Detection, Quantification and Monitoring of *Prosopis* in the Northern Cape Province of South Africa using Remote Sensing and GIS

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Abstract

Invasive Prosopis species pose a significant threat to biodiversity and ecosystem services in the Northern Cape Province of South Africa. The objective of the study was to use Remote Sensing and Geographical Information System (GIS) techniques to: (i) reveal areas susceptible to future invasion, (ii) describe the current extent and densities and, (iii) reveal the spatial dynamics of Prosopis over the past 30 years in the Northern Cape. Image classification products were generated using spectral analysis of seasonal profiles, various resolution image inputs, spectral indices and ancillary data. Classification approaches varied by scene and spatial resolution as well as application of the data. Coarse resolution imagery and field data were used to create a probability map estimating the area vulnerable to Prosopis invasion using relationships between actual Prosopis occurrence, spectral response, soils and terrain unit. Multi-temporal Landsat images and a 500m x 500m point grid enabled vector analysis and statistical data to quantify the change in distribution and density as well as the spatial dynamics of Prosopis since 1974. Fragmentation and change of natural vegetation was quantified using a combined cover density class, calculating patch density per unit (ha) for each biome. The extent of Prosopis cover in the Northern Cape Province reached 1.473 million ha or 4% of the total land area during 2007. The ability of the above mentioned remote sensing and GIS techniques to map the extent and densities of Prosopis in the study area demonstrated a high degree of accuracy (72%).

1. Introduction

Alien plant invasions have a major impact on biodiversity, ecosystem services, agriculture, forestry, the economy and human welfare. The genus *Prosopis* (Fabaceae) is one such invasive and four of the species, *Prosopis velutina*, *P. glandulosa* var. *glandulosa*, *P. glandulosa* var. *torreyana* and *P. chilensis* has invaded and is continuing to invade vast areas of rangelands in South Africa. Riparian habitats in many parts of South Africa are severely degraded by invasive alien species, especially tree communities on the river banks. These invasions reduce water yields from catchments and affect riverine functioning and biodiversity. In the arid environments the widespread replacement of *Acacia* dominated habitats by alien *Prosopis* has radically changed the habitat for birds, leading to reduced species richness and diversity (Dean *et al*., 2002). Studies have shown that invasive alien plant species can directly or indirectly affect the food security of local communities (Admasu, 2008). In areas where they spread, such as the Northern Cape, invasive species can destroy natural pasture, displace native trees and reduce grazing potential of natural rangeland (Admasu, 2008; Van Wilgen *et al*., 2008; Visser 2004).

There is evidence that *Prosopis* has spread at an alarming rate over the past decades (Visser, 2004, Hendeson 1998). However, the rate and spatial extent has never been accurately quantified due to the vastness of the potential area invaded and inaccessibility to many of the invaded areas. The availability of long-term archives with remotely sensed data and image processing techniques provides a cost- and time-effective means of mapping and monitoring invasions such as that of *Prosopis* (Joshi *et al*., 2003; Lloyd *et al*., 2002). Because of its spatial, temporal and spectral characteristics, satellite data has been very effective in mapping and monitoring the status and distribution of plant communities (Coops *et al*., 2009; Robinson *et al*., 2008). Reliable Invasive Alien Plant (IAP) species distribution data is required at a national and provincial level to assist with policy decisions, the strategic allocation of funding and effective implementation of control programmes.

2. Objective

The objective of the study was to use remote sensing and geographical information system (GIS) techniques to: (i) reveal areas susceptible to future invasion, (ii) describe the current extent and densities and, (iii) reveal the spatial dynamics of *Prosopis* in the Northern Cape Province.

3. Study Area

The vast and arid Northern Cape Province is South Africa’s largest province, covering 363 203 km^2, nearly a third or 30.5% of the country's land area (Figure 1). It is a dry region of fluctuating temperatures and varying topographies. The Northern Cape Province consists of 6 biomes (Mucina & Rutherford, 2006). The northern part is dominated by the Savanna and Desert Biome and the west by the Succulent Karoo Biome. The central part of the province is dominated by the Nama Karoo Biome.

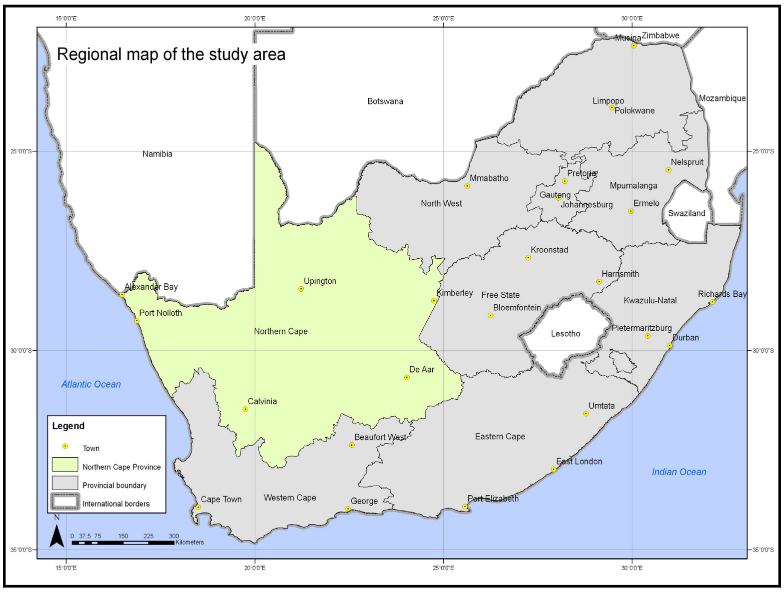

Figure 1: Regional map of the Northern Cape Province of South Africa.

4. Materials and Methods

The flowchart in figure 2 illustrates the workflow and processes that were followed to full fill the objectives of the project.

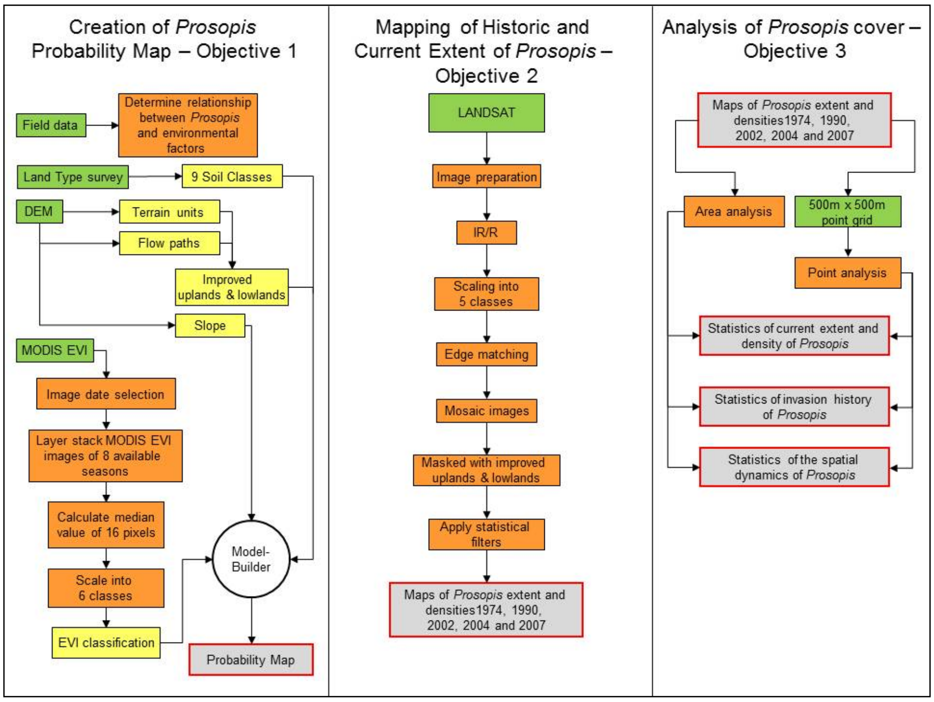

Figure 2: A flowchart illustrating the overall workflow of the project

4.1 Datasets

Selecting the correct scale or resolution of data is important when mapping or predicting the distribution and abundance of invasive alien plant species for understanding and managing of applications and monitoring strategies. For this study, the moderate resolution MODIS (LP DAAC, 2008) data (250 m x 250 m) was used to identify areas of potential invasion. The high resolution Landsat data (25 m x 25 m) was used to more accurately map the historical and current extent, the density and to determine the dynamics of *Prosopis*.

A number of field excursions were undertaken to collect training sites and information representative of different densities of *Prosopis* infestation. At each of the more than 700 training sites, descriptive information was recorded. The field data form recorded the geographical position and information regarding tree height, density and terrain unit for *Prosopis* as well as the two other dominant tree species. Soil attributes recorded included soil colour, clay content and lime stone (calcrete) on the soil surface or subsurface lime stone (hard carbonate). A colour digital photo of the sampling site was also taken for future reference. Since most of the land in the Northern Cape Province is privately owned, access to *Prosopis* infested properties was limited and data was therefore mainly collected alongside roads. During May 2007 an aerial survey was done in areas inaccessible by road to establish the presence and absence of *Prosopis*. Four canopy density classes were used, classified as closed (76% - 100%), dense (51% - 75%), medium (26 % - 50%) and sparse (0% - 25%).

Several existing datasets, including the National Land Type Survey (Land Type Survey Staff, 1972-2006) and NASA's Shuttle Radar Topography Mission (SRTM) (CGIAR-CSI, 2008) Digital Elevation Models (DEMs), were used to create new spatial layers to establish the relationship between the actual occurrence of *Prosopis* using field data, the broad soil patterns and terrain in the Northern Cape. The National Land Type Survey (Land Type Survey Staff, 1972-2006) is the source of information of generalised soil maps of the country.

4.2 Areas susceptible to *Prosopis* invasion

The distribution of plant species in their native area is influenced by a range of environmental factors (Foxcroft, 2002) including soil texture, degree of slope, geology, water availability (including ground water) and climate. For this objective of the study the relationships between terrain unit or landscape position, flow path, slope, soil and spectral vegetation response were used as the criteria to create a map of areas potentially susceptible to *Prosopis* invasion, also called a probability map, for the Northern Cape Province. These relationships were established using extensive field data collected over the whole study area.

According to the National Land Type Survey the Northern Cape has 19 generalised soil classes. Field data suggested that *Prosopis* occurs mainly on nine of these classes with 95% of all field points occurring on red to yellow apedal, freely drained moderate to deep soils with lime present in the landscape. These nine soil classes were extracted and used as one of the input layers in the model to create the probability map. GIS data of riparian zones and field data showed an association of 87% between *Prosopis* and drainage lines and certain terrain units. A terrain unit is any part of the land surface with homogeneous form and slope. Terrain units can be made up of all or some of the following kinds of units: crest (1), scarp (2), mid-slope (3), foot-slope (4) and valley bottom or flood plain (5) (Figure 3) (Land Type Survey Staff, 1972-2006).

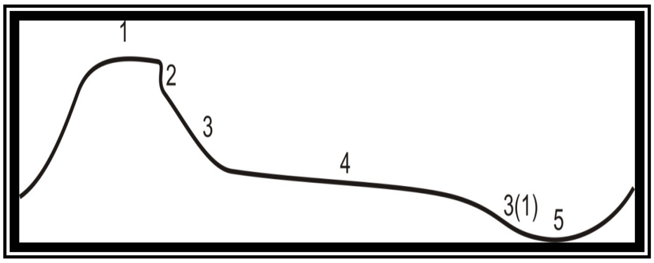

Figure 3: Terrain units, where 1 represents a crest, 2 a scarp, 3 a mid-slope, 3(1) a secondary mid-slope, 4 a foot-slope and 5 a valley.

TNTmips (MicroImages Inc., 2007) software was used to create accurate flow paths and terrain units for the study area using the 90 m DEM data. Terrain units 1 to 3 were merged to create information on the location of uplands and terrain units 4 and 5 were merged to create data on the location of bottomlands. Some small annual rivers were not mapped accurately by the terrain units; these dry riverbeds were included in the dataset using the flow paths created from the DEM data. Level 2 to 10 flow paths were used and individually buffered (25 m to 225 m) according to size, class 10 being the main rivers. By combining the buffered flow paths with the terrain units a new improved upland and bottomland dataset was created. This dataset was used in both the predicting and mapping phases of the project.

MODIS (LP DAAC, 2008) images were analysed to establish the annual phenology patterns of *Prosopis* and other vegetation types to discriminate between *Prosopis*, woodlands, dense and open bushland, shrubland and cultivated fields. Multi-band images were created from the 432 16-day MODIS EVI composites for each of the eight growing seasons. Pixel values for each vegetation cover were extracted from these seasonal images. The median value for each training point was plotted against the multi-band image for every growing season. The median instead of the mean values were used to eliminate outliers in the data set caused by fires and extreme rainfall events.

Results of the time series analysis suggested that the peak time of plant activity is during February to May. It is therefore expected that these bands are more likely to distinguish *Prosopis* from other vegetation types. The EVI images for late February and the beginning of March were selected for each of the eight seasons. These 16 images were layer-stacked to create a thematic image with 16 bands. The median value for the 16 bands was calculated for each pixel in the image. The image was classified into five probability classes, from low (class 1) to high (class 5), using visual interpretation and field data.

The soil, slope and upland and bottomland datasets were similarly coded according to the possibility to find *Prosopis*. The final step in creating the *Prosopis* probability map was to integrate the Modis EVI classification with the soil, slope and upland and bottomland datasets. The different datasets were intersected with each other using the Model Builder in ERDAS Imagine (Intergraph 2012). The model returned a high class value (5) where all input datasets presented a high probability value and a lower probability class value (1) for low probability to find *Prosopis* in the landscape. Range values of the probability map were determined using the percentage correspondence of the field data to the probability class in relation to the area of the total study area. The correspondence with the actual mapped *Prosopis* for 2007 was also calculated.

4.3 Mapping the actual and historic extent of *Prosopis* using Landsat images

After initial assessment, it was conclusive that late summer (February to April) images would be best suited to map *Prosopis*. Landsat images (FAO, 2000; CSIR-SAC, 2008) for five different assessment years (1970, 1990, 2002, 2004 and 2007) were sourced and othorectified to the same level of spatial accuracy.

The large geographical extent and variation in vegetation, landscape and climate demanded the use of a semi-automated procedure for the mapping of *Prosopis*. A two-step procedure was implemented. Firstly, all images were processed using the Simple Ratio (SR) vegetation index (Jordan, 1969) of Near Infrared/Red (NIR/R) where values on the lower end of the classification (0 to 1.1) were associated with vegetation of low green biomass or chlorophyll concentration such as vegetation of the Bushmanland Nama Karoo (Low & Rebelo, 1996). Values on the higher end of the classification (1.2 to 2.0) were associated with vegetation of high green biomass or chlorophyll concentration such as *Prosopis* or savanna vegetation. Discriminating between *Prosopis* and some woody vegetation was not achieved completely. The NIR/R index did, however, discriminate between much of the drier Savanna and Nama Karoo (Low & Rebelo, 1996) shrubland vegetation. The influence of geology and soil colour was also eliminated by the index. The IR/R images were not scaled according to fixed predetermined values and therefore know atmospheric correction was made. Change over time was instead determined between each mosaiced classification and not individually between images for two main reasons, namely (i) the variation in image dates and (ii) the variation in environmental conditions over the study area. Each individual image was therefore scaled manually into five density classes using visual interpretation, the field data points and expert knowledge. Care was taken to correct the classification at the seams of adjacent images in the mosaic. The subsequent step was to further remove areas not associated with the occurrence of *Prosopis*. The same intersecting procedure used with the probability map was implemented using the upland and bottomland datasets.

Two statistical filters were applied to the raster data. In these filters, the centre pixel of the moving window is replaced by the predefined value (mean, median or maximum) of all the pixels within the window (ERDAS Field Guide, 2008). Firstly, a 3 x 3 maximum filter was applied, to assist in the connection of isolated pixels which formed part of linear features such as rivers. Secondly a 3 x 3 median filter was applied to filter out single pixels which created a salt and pepper effect.

4.4 Analysis of the spatial dynamics and extent of *Prosopis* using Landsat data

The invasion history and spatial dynamics of *Prosopis* were analysed using the historic classification layers of the extent of *Prosopi*s invasion. Two methods were used to describe the invasion history and change in *Prosopis* cover since 1974. Firstly, an area comparison of cover and rate of change between 1974 and 2007 was done. Spatial analysis was done using a 500 m x 500 m point grid. The point grid was intersected with the *Prosopis* classification layers of the five assessment years to extract density and presence/absence data values to determine change through time. The riparian dataset and point grid information were used to establish the dispersal pattern of *Prosopis* in the riparian as well as outside the riparian zone.

Certain processes have been reported to influence changes in *Prosopis* cover. These include the recruitment of new plant patches, coalescence of expanding patches and the mortality of *Prosopis* plants (Ansley *et al*., 2001). To assist in the process of determining the dynamics of *Prosopis* in the study area between 1990 and 2007, three landscape metrics were computed: (i) the average distance to nearest patch from cell centre to cell centre, (ii) patch density per 10,000 ha and (iii) the increase or decrease in patch density.

4.5 Accuracy assessment of classifications

The accuracy assessment data was collected from two independent datasets, the NLC2000 (Van den Berg *et al*., 2008) and National Alien Invasive Plant Survey (NAIPS) databases (Kotze *et al*., 2009). The accuracy assessment data for this study was compiled by merging the selected points from these two datasets. A total of 1,849 points were used for accuracy assessment of the 2007 *Prosopis* classification through establishing the presence and absence of *Prosopis* on the classified map.

5. Results

5.1 Areas susceptible to invasion

Soil and position in the landscape are of equal importance to the distribution of *Prosopis* and the spectral vegetation response was combined with these factors to successfully create a map of possible occurrence of *Prosopis* in the landscape for the Northern Cape Province. The overall correspondence with the mapped *Prosopis* of 2007 was calculated to be 70%. Table 1 summarises the calculated areas of each probability class as well as the range values of each class.

Table 1: Area estimations of probability map

Probability class	Range value (%)	Area (ha)
1 Very Low	0-15	3,018,131
2 Very Low to Low	15-30	1,314,916
3 Low to Moderate	30-55	2,322,658
4 Moderate to High	55-80	950,348
5 High	80-100	389,042
Total area		7,995,095

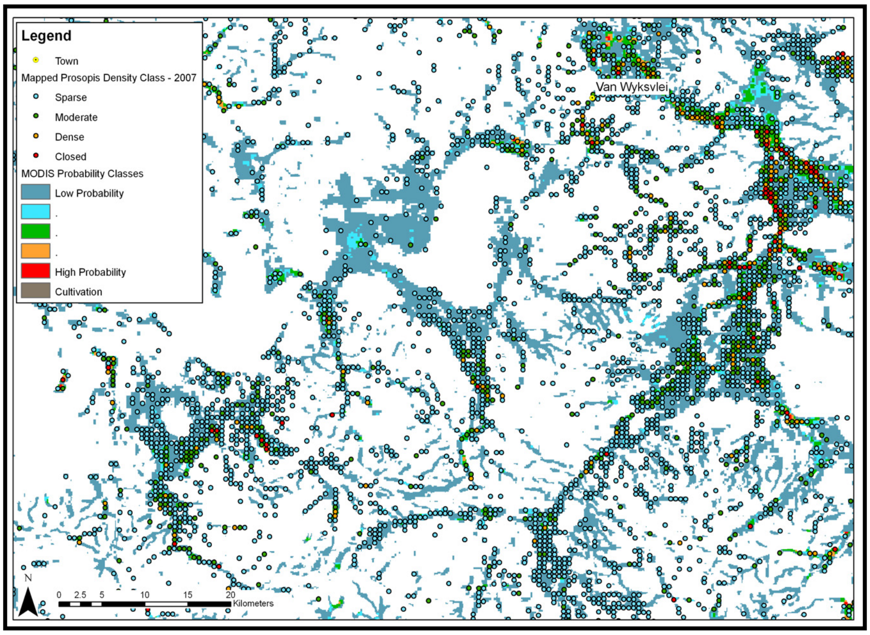

Figure 4: The distribution correspondence between the actually mapped density classes (points) of the Landsat 2007 data and the MODIS probability classes.

5.2 Invasion history of *Prosopis* from 1974 to 2007

According to our study, *Prosopis* was already highly dispersed in 1974 (127,821 ha) with most of the invasion occurring in the riparian areas (4.13%) and only 0.25% outside riparian areas (Table 2).

The rate of increase in canopy cover varied between riparian and lowlands, the most rapid rate of change being 13% in the riparian zone compared to only 0.25% in the lowlands (Table 2). The ratio of change in the riparian area compared to the lowlands has, however, turned around since 1990 with the most change now occurring on the lowlands. Expansion of *Prosopis* cover from 1990 to 2007 is visually displayed by the maps in Figure 5.

Table 2: Summary statistics for *Prosopis* cover from 1974 to 2007

Year	**1974**	**1990**	**2002**	**2004**	**2007**
Total area invested by *Prosopis* (ha)	127,821	314,580	480,515	711,285	1,473,953
% *Prosopis* of total land area	0.35	0.87	1.32	1.96	4.06
Number of *Prosopis* patches	79,578	253,825	400,366	497,974	640,253
Area of *Prosopis* in riparian zone (ha)	38,460	121,894	163,788	196,540	264,764
Area of *Prosopi*s outside riparian zone (ha)	89,360	192,684	316,726	514,744	1,209,188
% of riparian areas invaded	4.13	13.10	17.60	21.12	28.45
% outside riparian areas invaded	0.25	0.53	0.87	1.42	3.33

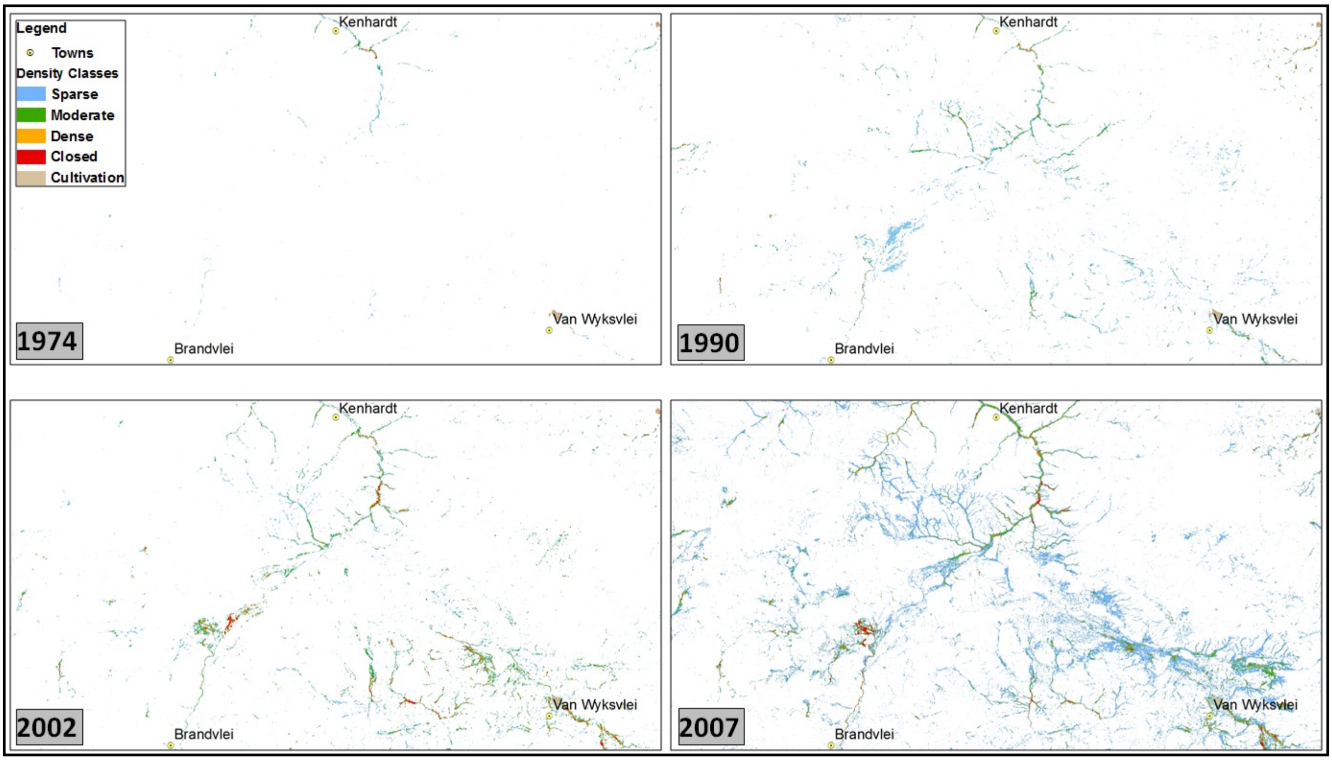

Figure 5: *Prosopis* cover for 1974, 1990, 2002 and 2007 for an area between Van Wyksvlei and Carnarvon. The *Prosopis* density classes are indicated by the different colours in the map.

5.3 Extent and densities of *Prosopis* canopy cover for 2007

The extent of *Prosopis* cover in the Northern Cape Province reached 1,473 million ha or 4% of the total land area during 2007 (Table 3). The condensed invaded area for all density classes combined was calculated to be 357,278 ha.

Table 3: Summary statistics of *Prosopis* cover during 2007

Total area invaded by *Prosopis* (ha)		1,473,953
Condensed invaded area		357,278
Percentage *Prosopis* on total land area (%)		4.06
Number of *Prosopis* patches		640,253
Total area per canopy density class (ha)	Sparse	1,017,030
	Moderate	293,169
	Dense	98,829
	Closed	64,923

5.4 Spatial dynamics of *Prosopis* in the Northern Cape Province

The total number of *Prosopis* patches over the province increased from 79,578 to 640,253 over the 33-year period from 1974 to 2007. Riparian zones had a relatively high point density and distance to nearest neighbour compared to the lowlands in 1974 (Table 4). *Prosopis* patches greater than 25ha were relatively uncommon in 1974. The number of patches increased substantially between 1974 and 2007 in all density classes, demonstrating continued patch recruitment (Figure

9). The density of 808 points showed an increase in canopy cover from sparse to closed, when compared between 1990 and 2007, while only 37 showed a decrease in canopy cover.

Table 4: Summary of *Prosopis* patch dynamics per density class from 1974 to 2007

Year		**1974**	**1990**	**2002**	**2004**	**2007**
Number of patches		79,578	253,825	400,366	497,974	640,253
Number of patches > 25ha		500	1,172	1,769	3,208	7,780
Number of grid points		5128	12385	19087	28431	58760
Number of points in riparian zone		1543	4799	6506	7856	10555
% Points in riparian zone		0.30	0.39	0.34	0.28	0.18
Area in riparian zone (ha)		38,461	121,895	163,789	196,541	264,765
Area outside riparian zone (ha)		89,360	192,685	316,727	514,744	1,209,188
% Riparian area invaded		4.13	13.10	17.60	21.12	28.45
% Lowland area invaded		0.25	0.53	0.87	1.42	3.33
Total area (ha)	Sparse	81,715	210,953	260,475	431,853	1,017,030
	Moderate	25,910	68,047	124,156	155,128	293,169
	Dense	12,199	24,931	69,964	81,865	98,830
	Closed	7,997	10,648	25,919	42,440	64,924
Average patch size (ha)	Sparse	1.78	1.41	1.21	1.69	27.30
	Moderate	1.31	1.03	1.04	1.05	17.86
	Dense	1.21	0.95	1.42	1.13	12.46
	Closed	2.16	0.91	1.62	2.00	26.79
Number of patches	Sparse	46,006	149,763	215,827	256,144	372,597
	Moderate	19,813	66,188	119,215	148,308	164,138
	Dense	10,051	26,221	49,347	72,286	79,286
	Closed	3,708	11,653	15,977	21,236	24,232

5.5 Assessment of classification accuracies

Accuracy assessment was performed by determining the percentage relationship between *Prosopis* presence observed in the field and that classified from image processing in an error matrix (Table 5).

Table 5: Error matrix of the relationship between reference data and the result of the 2007 Landsat image classification

Reference data			
Classification	*Prosopis* absent (1)	*Prosopis* present (2)	Row total
Prosopis absent (1)	726	203	929
Prosopis present (2)	288	632	920
Column total	963	835	1849
Overall accuracy = 1358/1849 = 73%			

The omission error (33%) describes the number of points that should have been classified as *Prosopis* but were omitted from the class. The commission error (22%) describes the number of points that were classified as *Prosopis* but in reality belong to other classes. Overall classification accuracy of 73% was reached with mapping the extent of *Prosopis* invasion in 2007 using Landsat TM data.

6. Discussion

Following the quantification of the rate of spread and spatial extent of *Prosopis* it can be concluded that this invasive tree is a significant threat to biodiversity and ecosystem services in the Northern Cape Province of South Africa. Earth observation data and GIS techniques proved to be a valuable tool to: (i) investigate and map areas susceptible to future *Prosopis* invasion, (ii) estimate the current extent and densities of *Prosopis* invasion, (iii) describe the spatial dynamics and (iv) assess the extent of transformation and fragmentation caused by *Prosopis* invasion on the natural vegetation in the Northern Cape Province.

The 9-year coarse resolution temporal MODIS EVI imagery combined with ancillary data proved to be very successful in predicting areas of possible future invasion as well as highlighting the relationship between habitat and *Prosopis* invasion. At first the 250 m x 250 m resolution of the MODIS data seemed to be too coarse for use in the study, but the temporal resolution more than compensated for that and it was possible to detect the moderate and large stands of *Prosopis*. It is believed that with some accuracy assessment and further refinement this procedure has the potential to be used as a long-term monitoring tool for *Prosopis* invasion.

Although the higher resolution Landsat images provided more accurate distribution data, the processing of the data was far more time consuming than moderate resolution MODIS images.

The multi-temporal Landsat data and the 500 m x 500 m point grid enabled vector analysis and statistical data to quantify the change in distribution and density as well as the spatial dynamics of *Prosopi*s since 1974. This modelling procedure can form a framework for similar assessment in future, providing that the data used are compatible and of the same quality. *Prosopis* is an aggressive invader increasing from 127,821 ha to 1,473,953 ha over the past 30 years, spreading rapidly over the landscape of the Northern Cape once it gets established, preferring riparian zones and alluvial lowlands rather than steeper rocky areas.

The densities and patch size of *Prosopis* trees have increased over the 30-year period suggesting high coalescence. Only 37 grid points showed a decrease in plant density, compared to 808 points with an increase in plant density between 1990 and 2007, almost 20 times more points, suggesting the longevity of the tree and stem- and seedling re-growth after control programmes.

Woodcock & Strahler (1987) discuss the difference between high resolution and low resolution imagery or spatial data and how the size and spatial relationship of the object of interest influence the variability within land-cover classes. In this study the fact that most of the *Prosopis* invasion occurs in drainage lines and many newly invaded areas are populated by young scattered trees which are generally not the dominant cover within a 500 m x 500 m cell due to their linear shape, emphasises the selection of the appropriate scale or resolution of data application and understanding of ecological processes, management applications and monitoring strategies.

Although the methodologies used in this study mainly focused on the invasion of *Prosopis* in the Northern Cape Province, they can be used to evaluate the invasion of this species in other arid and semi-arid areas, e.g. invaded areas in Namibia and Botswana.

To achieve long-term success with control programmes, IAP species need to be targeted with effective and integrated methods. Good baseline data forms the basis of any study or management programme, whether it is in a model trying to estimate the economic impact, determining carbon sequestration, monitoring habitat destruction or measuring water use. Detailed information of the total geographical extent of *Prosopis* invasion at a detailed temporal and spatial scale is not currently available for South Africa. Information like this can lead to the implementation of best practice management procedures to perform strategic follow-up surveillances and control programmes as well as early detection of new infestations over the entire distribution area of *Prosopis*. This might include the refinement and adoption of the procedure to include detailed airborne and satellite information to perform biomass estimates, and monitoring of management practices.

7. Acknowledgement

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