and make mustering difficult; the conversion of grassland into woodland causes accelerated erosion; and their long lateral roots (more than 30 m), and deep taproots (up to 80 m) alter the hydrology of the ecosystem (Agriculture & Resource Management Council of Australia & New Zealand, (2001); Meadly, 1962).

The conversion of grasslands into woodlands is a worldwide concern (Archer, 1995; Whiteman and Brown, 1998). Factors regulating the balance between the two have been much debated. However, it is generally agreed that a significant cause seems to be the reduction of grass biomass from high levels of domestic herbivory, coupled with a reduction in grassland fires, which would kill young seedlings to the advantage of grasses (Van Auken, 2000). The introduction of cattle and other domestic livestock are viewed as factors involved in modifying the rate at which grasslands have transformed into woodlands, with such animals eating the palatable pods, scarifying them either by mastication or by passage through the digestive tract and then voiding them some distance from the parent plants in a moist, nutrient rich dung conducive for germination and establishment (Brown and Archer, 1987; Brown and Archer, 1989). Altered precipitation and temperature patterns, as well as increased levels of atmospheric carbon dioxide may also play some role, although there have been no conclusive findings (Van Auken, 2000).

Regardless of the cause, the altered ecological state makes conversion back to grasslands difficult and thus requires the development of logical, timely, well-directed and costed management strategies. However, such strategies can not be developed without several data prerequisites such as: Knowledge of the severity of the problem in terms of its extent and intensity; an accurate description of the rates of shrub invasion; reliable inferences about proximate causes of the process; and a means of prioritising management actions and targeting control technologies at subpopulations (e.g. high seed producing plants) critical to the maintenance of the larger population (Whiteman and Brown, 1998). Additionally, follow up monitoring to assess the performance of various control techniques must be made in a timely manner.

In order to generate the information required for developing control strategies, an effective and relatively low cost method of mapping the weed over large areas is required. To this end this paper focuses on quantifying the rate at which mesquite increased from 1957 to 1998 (prior to the introduction of biological control, see Section 3.1) using multi-temporal panchromatic aerial photography. The second objective is to relate precipitation to the relative increase or decrease of mesquite and hence assess its role as one of the possible causes of ongoing mesquite establishment.

REVIEW OF AERIAL PHOTO CLASSIFICATION SCHEMES

A study on the temporal effects of shrub invasion that pre-dates satellite remote sensing has little choice but to use panchromatic aerial imagery. Such imagery has excellent spatial resolution, but unfortunately provides limited spectral information for classification of vegetation types (Goslee et al., 2003). Due to this limited spectral information, researchers have often implemented what they consider the best technique for the size and density of their study area.

For example, manual delineation of shrub canopies (e.g. Ansley et al., 2001) avoids the need for detailed spectral information, however, is impractical for studies of more than a few hectares due to the person-hours involved in their capture via digitisation. It can also prove inadequate if the shrub canopy is too sparse or small to be easily resolved (Hudak and Wessman, 1998). Researchers wanting to study larger areas and over a greater time-slice have often adopted more automatic techniques such as thresholding (e.g. Lahav-Ginott et al., 2001; Hutchinson et al., 1999) and techniques designed to augment thresholding (Whiteman and Brown, 1998; Anderson and Cobb, 2004). These techniques are relatively simple to implement and in many cases can prove to be reasonably accurate, as reported in the studies mentioned.

However, for complicated environments (e.g. where there is a large variability in the background from competing vegetation and soil) the chosen threshold value may not be appropriate for the entire region. For example, Goslee et al. (2003) found that thresholding returned large areas of background while simultaneously missing many of the shrubs under study. In order to overcome the shortcomings of the thresholding technique, Goslee et al. (2003) present an algorithm whereby each shrub is marked by a point which is then automatically expanded outward until an edge difference is found. While this technique is semi-automatic, thus an improvement on manual delineation, it would still take considerable person-hours to mark every individual shrub for studies over large and/or very dense areas (e.g. their study was restricted to 75 ha).

Laliberte et al. (2004) implement the fractal net evolution approach (FNEA) for mapping mesquite from panchromatic datasets (e.g. aerial photography and QuickBird imagery). FNEA utilises fuzzy set theory to extract the objects of interest, at the scale of interest, by first segmenting the image at both fine and coarse scales, simultaneously. Initially the image is segmented based on three parameters (scale, colour and shape) and classification is then performed on these objects, rather than the single pixels (Hay et al., 2003; Laliberte et al., 2004). A comparison between a simulated pixel based analysis and the results obtained from FNEA showed that the former method overestimated shrubs in dark background areas and underestimated shrubs in lighter areas, unlike the FNEA technique which could account for the varying backgrounds by assigning two fuzzy membership functions to them (Laliberte et al., 2004).

Other methods used for aerial photo classification of vegetation include textural analysis (Hudak and Wessman, 1998), segmentation methods (Haara and Nevalainen, 2002; Uuttera et al., 1998), unsupervised clustering algorithms such as ISODATA (e.g. Manson et al., 2001) and supervised methods such as the maximum likelihood classifier (e.g. Kadmon and Harari-Kremer, 1999). These techniques have the advantages of being embedded in most image processing software packages and their relative speed and minimal user interaction mean they can be used on large areas.

MATERIALS AND METHODS

Study Area

This research was conducted on a 26,230 ha portion of the mesquite infestation found on Mardie Station (21^{0}11’18’’S, 115^{0}56’57’’E), in the Northwest Pilbara of Western Australia, as shown in Figure 1. The main mesquite taxa in this area include *P. glandulosa* x *P. velutina*, *P. julifora* and *P. pallida* x *P. glandulos* var *torreyana* (van Klinken and

Campbell, 2001). Most of these usually grow as thorny shrubs about 3 – 5m high; however, *P. pallida* has a tree-like appearance and can grow to 15 m in height (Osmond et al., 2003). This is the worst infestation in Australia, with mesquite being the dominant species in the area today. As such, this study was restricted only to this infestation to limit misidentification of species. Average rainfall over the last 68 years is about 120 mm, with approximately 48% falling between February and May. Mean maximum monthly temperature ranges from 26^0 C in July to 37^0 C in December.

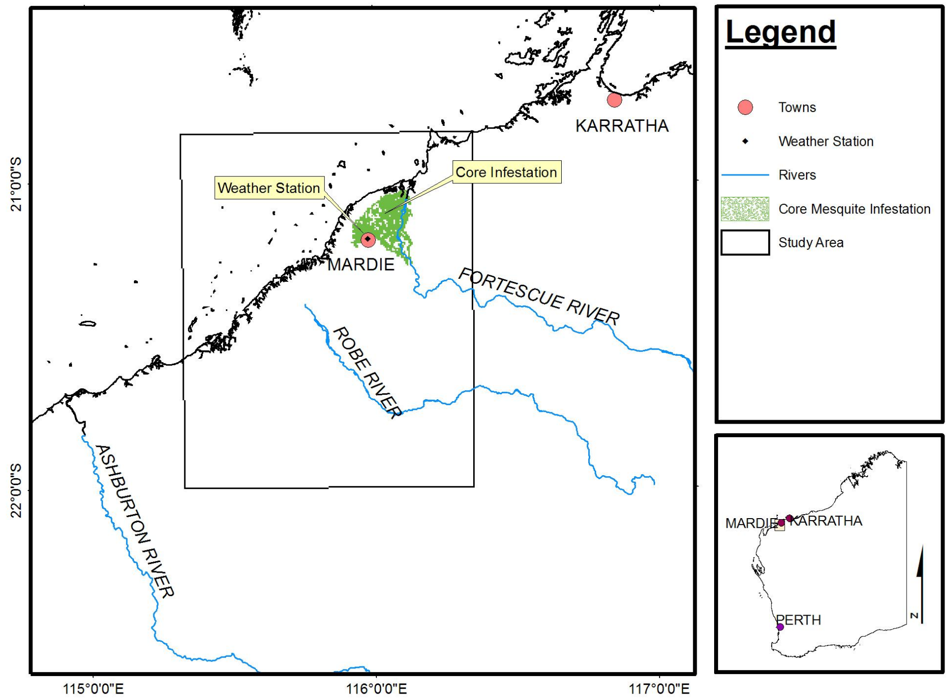


Figure 1: Study Area Location. The bounding box represents the study area for on-going research, whilst this study was restricted to the core infestation.

Various methods of control have been implemented over several decades (since 1952), each with their own advantages. These include chemical spraying, which is useful on young shrubs and isolated outbreaks, and chaining and blade ploughing, both more useful over larger areas. Budgetary considerations mean these techniques are applied sparingly and all efforts to date have not succeeded in preventing its spread or recovering any land previously lost to it (Osmond et al., 2003). A biological control agent, the leaf-tying moth (*Evippe* sp.) was introduced in 1998 and has rapidly established causing a reduction of foliage cover by more than 50% and has significantly reduced pod production (van Klinken et al., 2003). A trial is currently underway to integrate mechanical control with the strategic use of fire, to find the best strategy to optimise fuel loads to generate fires of sufficient intensity to kill fire-tolerant mesquite (Osmond et al., 2003).

Aerial Photography Dataset

Aerial photographs of the study site were obtained from the Department of Land Information, Western Australia. Four sets of black and white photography plus one orthophoto mosaic were selected: September 1957 (1:40,000); December 1967 (1:90,000); August 1970 (1:40,000); September 1993 (1:50,000); and the orthophoto mosaic was acquired August 1998 (1:25,000). In total, 57 photographs were required to cover the study area over the five decades. All photographs were scanned at a resolution of 600 dpi using a simple desktop scanner (Canon N640P ex). Each image was then rectified to the orthophoto mosaic and rescaled to 1.4 m resolution using nearest neighbour resampling so that cells coincided with the same resolution as the orthophoto.

Image Analysis

Due to the large extent of the study area, a method that could classify mesquite with minimal user interaction was required. Based on the literature review, this includes thresholding (and its variants), the fractal net evolution approach (FNEA), unsupervised clustering algorithms such as ISODATA, and supervised methods such as the maximum likelihood classifier. Experimentation of the thresholding technique found it to be inadequate for our purposes as it was difficult to identify a threshold suitable for all shrubs, thus some shrub canopies were overestimated (errors of commission) and others were underestimated (errors of omission).

We implemented a technique based on the principles of segmentation and the ISODATA unsupervised clustering technique. The procedure adopted is shown in Figure 2. Firstly, as the unsupervised classification technique requires relatively homogenous class values throughout (Anderson and Cobb, 2004) the images were clipped so that overlap was small and so the degrading quality at the edges of the photos was minimal. The alternative is to calibrate all images to a master image so that the between image variance is kept to a minimum but this relies heavily on developing a strong linear relationship between image pairs, and thus can be no better than processing image by image and concatenating the results post-classification.

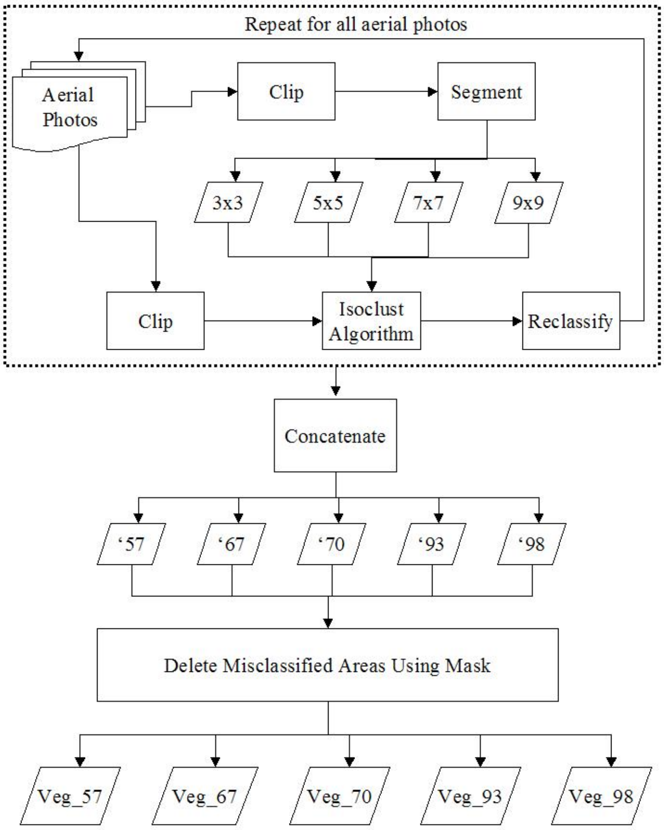


Figure 2: Methodology implemented to classify aerial photographs. Note: The 'clip' process is identical and has only been redrawn to simplify line-work.

Segmentation produces categories of similarity by grouping pixels with similar standard deviations together. Various filter windows can be used from which standard deviation is based. Additionally, a threshold value is used to determine the tolerance for which pixels with a similar standard deviation will be grouped together (Eastman, 2004). We chose to produce segmentation images of the clipped aerial photographs using various window sizes (e.g. 3x3, 5x5, 7x7 and 9x9) with a unique threshold value for each image, chosen so that approximately 5 classes (segments) were determined for each image (found by trial and error). This process added further dimensions to the data by incorporating images of homogeneity, thus adding efficacy to the unsupervised iterative self-organising cluster analysis (ISOCLUST) classification process. The original aerial photograph and the four segmented images were used in the classification process (performed in IDRISI 14.02 Kilimanjaro) with three iterations and the retaining of five clusters. Clusters that were classed as vegetation (usually one class, but rarely two classes were required to be aggregated) were then extracted via reclassification to form a binary image. After all photos of a particular year were processed in this manner the results were concatenated to form a single image.

Visual assessment of this technique over many randomly chosen areas of the images suggested it works well at classifying vegetation in the aerial photographs. However, there were occasions where riverbanks were classified as vegetation because the technique could not differentiate between the digital numbers of the two cover types. To overcome this situation, a mask was developed via screen digitising so that all rivers were excluded from the final results and was applied using map algebra. It should be noted that the technique used was not able to discriminate between the different species of mesquite in the area, nor that of any other vegetation type, an extremely difficult proposition with panchromatic imagery. Nonetheless, the aim of this study was to mimic the changing dynamics of the area, hence the classification accuracy is suitable for this purpose. Furthermore, statistics (as described in Section 3.4) should not be overly affected by the addition of the more static vegetation types such as Eucalypt, which are not invasive (van Klinken, 2004).

Statistical Analysis

A landscape analysis software program (FRAGSTATS v.3.3) was used to quantify the spatial dynamics of mesquite canopy patches over time. A patch was defined as all cells contiguous in any of eight directions. Therefore, it should be recognised that we are not reporting individual mesquite shrubs where canopies are joined by at least one cell. Statistics computed include class area (total area occupied by vegetation), patch density, the mean patch shape index and the mean nearest neighbour distance. Class area is defined as the sum of the areas (m^2) of all patches divided by 10,000 to convert it to hectares; patch density is defined as the number of discrete mesquite areas per hectare; mean nearest neighbour distance is the average edge-to-edge distance (m) from each patch centroid to its closest neighbour's centroid; mean shape index was used to quantify the shape complexity and equals one for a patch with the simplest raster shape, a square, and increases (unbounded) when the shape of a patch becomes more complex (McGarigal and Marks, 1995).

The number of hectares invaded per year was calculated by subtracting the class area of an earlier acquisition date from that of a later acquisition date and dividing this amount by the number of months, converted to years, between them (Ansley et al., 2001). Similarly, since images have irregular temporal spacing, all metrics presented in the graphs shown in Figures 4, 5 and 6 were rescaled by year by linearly interpolating the difference between two acquisition dates over that timeframe. For example, the nearest neighbour distance changed from 8.76 m in 1957 to 7.96 m in 1967, which is a difference of 0.08 m per year, over the ten years; hence 1958 is assumed to be 8.76 m minus 0.08 m, or 8.68 m, 1959 is assumed to be 8.68 minus 0.08 or 8.61 and so on.

RESULTS AND DISCUSSION

Figure 3(a) to (g) depicts the outputs from the classification methodology. Figure 3(a) is a portion of the 1998 orthophoto mosaic; Figure 3 (b) to (e) are outputs from the segmentation process using windows of 3x3, 5x5, 7x7, and 9x9, respectively. The segmented image, using a 3x3 window, classifies vegetation as 'segment 3'; vegetation is a mixture of 'segment 3' and 'segment 4' after using the 5x5 window; and 'segment 4' and 'segment 5' characterise vegetation when the 7x7 and 9x9 windows are used. The results of using the orthophoto mosaic and the four segemented images in the ISOCLUST algorithm (Figure 3 f) show vegetation to be classified as 'class 2'. Therefore, in this particular case, a binary layer was then created by retaining only pixels classified as 'class 2' (figure 3 g). All other pixels were set to '0'. All subsequent photos were processed in a similar manner and concatenated to form one binary image for each acquisition date. Such images were then used as input into the landscape analysis software program.

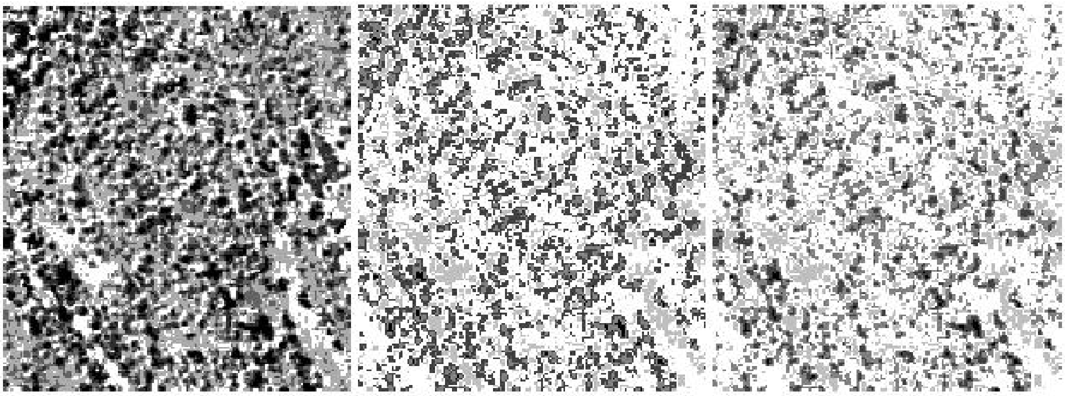
Figure 4 shows precipitation from 1930 to 1998 to be highly variable between years (coefficient of variation = 50.97%, n = 68 years), with the trend suggesting it is drier today than it was in 1930. Many of the peaks above average often coincide with tropical cyclones in the area, e.g.: 1934, 1945, 1961, 1965: Cyclone Joan, 1973: Cyclone Kerry, 1989: Cyclone Orson, 1995: Cyclone Bobby (Bureau of Meteorology, 2005). Over the duration of the 41-year period of this study (1957 to 1998), 12 years had above average rainfall, and 29 years were below average. Average annual precipitation from 1957 to 1967 was 134 mm, or 11.6% above the long-term average. At the same time mesquite was encroaching at a rate of approximately 9 ha per year. Class area (total area occupied by non-grass vegetation) was 250 ha. Average annual precipitation from 1967 to 1970 was 146 mm, or 21% above the long-term mean, with mesquite advancing at a rate of 44 ha per year during this timeframe; class area at this time was 342 ha.

From 1970 to 1993 the average rainfall was 98 mm, 86% of the long-term mean, however, this relatively dry period failed to curb its invasiveness, accelerating at a rate of 54 ha per year. Average or above average rainfall appears more common prior to 1970, and since that time above average rainfall has only been achieved three times, and all of those events were influenced by tropical cyclones as detailed above. Twelve out of the 23 years had rainfall at less than 75% that of the long term mean, and could be defined as drought years (Laliberte et al., 2004) and six of these occur between the years 1981 and 1987, which may be seen as a period of prolonged drought. It is possible that this period of relative dryness may have been a period where grasslands failed to survive and when mesquite capitalised, however, no images could be located for this timeframe, so it is difficult to define exactly what effect this had on mesquite and grasses in the area. By 1993 the total area occupied was 1705 ha.

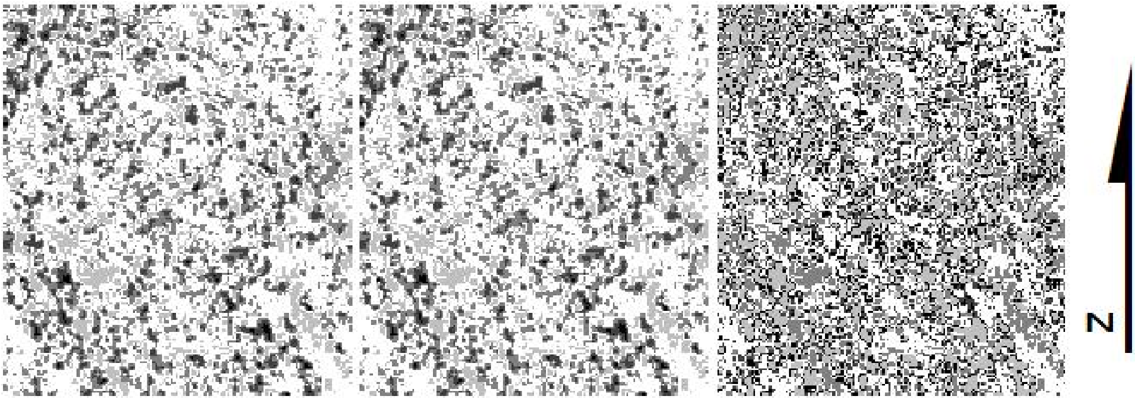
From 1993 to 1998 average annual precipitation was 120 mm, approximating the long-term mean. Interestingly, encroachment appears to be slower during this timeframe than the previous 26 years, increasing at a rate of 25 ha per year. This relative slowing may be the result of space and resources becoming more limiting (Ansley et al., 2001);

however, it is impossible to be sure without a follow up study. The number of hectares occupied by 1998 was 1828 ha or 7% of the study area.

a) Orthophoto b) Segment 3x3 c) Segment 5x5



d) Segment 7x7 e) Segment 9x9 f) ISOCLUST Results



g) Binary Image of Veg.

Figure 3: a) The original 1998 orthophoto mosaic; segmentation images using a 3x3 (b) , 5x5 (c), 7x7 (d) and 9x9 (e) window, respectively; f) results of using segmentation images and the orthophoto mosaic as input into the ISOCLUST algorithm; g) the final classification map of vegetation.

In addition to assessing the rate of encroachment according to class area statistics, other processes can be described by patch density (PD), mean patch shape (MPS) and the mean nearest neighbour distance (MNND). According to Ansley et al. (2001), changes in temporal dynamics can be influenced by three processes: recruitment of new patches, the coming together (coalescence) of existing patches, and mortality. The latter is the only process that could cause a decrease in patch density. In general, single shrubs tend to be nearly round, so shortly after establishment the MPS is low, but when shrub canopies begin to coalesce the shape complexity rises until they have come together entirely, forming once again a simpler shape (Goslee et al., 2003). The MNND would decrease if recruitment was frequent and only increase if mortality was higher than recruitment.

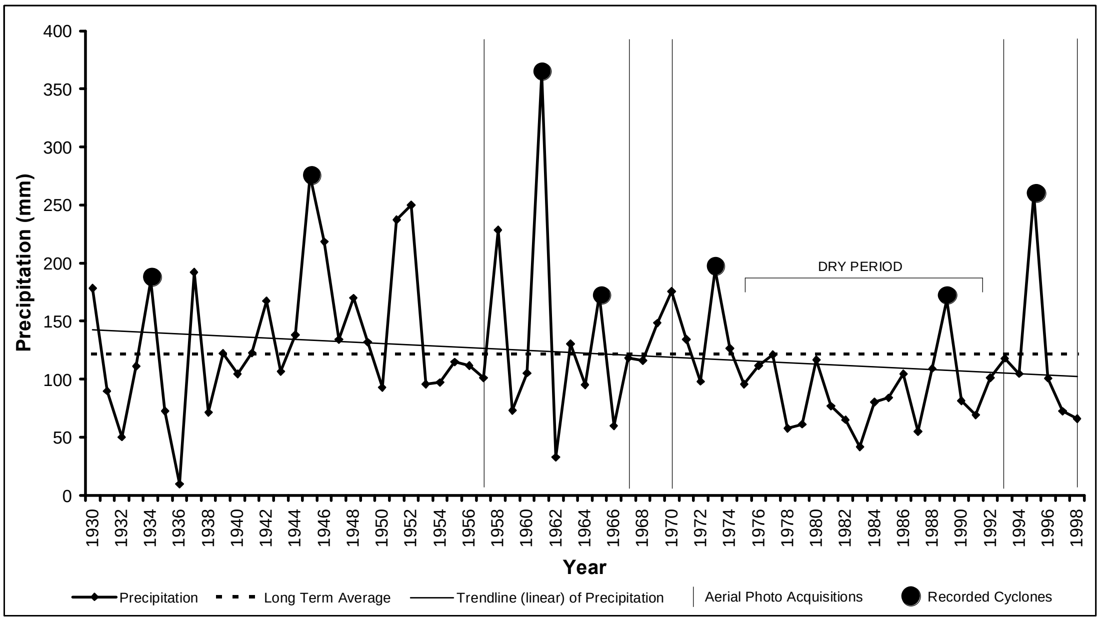


Figure 4: Annual precipitation from the Mardie weather station from 1930 to 1998.

Figure 5 illustrates consistent increases in patch density over the timeframe of the study, characteristic of continuous recruitment. The slowest period of recruitment appears to be as mesquite is beginning to establish itself (1957 to 1967), but from that time the number of mesquite patches per hectare increases almost linearly. As mentioned by Goslee et al. (2003), studies of this kind tend to underestimate shrub patches because the images do not pick up patches less than the grain size of the aerial photograph (1.4 m). Furthermore, by definition, a patch are any contiguous cells in eight directions, hence any coalesced shrubs are counted as one shrub. In 1998, a patch density of 5333 was found, which implies that there are at least that number of shrubs per hectare in the study area and plausibly numerous more.

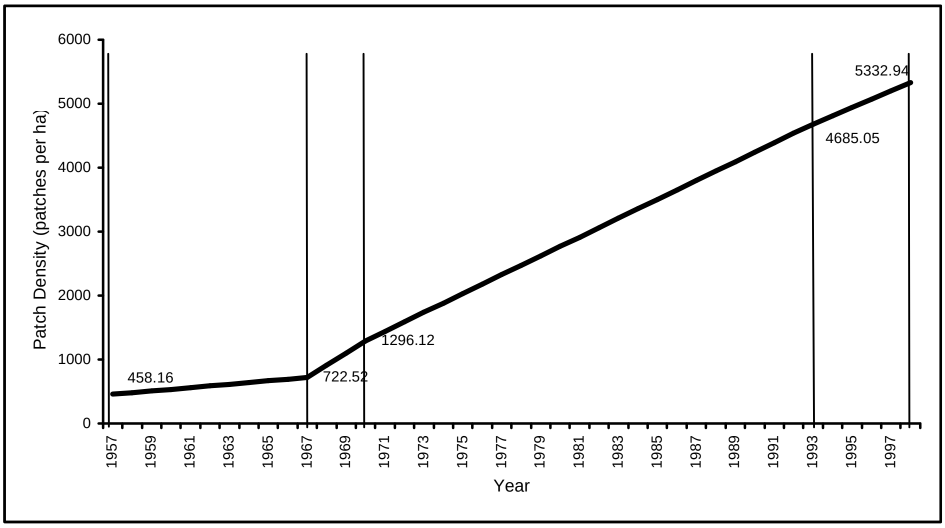


Figure 5: Patch Density – The number of patches per hectare.

Mean patch shape, as shown in Figure 6, showed very little significant change over the duration of the study. It is assumed that the rate of recruitment at all times was such that it balanced out the increasing shape complexity of any coalescing shrubs. Perhaps the use of this metric over such large areas is limited given the three processes are operating at the same time and hence averaging can have a considerable impact on the result. Used in more localised studies it could help explain and predict the patterns of wind erosion and deposition patterns (Goslee et al., 2003). Figure 7 shows that the nearest neighbour distance decreased almost linearly over the timeframe of the study, consistent with the linear increase in patch density. This is indicative of steady recruitment and/or coalescence over the study period, with any mortality not affecting this rate.

Figure 6: The mean patch shape index – A measure of shape complexity.

Figure 7: Mean nearest neighbour distance – The average edge-to-edge distance from patch centroid to its closest neighbour's centroid.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

The use of archival aerial photographs permitted the assessment of the processes involved in the conversion of grassland to shrubland and quantitatively defined invasion rates. An attempt to relate the rate of change to precipitation appears unfounded, with frequent episodic rainfall from tropical cyclones significantly affecting year-to-year averages and long-term trends. Furthermore, the highest rate of encroachment was recorded over a period that contained several years of continuous drought. As mentioned, the effect this drought period had on seedlings is not known, but its effect on established stands seems to be minimal. Additionally, the slowest rate of encroachment occurred in a period of above average precipitation (1957 to 1967). To further investigate the effect of precipitation, research into the amount of soil moisture required for seedling establishment is required.

Our results suggest that shrub encroachment has been continuous over the duration of the study, with high rates of increase occurring since 1967. Even at the rates observed in 1998 (25 ha per year), the continued conversion of grassland into shrubland may be irremediable without substantial efforts designed to control and confine it. If the rate found in the more recent period approximates today's level of encroachment then this implies that control methods aimed at destruction would need to eradicate a similar amount to keep the infestation at an idle state. More knowledge needs to be derived from the temporal dataset created to assist developing control methods aimed at containment, such as a detailed awareness of the periphery of the core infestation and how fast this is changing over time.

Furthermore, the effects of grazing and grazing history (in terms of head of cattle per year) need to be quantified. If cattle are deemed the most efficient vector of spread then their movement will need to be controlled, with the possible exclusion of such animals from heavy seed producing areas (Brown and Carter, 1998). Developing causative inferences from various factors (e.g. distance to water courses, aspect, elevation, landforms) would enable the construction of models representing the weeds preferred habitat. Such a map could be used to prioritise management and assist the timing of follow up control.

Finally, the techniques presented here can be readily transferred to assess the relative efficiency of the various control techniques such as fire, chaining, blade ploughing or combinations of these. To this end, after control methods are implemented, it is imperative that imagery be acquired at regular anniversary dates.

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